

**OPTIMIZATION OF ALCOHOL-GASOLINE BLENDED FUEL FOR  
IMPROVING PERFORMANCE AND REDUCING EXHAUST  
EMISSION OF A SPARK IGNITION ENGINE**

**MD. MASUM BILLAH**

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Name of the candidate: **Md. Masum Billah**

Registration/Matric No: **KGA 110036**

Name of the Degree: **Master of Engineering Science**

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## ABSTRACT

Alcohols are potential renewable alternatives to gasoline because of their bio-based origin. Alcohols with higher carbon number (such as propanol, butanol, pentanol and hexanol) have ability to dissolve properly with gasoline as like as ethanol. They possess higher energy content, octane number and can displace more petroleum gasoline than that of conventional ethanol-gasoline blended fuel. Therefore, this study focuses on improvement of different physicochemical properties using multiple alcohols at different proportion compared to that of the conventional ethanol gasoline blend. To optimize the properties of multiple alcohol-gasoline blends, properties of each fuel were measured. An optimization tool of Microsoft Excel “Solver” was used to find out the optimum blend. Based on properties test result, three optimum blends ratios were selected which possessed maximum heating value (MaxHV), maximum research octane number (MaxRON) and maximum petroleum displacement (MaxPD). Here, the MaxHV is the blend of 8.58% Propanol, 5.7% Butanol, 1% Pentanol and 84.72% Gasoline; and the MaxRON is the blend of 19.57% Propanol and 80.43% Gasoline; and the MaxPD is the blend of 4.8% Ethanol, 9.61% Propanol, 5.44% Pentanol and 80.15% Gasoline. The results from the above three optimized blended fuels were compared with two conventional fuels such as gasoline and E15 (15% Ethanol + 85% Gasoline).

A four-cylinder spark ignition engine was used to test above mentioned five (5) fuels. The engine was tested with different load and engine speed conditions. The collected parametric results were: engine torque, brake power, brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), CO, CO<sub>2</sub>, HC and NO<sub>x</sub> emission.

From test results, it can be found that all optimized blends performed well in SI engine. Among the optimized blends, MaxRON blend exhibits highest BTE and improvement in BSFC than that of E15. In terms of engine emission, MaxHV blend significant

reduction of CO, HC and NO<sub>x</sub> emission is achieved than that of E15 as well as gasoline, however, CO<sub>2</sub> emission is increased.

## ABSTRAK

Alkohol berpotensi sebagai alternatif yang boleh diperbaharui untuk petrol kerana sifat asal berasaskan bio mereka. Alkohol dengan jumlah karbon yang lebih tinggi (seperti propanol, butanol, pentanol dan hexanol) mempunyai keupayaan untuk larut sempurna dengan petrol seperti etanol. Mereka mempunyai kandungan tenaga yang lebih tinggi, nombor oktana dan ia boleh menggantikan lebih banyak petrol petroleum berbanding dengan bahan api sebatian etanol-petrol konvensional. Oleh itu, kajian ini memberi tumpuan terhadap memperbaiki sifat fizikokimia yang berbeza menggunakan pelbagai alkohol di bahagian yang berlainan berbanding dengan campuran etanol petrol konvensional. Untuk mengoptimumkan sifat-sifat pelbagai campuran alkohol petrol, sifat-sifat setiap bahan api telah diukur. Alat pengoptimuman Microsoft Excel "Solver" telah digunakan untuk mengetahui campuran yang optimum. Berdasarkan sifat-sifat hasil dari ujian, tiga campuran nisbah optimum telah dipilih yang mempunyai nilai maksimum pemanasan (MaxHV), bilangan maksimum oktana penyelidikan (MaxRON) dan anjakan petroleum maksimum (MaxPD). MaxHV adalah campuran 8.58% propanol, butanol 5.7%, 1% Pentanol dan 84.72% Petrol; MaxRON adalah campuran 19.57% propanol dan 80.43% Petrol; dan MaxPD adalah gabungan sebanyak 4.8% etanol, propanol 9.61%, 5.44% Pentanol dan 80.15% petrol. Tiga hasil dari campuran bahan api yang optimum itu kemudiannya dibandingkan dengan dua bahan api konvensional seperti petrol (100%) dan E15 (15% Ethanol + 85% Petrol).

Enjin pencucuh 4 lejang digunakan untuk menguji lima (5) bahan api yang dinyatakan seperti di atas. Enjin ini telah diuji dengan beban dan keadaan kelajuan enjin yang berbeza. Keputusan parametrik yang dikumpul ialah: kecekapan haba brek (BTE), penggunaan bahan api tentu brek (BSFC), Tork (kilas), pelepasan CO, CO<sub>2</sub>, HC dan NO<sub>x</sub>.

Keputusan ujian tersebut mendapati bahawa semua campuran yang optimum dalam enjin SI berprestasi baik. Di antara campuran yang optimum, campuran MaxRON menunjukkan BTE yang tertinggi dan peningkatan dalam BSFC berbanding dengan E15. Dari segi pelepasan enjin, campuran MaxHV dapat mencapai pengurangan pelepasan CO, HC dan NO<sub>x</sub> yang ketara berbanding dengan E15 dan juga petrol. Bagaimanapun, pelepasan CO<sub>2</sub> bertambah.

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## LIST OF ABBREVIATIONS

EPA	Environmental Protection Agency
IEA	International Energy Agency
EIA	Energy Information Administration
GHG	Green House Gases
ASTM	American Society for Testing and Materials
CR	Compression Ratio
PFI	Port Fuel Injection
RON	Research Octane Number
RVP	Reid Vapor Pressure
HoV	Heat of Vaporization
LHV	Lower Heating Value
C <sub>2</sub>	Ethanol
C <sub>3</sub>	Propanol
C <sub>4</sub>	Butanol
C <sub>5</sub>	Pentanol
C <sub>6</sub>	Hexanol
SI	Spark Ignition
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
ExT	Exhaust gas Temperature
HRR	Heat Release Rate
BSCO	Brake Specific Carbon monoxide
BSCO <sub>2</sub>	Brake Specific Carbon dioxide
BSHC	Brake Specific Hydrocarbon

BSNO <sub>x</sub>	Brake Specific Nitrogen oxides
CO	Carbon monoxide
CO <sub>2</sub>	Carbon dioxide
HC	Hydrocarbon
NO <sub>x</sub>	Nitrogen oxides
E15	15% Ethanol + 85% Gasoline
E10	10% Ethanol + 90% Gasoline
MaxRON	Blend of Maximum Research Octane Number
MaxPD	Blend of Maximum Research Petroleum Displacement
MaxHV	Blend of Maximum Research Heating value
rpm	revolution per minute

# CHAPTER 1: INTRODUCTION

## 1.1 Overview

The dominant role of the combustion of fossil fuels is indisputable in modern society. It provides the largest and most reliable source of energy that drives both the global economy and our way of life. The negative side effects of this reliance have impacted economies, the environment, and human health. Fossil fuels are by nature a finite resource. The high cost of these fuels can be linked to large trade deficits. Price volatility has led to economic uncertainty. The detrimental effects to the environment are the result of pollutant emissions brought about by the burning of fossil fuels. These pollutants include particulate matter (e.g. soot), nitrogen oxides, unburned hydrocarbons, and greenhouse gases (e.g. CO<sub>2</sub>). More recently the physiological effects of particulate matter on human health have begun to be understood. For example, particulate matter has been linked to the decrement of lung function in children (Thurber et al., 1998).

Throughout history, the expansion of human civilization has been supported by a steady growth in our use of high-quality exosomatic energy. This growth has been driven by increasing population and increasing level of activity. The demographic data from the various countries of the world has been analyzed by many separate entities, including the United Nations. Figure 1.1 shows the expected future growth curve. As we learned to harness the energy sources around us we progressed from horse-drawn plows, hand forges and wood fires to our present level of mechanization with its wide variety of high-density energy sources. As industrialization has progressed around the world, the amount of energy each one of us uses has also increased, with the global average per capita consumption of all forms of energy rising by 50% in the last 40 years alone

(Chefurka, 2007). Figure 1.2 (a-b) shows a steady increase of population reaching about 8 billion along with sharp increase in Gross Domestic Product (GDP) from 1980 to 2030 (Colton, 2011). These have driven the energy demand to increase steadily till 2030 (Figure 1.2 (c)). Energy is a crucial factor for humanity to maintain the economic growth and high standard of living. The consumption of primary energy in the world is expected to reach 22.3 Giga tons of oil equivalent (Gtoe) in 2050, from the current 10 Gtoe (European Commission, 2006). Coal and oil provide 5.7 and 5.9 Gtoe and natural gas 4.1 Gtoe; renewable and nuclear energy contribute 3.4 and 3.2 Gtoe. This represents a significant structural change in the world fuel-mix, in particular after 2030, when renewable and nuclear energy sources benefit from a sustained development, which translates in a rapid increase of their market share: in 2050, 30% of world energy supply comes from non-fossil sources.

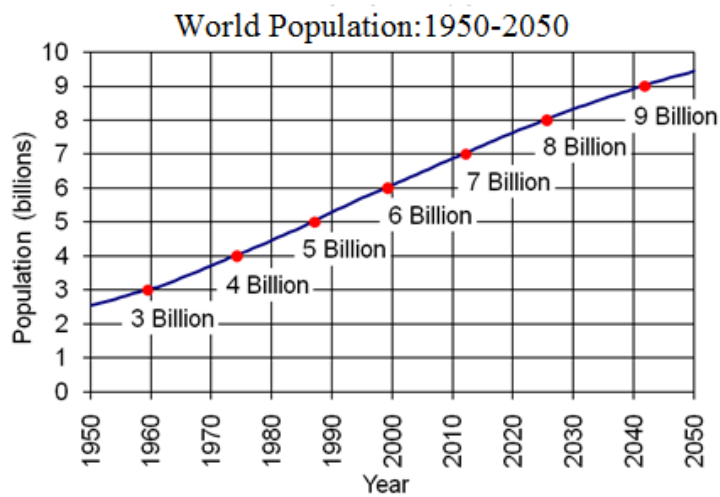


Figure 1.1: Projected world population growth (Bureau, 2011)



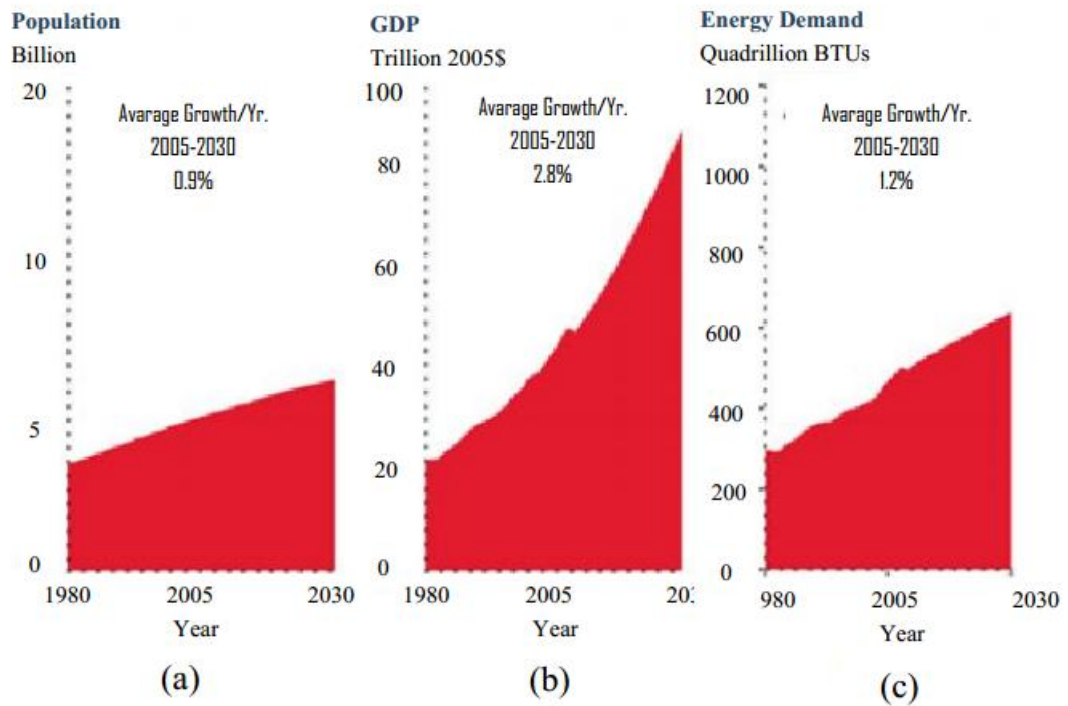


Figure 1.2: Global progress and demand of energy (Colton, 2011)

Historically, fossil fuels have played a vital role in the global energy demand. Fossil fuels are finite resources. Today, fossil based crude oil is the raw material for the fuel for aircraft, cars, busses, ships etc. For the last 40 years the oil requirements of our transportation modes have also increased steadily (Alekkett, 2009).

Nowadays, the most compelling technological concern of both energy demand and supplying issues are establishing the successor of fossil fuel-derived energy resources. Thus, biofuels especially, biodiesels are receiving significant attention because of these environmental as well as energy concerns. The use of biodiesel is becoming popular due to its adaptation with current transportation infrastructure and requires minimal modification for its use. Today, biofuels provide around 3% of total road transport fuel globally (on an energy basis), and considerably higher shares are achieved in certain countries as reported by International Energy Agency (2011).

The replacement of petroleum diesel with alternative fuels is an important issue among all energy based researchers and manufacturers. Increasing petroleum fuel price, threats to the environment from engine exhaust emissions, depletion of fossil fuels, global warming effects and energy concerns have generated more interest in alternative sources of fuel (Gürü et al., 2009). However, global energy consumption has increased sharply in recent decades. According to the IEA, global energy consumption will increase by about 53% by 2030 (Ong et al., 2011). The United States' EIA has projected that the world's liquid fuel consumption will increase from 86.1 million barrels/day, to 110.6 million barrels/day by 2035 (Cecrle et al., 2012). The emissions caused by the burning of petroleum-derived fuel also have a serious impact on both the environment and human health. One of the main sources of an increase in CO<sub>2</sub> emission is the burning of fossil fuels. This is largely responsible for an increase in global warming. It has been suggested that, if strict regulation concerning fossil fuel's emission is not taken soon, by 2030, an increase of 39% of GHG emission from fossil fuel will be observed. Several factors such as world-wide environmental concerns, price hiking of the petroleum products as well as the expected depletion of fossil fuel has promoted to look over the clean combustion using alternative-fuel sources (Mekhilef et al., 2011). Therefore, to develop clean alternative fuels those are locally available, environmentally acceptable and technically feasible have become a topic on the global agenda. Biofuels can be used as a good substitute for fossil fuels in the transport sector. There is no need to modify the engine or fuelling process to use biofuel, thus simplifies their adoption. Due to these reasons, biofuels are considered as one vital alternative to reduce CO<sub>2</sub> emissions and decrease reliance on fossil fuel. Moreover, it has several advantages such as: it is renewable, can provide energy security to a country for a long period of time and decrease reliability on imports or foreign volatile markets, and also production process can eliminate the unemployment problem. Figure 1.3 presents energy demand

until 2030, from this it can be seen that, the demand will be a significant amount which will be one of the key player to meet the future energy demand by 2030 (Tunison, 2011).

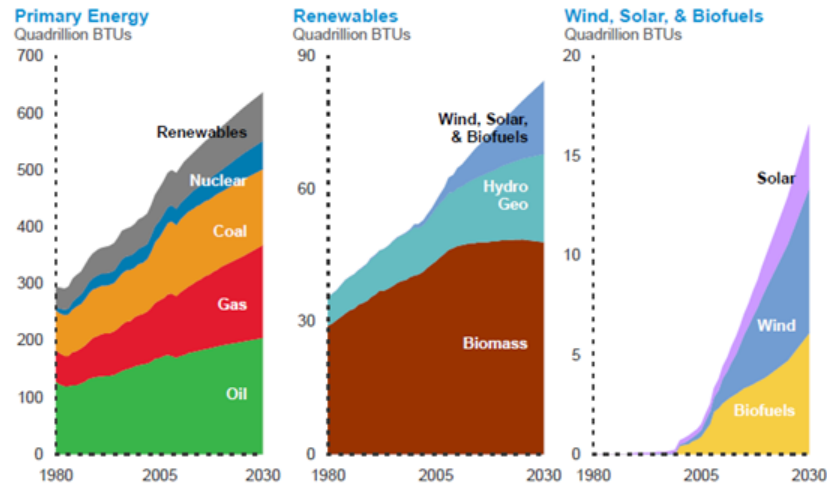


Figure 1.3: Energy demand until 2030 (Tunison, 2011)

As biofuel emit less GHG and engine exhaust emissions, have good safety and environmental characteristics, it can be an attractive alternative to petroleum-based fuel used in internal combustion engine. On the other hand, the use of crude vegetable oils as fuel may give rise to a variety engine problem, such as carbon deposits on piston and head of engine, coking of injectors on piston and head of engine, and also extreme engine wear (Jayed et al., 2011). In order to make biofuel the most promising alternative of petroleum, these problems need to be solved as soon as possible.

## 1.2 Background

The use of alcohols as substitutes for gasoline in spark ignition (SI) engines has been investigated extensively (Balki & Sayin, 2014; Manzetti & Andersen, 2015). This alcohol enriches oxygen, enhance octane, and reduce carbon monoxide (CO) emission. As an alternative fuel, ethanol is the most widely used alcohol type (Ayhan Demirbas, 2009). It can be combined with gasoline because of its simple chemical structure, high octane number and oxygen content, and accelerated flame propagation (Anderson et al., 2012). Many experimental studies (Al-Hasan, 2003; Bailey, 1996) have confirmed that ethanol increases engine efficiency, torque, and power. However, its brake specific fuel consumption (BSFC) is higher than that of gasoline (Koç et al., 2009).

Balki et al. (2014) studied the performance, combustion, and emission characteristics of a single-cylinder gasoline engine fuelled by gasoline, ethanol, and methanol. Pure ethanol and methanol enhanced torque by 3.7% and 4.7%, at the expense of a 58% and 84% increase in BSFC, respectively, compared with those of gasoline fuel. NO<sub>x</sub>, CO, and HC emissions by engines containing methanol and ethanol decreased by 49% and 47.6%, 22.6% and 21.25%, and 21.6% and 19.13%, respectively, compared with those emitted by gasoline. However, CO<sub>2</sub> emissions increased by 4.4% and 2.51% respectively. Costa & Sodr  (2010) investigated the performance and emission of hydrous ethanol (6.8% water content) and a blend of 78% gasoline–22% ethanol (E22) at varying engine speeds. Hydrous ethanol displayed a higher break thermal efficiency (BTE) and BSFC than E22 throughout the entire speed range. Moreover, hydrous ethanol reduced CO and HC emissions but increased CO<sub>2</sub> emissions. Koç et al. (2009) experimentally investigated the performance and pollutant emissions of unleaded gasoline–ethanol blends. The torque and BSFC values of E50 and E85 were higher than those of gasoline by 2.3% and 2.8% and 16.1% and 36.4%, respectively. Moreover, the addition of ethanol to gasoline significantly reduced CO, HC, and NO<sub>x</sub> emissions.

Ethanol–gasoline blends also accommodated high compression ratios without inducing knocking due to high octane number.

In many countries, governments mandate the integration of ethanol with gasoline. The Environmental Protection Agency (1994) issued a waiver that authorizes the incorporation of up to 15% ethanol into gasoline for cars and light pickup trucks made in 2001 onwards (Wald, 2010). The US Renewable Fuel Standard mandates the production of up to 36 billion gallons of ethanol and advanced bio-fuels by 2022 (Report Rabobank, 2012).

Certain properties of ethanol make it less desirable as an alternative of gasoline. One of the major restrictions related to the use of ethanol is its low heating value. To meet the high demand of alternative fuel, alcohols (such as butanol, pentanol etc.) with higher carbon numbers can be utilized as enhanced alternatives because the use of ethanol as fuel in gasoline engines is mainly limited by its low heating value. Alcohols with high carbon numbers have a higher LHV than ethanol. The advantages of a higher octane number of ethanol may be properly utilized by blending with higher carbon number alcohol as high carbon number alcohol having a low octane number. Thus, multi-alcohol gasoline may provide better results in fuel property as well as engine output. On the other hand all of these alcohols can be produced from coal-derived syngas that is a renewable source (Campos-Fernandez et al., 2013). Moreover, the concept of biorefinery for higher-alcohol production is to integrate ethanol formation via fermentation with the conversion of this simple alcohol intermediate into higher carbon number alcohols (Olson et al., 2004). Some authors have optimized fuel properties using blends of multiple alcohols with gasoline and get better fuel properties than conventional ethanol gasoline blend (Lawyer et al., 2013).

Some studies have compared different alcohol—gasoline blends (Gravalos et al., 2013). Gravalos et al. (2013) integrated approximately 1.9% methanol, 3.5% propanol, 1.5% butanol, 1.1% pentanol, and variable concentrations of ethanol with gasoline in a single-cylinder gasoline engine. A total of 30% alcohol was incorporated into the gasoline. The alcohol—gasoline blend emitted less CO and HC but more NO<sub>x</sub> and CO<sub>2</sub> than pure gasoline. In the present study, multiple alcohol—gasoline blends also emit more acceptable levels of CO and HC than the ethanol—gasoline blend. Yacoub et al. (1998) integrated methanol, ethanol, propanol, butanol, and pentanol with gasoline in an engine and analyzed its performance and emissions. Each alcohol was blended with gasoline containing 2.5% and 5% oxygen. The alcohol—gasoline blend displayed better BTE, knock resistance, and emissions than gasoline, but its BSFC was higher. Alcohols with low carbon content (e.g. C<sub>1</sub>, C<sub>2</sub>, and C<sub>3</sub>) contain high levels of oxygen. Hence, relatively less of these alcohols are required to reach the targeted oxygen percentage than alcohols with high carbon content (e.g., C<sub>4</sub> and C<sub>5</sub>). Alcohol percentage and properties varied across blends. Thus, different alcohol—gasoline blends cannot be compared properly under optimized oxygen concentrations. Gautam et al. (2000) prepared six alcohol—gasoline blends with various proportions of methanol, ethanol, propanol, butanol, and pentanol that total 10% alcohol. The alcohol—gasoline blends emitted lower brake specific CO, CO<sub>2</sub>, and NO<sub>x</sub> than pure gasoline. However, they did not blend alcohols in any specific volume percentage or considering fuel properties.

Engine performance, combustion and emission are directly affected by the physicochemical properties of fuel. However, no research has been done considering to improve fuel properties of the multi alcohol gasoline blend. There is a lack of research on optimization of fuel properties of multiple alcohol-gasoline blends and their effect on engine performance, combustion and emission. Other hand, these days many research are going on producing higher carbon number alcohols from renewable sources

(Ammar, 2013; Grotkjaer et al., 2011; Jain & Yan, 2011; Komonkiat & Cheirsilp, 2013; Lan & Liao, 2013).

### **1.3 Objectives of study**

In this research work, total five alcohols were used which are ethanol, propanol, butanol, pentanol and hexanol with gasoline. The considered aims of study are as follows:

- To investigate fuel properties of ethanol, propanol, butanol, pentanol, hexanol, gasoline and their blends.
- To improve fuel properties than traditional ethanol-gasoline blend, optimum blend ratio will be found by using ethanol, propanol, butanol, pentanol, hexanol and gasoline.
- To investigate engine performance, combustion characteristics and emission at different engine operation conditions using optimum blends, E15 and gasoline fuels.

### **1.4 Scope of work**

This study aims to analysis the possibility of multi-alcohol-gasoline blends in gasoline engine and ethanol, propanol, butanol, pentanol and hexanol were used as alcohol. Physicochemical properties of alcohols such as lower heating value, Reid vapor pressure, research octane number, density, oxygen content, heat of vaporization are comprehensively discussed and compared with gasoline. Possible combinations of all alcohol with gasoline are calculated and the properties of the fuel blends are predicted theoretically and valid with experimental data. Among the entire blend combination

three blend ratios are chosen on the basis of maximum LHV, maximum RON and maximum petroleum displacement. Finally, engine performance and emission analysis was carried out with those three optimized blend and compared with E15 and gasoline.

## **1.5 Organization of dissertation**

This dissertation is made up of five chapters. The organization of the chapters is listed as follows:

**Chapter 1** gives a short overview of the research topic together with specific goals to be achieved. This section comprises of requirement of energy, problems of fossil fuel, its viable alternative, and advantages and disadvantages of alcohols as an alternative of gasoline. This is followed by a background that shows the uses of ethanol in gasoline engine and the problems associated with fuel properties of ethanol. After that, problems associated with ethanol and significance of multi-alcohol-gasoline blends was discussed. Finally, objectives and scopes of this study are discussed.

**Chapter 2** gives a brief of the alcohols as gasoline alternative. At first, the physicochemical properties of alcohol are described. The next part describes a general discussion about spark ignition engine. Subsequently, the effect of alcohol blends with gasoline on engine performance and emission are described.

**Chapter 3** explains in detail the materials and experimental techniques to achieve the objectives of this study.



**Chapter 4** is dedicated to show all the results that have been obtained from the experimental work and present the findings of the study followed by a detailed discussion and analysis of these findings besides comparing them with the existing results included in the literature.

**Chapter 5** provides a summary of the key findings in the light of the research and puts forward some recommendations for the future studies.

## CHAPTER 2: LITERATURE REVIEW

### 2.1 Introduction

The consumption of energy has ever-increasing trend mainly due to two reasons: (1) changes in lifestyles and (2) the significant growth of the population. Petroleum-based fossil fuels presently provide the major portion of the energy supply; however, their sources are limited on this Earth. In the twentieth century, the research emphasis was on the development of fossil crude oil, coal, and natural gas based refinery to exploit the cheaply available fossil feedstock to meet the growing demand of the population (Chandra et al., 2012). In the twenty-first century, the adverse effect of greenhouse gas emissions on the environment, together with declining petroleum reserves and future energy security, is pronounced well. The combustion of fossil fuels is a big contributor to carbon dioxide (CO<sub>2</sub>) emission, which is a direct contributor to global warming. Every year about 25 billion tonnes of CO<sub>2</sub> are generated worldwide by anthropogenic activities (T. Abbasi & Abbasi, 2011). Therefore, the present research is focused on alternative energy sources for sustainable development of the economy and society (Chandra et al., 2012). Fossil fuels still represent 80% of total energy supply whereas biofuel contribute only 1% (Azadi et al., 2012).

The main alternative fuels utilized so far are oxygenates (alcohol, ether etc.), vegetable oils and their esters, gaseous fuel (hydrogen, liquefied petroleum gas etc.), gas to liquids (GTL) and coal derivatives. Ethanol has attracted attention worldwide because of its potential use as an alternative automotive fuel (Ganguly et al., 2012). Use of ethanol as a fuel is not a new concept. In 1826, Samuel Morey developed an engine that ran on ethanol (Hardenberg, 1992). The use of ethanol blended with diesel was a subject of

research in the 1980s. At that time, it was shown that ethanol blends were technically acceptable as a fuel for existing engines. However, the relatively high production cost of ethanol at that time hindered its regular use and made it a backup fuel in cases of fuel shortages. However, the economics have become much more favorable for the production of ethanol and it is now able to compete with standard petroleum-based fuel (Hansen et al., 2005).

Nonetheless, the derivation of alcohols with high carbon numbers from renewable sources has increasingly been investigated (Ammar, 2013; Grotkjaer et al., 2011; Jain & Yan, 2011; Komonkiat & Cheirsilp, 2013; Lan & Liao, 2013). Higher carbon number alcohols can be produced from a variety of non-food biomass, such as forest wood feedstocks, agricultural residual and marine algae through the biochemical conversion process (A. Demirbas, 2007). In particular, the application of such alcohols as gasoline engine fuel must be examined extensively. Thus recently, investigations on higher chain alcohols, such as butanols, have received much interest. Butanols can mix well with gasoline fuel, and its energy density, octane number, flashpoint and boiling point are all higher compared with those of ethanol (Wei et al., 2014). Few researcher (Balamurugan & Nalini, 2014; Campos-Fernández et al., 2012; J. Campos-Fernandez et al., 2013) shows interest in other higher carbon number alcohols for engine test.

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

## **2.2 Alcohols as an alternative fuel**

Fuel derived from organic matter such as renewable plants and animal materials, industrial, and/or commercial, are known as biofuel. Examples of biofuels include ethanol (often made from corn in the United States and sugarcane in Brazil), biodiesel (produced from vegetable oils and liquid animal fats), green diesel (derived from algae and other plant sources) and biogas (methane derived from animal manure and other digested organic material). Biofuels are most useful in liquid or gas form because they are easier to transport, deliver and burn cleanly. Currently, the most popular biofuels are biodiesel and bioethanol. Nowadays, the most compelling technological concern of both energy demand and supplying issues are establishing the successor of fossil fuel-derived energy resources. Thus, biofuels especially, biodiesels are receiving significant attention because of these environmental as well as energy concerns. The use of biodiesel is becoming popular due to its adaptation with current transportation infrastructure and requires minimal modification for its use.

At present, blends of bioethanol and gasoline are more common in vehicles with fuel injection engines. Bioethanol and ethanol is practically the same product. They have the same molecular and structural formula, and are the same substance. In other words, bioethanol is just plain ethanol, which is produced from sugar derived from plants. Usually, it is produced from various feed stocks such as sugar cane, sugar beet, sorghum, grain, switch grass, barley, hemp, kenaf, potatoes, sweet potatoes, cassava, sunflower, fruit, molasses, corn, stover, grain, wheat, straw, cotton, and other biomass, as well as many types of cellulose wastes and harvests.

Generally, ethanol or bioethanol is more reactive than hydrocarbon fuels, such as gasoline (Costa & Sodre, 2010). It contains hydroxyl radicals as the polar fraction and carbon chains as the non-polar fraction; hence it can be easily dissolved in both non-

polar (e.g. gasoline) and polar (e.g. water) substances (Costa & Sodre, 2010). Because of the regenerative and biodegradable characteristics of ethanol, it is widely used as an alternative fuel at present. The use of gasoline containing 3–10 vol.% bioethanol is being promoted in many parts of the world for last few years (Yunoki & Saito, 2009). The use of pure ethanol requires some modifications to SI engines; thus low concentration blends of ethanol are usually used without any modification of the SI engine (Balat & Balat, 2009). Worldwide ethanol production in terms of feedstock can be categorized into three major groups (Balat & Balat, 2009):

1. Ethanol from sucrose-containing biomass such as sugar cane, sugar beet, sweet sorghum and fruits.
2. Ethanol from starchy biomass such as corn, milo, wheat, rice, potato, cassava, sweet potatoes, and barley.
3. Ethanol from lignocellulosic biomass such as wood, straw, and grasses.

### **2.3 Fuel properties of alcohols**

Alcohols are characterized as organic compounds with a hydroxyl functional group (-OH) bound to a carbon atom. The Table 2.1 shows the common name of alcohols up to six carbon counts together with their chemical composition. Alcohols contain oxygen as part of the hydroxyl group and the oxygen content is one of the main differentiating factors and will be used alternately with carbon count to distinguish between the different alcohols. For alcohols with a carbon count of 3 or higher, isomers exist that can be differentiated by their structure and the locating of the hydroxyl group. The straight chain isomer with the hydroxyl group connected to the terminal carbon is commonly referred to as n-isomer or 1-isomer (such as n-butanol or 1-butanol). The

branched isomer with the OH-group at the terminal carbon is called iso-structure. The properties of certain alcohol isomers with the same carbon count differ significantly based on structural differences. Also, there are significant limitations in the availability of property data especially for many of the less common isomers of longer-chain alcohols. Current production levels of the most common alcohol isomers, such as methanol, ethanol, iso-propanol, n-butanol and iso-butanol each exceed 1 billion lbs. per year.

Table 2.1: Overview of alcohols

Name	Carbon number	Chemical composition	Oxygen content (mass %)	Carbon content (mass %)	Hydrogen content (mass %)
<b>Ethanol</b>	2	C <sub>2</sub> H <sub>5</sub> OH	34.7	52.2	13.1
<b>Propanol</b>	3	C <sub>3</sub> H <sub>7</sub> OH	26.7	60.0	13.3
<b>Butanol</b>	4	C <sub>4</sub> H <sub>9</sub> OH	21.6	64.9	13.5
<b>Pentanol</b>	5	C <sub>5</sub> H <sub>11</sub> OH	18.2	68.2	13.6
<b>hexanol</b>	6	C <sub>6</sub> H <sub>13</sub> OH	15.7	70.6	13.7

The physical and chemical properties indicate the quality of fuel to be combusted in an engine. Engine combustion quality, performance and emission characteristics are dependent on them. Some of the properties alcohols as gasoline engine fuel are compared in Table 2.2. The significant physicochemical properties of methanol, ethanol and butanol are discussed below.

Table 2.2: Comparison of gasoline and ethanol fuel properties (A. Al-Hasan, 2003; Brown, 2008; Campos-Fernández et al., 2012; Celik, 2008; Chen et al., 2010; Kumar et al., 2013; Kumar et al., 2010; Sundar & Saravanan, 2011; Yeung & Thomson, 2012; Yücesu et al., 2006).

Property	Gasoline	Ethanol	Propanol	Butanol	Pentanol	Hexanol
Molecular weight (kg kmol <sup>-1</sup> )	114.15	46.07	60.1	74.12	88.15	102.18
Kinematic viscosity(mm <sup>2</sup> /s)	0.6	1.5	1.938	2.593	3.05	5.32
Oxygen (mass %)	0-4	34.7	26.6	21.6	18.1	15.7
Density (kg m <sup>-3</sup> )	765	785	803	809.8	814	814
Freezing Point(°C)	-40	-114	-126	-89.3	-75	-70
Boiling Point(°C)	27-225	78	97	117	138	158
Specific gravity	0.7-0.78	0.794	0.8	0.81	0.81	0.82
Heat of vaporization (kJ kg <sup>-1</sup> )	400	900	803	810	814	814
Heat of combustion(MJ/kg)	43.5	27	29.7	32.8	34.5	35.8
Reid vapour pressure at 37.8°C(kPa)	53-60	19.2	17.1	13.9	9.9	5.2
LHV (kJ kg <sup>-1</sup> )	44,000	26,900	30200	33100	34700	36000
Research Octane Number	91-100	107	104.9	98.3	85.8	69.3
Motor Octane Number	82-92	88.2	87.8	84.4	75.9	64.1
Cetane number	8	May-20	12	17	20	42
Flash point(°C)	-13	12	22	35	43	68
Auto ignition temperature(°C)	257	425	371	397	342	293
Water solubility	0	∞	∞	0	0	0
Colour	Colourless to light amber glass	Colourless	Colourless liquid	Colourless liquid	Colourless liquid	Colourless liquid

### 2.3.1 Ethanol

Ethanol with a chemical formula C<sub>2</sub>H<sub>5</sub>OH is a key component of alcoholic beverages. It is a colorless, transparent, neutral, volatile, flammable, oxygenated liquid hydrocarbon, which has pungent odor and a sharp burning taste (Ganguly et al., 2012). It is produced by both biological and physical process. Usually, it can be produced from a various feed stock such as sugar cane, sugar beet, sorghum, grain, switch grass, barley, hemp, kenaf, potatoes, sweet potatoes, cassava, sunflower, fruit, molasses, corn, stover, grain, wheat,

straw, cotton, other biomass, as well as many types of cellulose wastes and harvestings; this types of ethanol is called as bioethanol. Bioethanol production is readily achieved through fermentation of glucose in sugars and starchy biomass. There are two major ways to produce ethanol, one is alcoholic formation and another is the reaction of ethane with steam.

Alcoholic fermentation (Costa & Sodre, 2010):

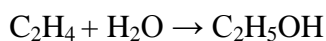


(Glucose)                      (Glucose)              (Fructose)



(Fructose)              (Ethanol)

Reaction of ethane with Steam:



(Ethane) (Steam)              (Ethanol)

Ethanol is a flammable polar solvent and is miscible with water. It has a vapor density of 1.59, which indicates that it is heavier than air. Consequently, ethanol vapors do not rise, similar to gasoline vapors. The specific gravity of ethanol is 0.79, which indicates that it is lighter than water; however, it is water-soluble. The auto-ignition temperature, boiling point, flash point, and melting point of ethanol are 425°C, 78°C, 12°C and -114°C, respectively (Bailey, 1996). Ethanol is less toxic than gasoline and methanol, and is not carcinogenic. Like gasoline, the major risk when using ethanol as a motor fuel is flammability. In pure form, ethanol burns without any smoke and it is difficult-to-see blue flame. In denatured form there is little to no smoke, but a slight orange flame may be visible. Due to high octane number, ethanol is a good fuel for gasoline engines (Cohn et al., 2013).



### 2.3.2 Propanol

As propanol is the most difficult and expensive alcohol to produce, many research is going on these days to produce it from renewable sources (Ammar, 2013; Grotkjaer et al., 2011; Jain & Yan, 2011). Methanol and ethanol have been studied extensively and they are used currently as gasoline additives. Both these fuels however, have low energy densities, relatively high vapor pressures, and they are notably hydroscopic. On the other hand, saturated C<sub>3</sub> alcohols, namely n-propanol and iso-propanol, have a better energy density and lower affinity for water compared to methanol and ethanol. Propanol has the potential to be used as a liquid fuel due to the characteristics which allow usage in current engines. Though both propanol isomers can be produced commercially via fermentation, currently they are produced largely from petro-chemical feedstocks (Veloo & Egolfopoulos, 2011).

### 2.3.3 Butanol

Butanol is a four-carbon atom alcohol that exists as four isomers: n-butanol CH<sub>3</sub>-CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>OH (normal-butanol), 2-butanol CH<sub>3</sub>CH<sub>2</sub>CHOHCH<sub>3</sub> (secondary-butanol), i-butanol (CH<sub>3</sub>)<sub>2</sub>CH<sub>2</sub>CHOH (iso-butanol) and t-butanol (CH<sub>3</sub>)<sub>3</sub>COH (tert-butanol). All of the isomers produce about the same energy, but the manufacturing methods for each are totally different. All four isomers have the same formulae and the same amount of heat energy but have different molecular structures that affect their properties. Despite their similar molecular weights and functional groups, they have different solubility.

n-Butanol is a linear aliphatic alcohol. It is a colorless, flammable, slightly hydrophobic liquid with distinct banana-like aroma and strong alcoholic odor. Direct contact may result in irritation to the eyes and skin, and its vapors have an irritant effect on mucous

membranes and a narcotic effect when inhaled in high concentrations. It is completely miscible with most common organic solvents, but only sparingly soluble in water. Iso-Butanol is a colorless liquid with sweet musty odor. It is miscible with all common organic solvents and only slightly soluble in water, while sec-butanol (2-butanol) is a flammable, colorless liquid that is slightly soluble in water and completely miscible with polar organic solvents. t-Butanol (3-butanol) is a clear liquid with camphor-like odor. It is highly soluble in water and miscible with ethanol and diethyl ether. It has a tendency to be solid at room temperature (melting point slightly above 251°C).

#### **2.3.4 Pentanol**

Pentanol is among the longer carbon-chain alcohols that could be blended with conventional fuels. An additional attractive advantage of pentanol is that they are molecules with significantly longer carbon-chains than ethanol, which means that they can be produced via processes that can consume substantially less energy than ethanol, since the biological processes that break down large macromolecules can stop earlier, i.e. at the level of a four-carbon alcohol, as opposed to continuing to the formation of a two-carbon alcohol which would require a comparatively larger energy investment (Campos-Fernández et al., 2012). Pentanol have higher energy density and cetane number comparing with ethanol and butanol. The properties of n-pentanol are presented also in Table 2.2. It is seen that its physical properties are similar to those of gasoline fuel, such that, it is likely to be a more attractive additive to gasoline fuel, among all the alcohols

### **2.3.5 Hexanol**

Hexanol has a higher energy density (i.e., LHV) than ethanol, which would lead to better vehicle fuel economy. The long alkyl chain of 1-hexanol will cause it to be more non-polar than ethanol, so it would have greater mixing stability and the potential to be blended at higher proportions with conventional fuels. Unlike ethanol, which is miscible with water, n-butanol and 1-hexanol are immiscible with water. Thus, 1-hexanol could be distributed in existing pipelines without risk of water contamination, and may lead to fewer storage and transportation problems. 1-Hexanol is less volatile and has less evaporative emissions compared to the other biofuels. As shown in Table 2.2, 1-hexanol has a lower vapor pressure than ethanol and n-butanol at any given temperature. However, octane number of hexanol is very low.

### **2.4 Combustion of spark ignition engine**

The sequence of events which take place inside the engine cylinder is illustrated in Figure 2.1. Several variables are plotted against crank angle through the entire four-stroke cycle. Crank angle is a useful independent variable because engine processes occupy almost constant crank angle intervals over a wide range of engine speeds. The figure shows the valve timing and volume relationship for a typical automotive spark-ignition engine. To maintain high mixture flows at high engine speeds (and hence high power outputs) the inlet valve, which opens before TC (Top dead Center), closes substantially after BC (Bottom dead Center). During intake, the inducted fuel and air mix in the cylinder with the residual burned gases remaining from the previous cycle. After the intake valve closes, the cylinder contents are compressed to above atmospheric pressure and temperature as the cylinder volume is reduced. Some heat

transfer to the piston, cylinder head, and cylinder walls occurs but the effect on unburned gas properties is modest.

Between 10 and 40 crank angle degrees before TC an electrical discharge across the spark plug starts the combustion process (John B Heywood, 1988). A distributor, a rotating switch driven off the camshaft, interrupts the current from the battery through the primary circuit of the ignition coil. The secondary winding of the ignition coil, connected to the spark plug, produces a high voltage across the plug electrodes as the magnetic field collapses. Traditionally, cam-operated breaker points have been used; in most automotive engines, the switching is now done electronically. A turbulent flame develops from the spark discharge, propagates across the mixture of air, fuel, and residual gas in the cylinder, and extinguishes at the combustion chamber wall. The duration of this burning process varies with engine design and operation, but is typically 40 to 60 crank angle degrees, as shown in Figure 2.1. As fuel-air mixture burns in the flame, the cylinder pressure in Figure 2.1 (solid line) rises above the level due to compression alone (dashed line). This latter curve-called the motored cylinder pressure-is the pressure trace obtained from a motored or non-firing engine. Note that due to differences in the flow pattern and mixture composition between cylinders, and within each cylinder cycle-by-cycle, the development of each combustion process differs somewhat. As a result, the shape of the pressure versus crank angle curve in each cylinder, and cycle-by-cycle, is not exactly the same.

There is an optimum spark timing which, for a given mass of fuel and air inside the cylinder, gives maximum torque. More advanced (earlier) timing or retarded (later) timing than this optimum gives lower output. Called maximum brake-torque (MBT) timing, this optimum timing is an empirical compromise between starting combustion too early in the compression stroke (when the work transfer is to the cylinder gases) and

completing combustion too late in the stroke (and so lowering peak expansion stroke pressures).

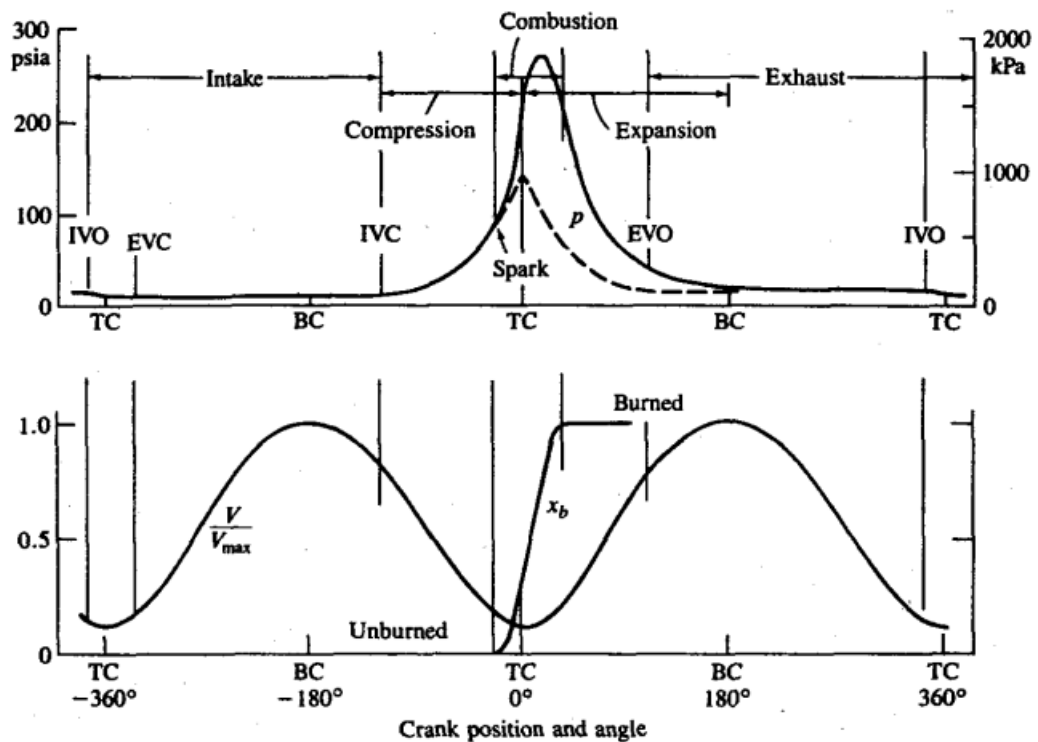


Figure 2.1: Different stages of combustion in SI engine (John B Heywood, 1988)

## 2.5 Exhaust gas emissions from spark ignition engines

Exhaust emissions from engine are a major contributor to air pollution due to the large number of vehicles on the road. However, emissions from motor vehicles have substantially changed over the last decade because of new fuels, changed engine designs, and improved emission-control technology. This section describes common pollutants that SI engines emit.

### 2.5.1 Nitrogen oxides

Under the high pressure and temperature conditions in an engine, nitrogen and oxygen atoms in the air react to form various nitrogen oxides, collectively known as NO<sub>x</sub>. NO<sub>x</sub> is a mixture of such compounds: nitric oxide (NO), nitrogen dioxide (NO<sub>2</sub>), nitrous oxide (N<sub>2</sub>O), di-nitrogen trioxide (N<sub>2</sub>O<sub>3</sub>), di-nitrogen tetroxide (N<sub>2</sub>O<sub>4</sub>), and di-nitrogen pentoxide (N<sub>2</sub>O<sub>5</sub>) (Cooper & Alley, 1994). Among them, nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>) are most prominent (Normann et al., 2009). The other five nitrogen oxides are known to exist, but in very small quantities. Nitric oxide is a colorless, odorless gas. Its ambient concentration is usually far less than 0.5 ppm. Nitrogen dioxide is a corrosive, toxic, and reddish-brown gas. It is quite visible in sufficient amounts (F. N. Alasfour, 1998; J.B. Heywood, 1995). Oxidation of nitrogen molecules at high temperature inside the cylinder is the cause of NO<sub>x</sub> formation as a byproduct (Chong et al., 2010).

During combustion of hydrocarbon fuels, some NO<sub>x</sub> is quickly formed before formation of thermal NO<sub>x</sub>, in the laminar premixed flame zone, which is known as prompt NO<sub>x</sub> (Fluent Inc., 2001). There is a good evidence that prompt NO<sub>x</sub> can be formed in a significant quantity in some combustion environments; such as in low-temperature, fuel rich conditions and where residence time is short. Prompt NO<sub>x</sub> is most prevalent in rich flames. The actual formation involves a complex series of reactions and many possible intermediate species. Generally, in low temperature (below 750°C) and fuel rich condition, nitrogen molecules react with hydrocarbon radicals to form amines or cyano compound. After that, these nitrogen-containing fragments react with atmospheric nitrogen to form NO.

### **2.5.2 Hydrocarbon**

Hydrocarbons are, quite simply, raw unburned fuel. When combustion does not take place at all, as with a misfire, large amounts of hydrocarbons are emitted from the combustion chamber. SI engines emit more hydrocarbon (HC) emissions than a diesel engine. The most common cause of excessive hydrocarbon emissions is misfire which occurs due to ignition, fuel delivery, or air induction problems. Depending on how severe the misfire, inadequate spark or a noncombustible mixture (either too rich or too lean) will cause hydrocarbons to increase to varying degrees. For example, a total misfire due to a shorted spark plug wire will cause hydrocarbons to increase dramatically. Conversely, a slight lean misfire due to a false air entering the engine may cause hydrocarbons to increase only slightly.

Excess hydrocarbon can also be influenced by the temperature of the air/ fuel mixture as it enters the combustion chamber. Excessively low intake air temperatures can cause poor mixing of fuel and air, resulting in partial misfire. Hydrocarbons react in the presence of nitrogen oxides and sunlight to form ground-level ozone, a major component of smog. Ozone irritates the eyes, damages the lungs, and aggravates respiratory problems. It is our most widespread and intractable urban air pollution problem. U.S. Environmental Protection Agency (1994) reported that a number of exhaust hydrocarbons are also toxic, with the potential to cause cancer.

### **2.5.3 Carbon monoxide**

Carbon monoxide is a poisonous gas. When inhaled, it replaces the oxygen in the blood stream so that the body's metabolism cannot function properly. Small amounts of CO concentration slow down physical and mental activities and produce headaches, while large amounts can kill. During combustion, CO is formed whenever charge is burned

with an insufficient air supply. Even the amount of air which is theoretically sufficient to complete combustion, in practical cases it may not be complete. This will lead to incomplete combustion products containing some free oxygen and some carbon monoxide. The CO emissions in the exhaust represent lost chemical energy that is not fully utilized in the engine (Ozsezen & Canakci, 2010). When the reaction temperature falls below 1500K, the burning deteriorates and the amount of CO increases. The OH radical is the one which transforms CO to CO<sub>2</sub> (Ilkilic & Behcet, 2010).

## **2.6 Effect of different alcohols on SI engine performance and emission**

Gasoline engine is an internal combustion engine with spark-ignition, designed to run on gasoline and similar volatile fuels and it was invented by German inventor Nicolaus August Otto in 1876 in Germany (Otto, 1877). Though gasoline engine designed for gasoline, alcohols has been use as a fuel for gasoline since their invention. Reports on the use of alcohol as a motor fuel were published in 1907 and detailed research was conducted in the 1920s and 1930s (J. L. Smith & Workman, 1980). The use of alcohols as substitutes for petrol in spark ignition (SI) engines has been investigated extensively. These alcohols enrich oxygen, enhance octane, and reduce carbon monoxide (CO) emission.

### **2.6.1 Ethanol**

In quest of renewable sources, researchers have tested many alternative sources. Among them bio-ethanol is by far the most widely used biofuel and is being used for transportation since nineteenth century (Al-Baghdadi, 2003; Balat & Balat, 2009; Koç



et al., 2009). However, if pure ethanol as fuel is used, some modification on the engine designs is necessary. The use of pure ethanol requires some modifications to SI engines; thus low concentration blends of ethanol are usually used without any modification of the SI engine (Balat & Balat, 2009). In this section, we provide a comprehensive review of the latest research regarding performance and emission behavior of gasoline engine using ethanol-gasoline blends.

Many experiments have been carried out to investigate the performance and emission of ethanol gasoline blend in gasoline engine (Schifter et al., 2013; Zhuang & Hong, 2013). Niven (2005) and Manzetti & Andersen (2015) reviewed the performance of emission of a gasoline engine when fueled with ethanol-gasoline blend. Manzetti & Andersen (2015) reported about the standard emission that bioethanol –gasoline blends reduces CO and HC emission, though CO<sub>2</sub> emission increase due to improved combustion. However, NO<sub>x</sub> emission depends on engine type rather than bioethanol-gasoline concentration.

Liu et al. (2011) studied, 10% and 20% ethanol in gasoline blends compared with gasoline in a three cylinder port fuel injection gasoline engine. Addition of ethanol increases oxygen content in fuel, thus with increasing ethanol fraction in the gasoline results in lower hydrocarbon (HC), carbon dioxide (CO<sub>2</sub>) and NO<sub>x</sub> emission than gasoline. Venugopal et al. (2012) studied the performance, emission and combustion characteristics in a port fuel-injected engine with 10% hydrous ethanol by volume in gasoline and compared with gasoline. Hydrous ethanol improved torque and thermal efficiency and lower HC at 25% throttle. They attributed this to presence of oxygen in the fuel and higher combustion rate. Costa & Sodré (2011) investigated the performance and emission of hydrous ethanol (6.8% water content) and 78% gasoline-22% ethanol blend (E22) with varying speeds on different compression ratio. They found hydrous ethanol produced higher break thermal efficiency (BTE) and break specific fuel

consumption (BSFC) than E22 in entire speed range but higher torque and brake mean effective pressure (BMEP) were observed for high engine speeds. Hydrous ethanol reduced CO and HC emissions but increased CO<sub>2</sub> emission.

Koç et al. (2009) experimentally investigated performance and pollutant emissions characteristics of gasoline-ethanol blend with two different compression ratios. The results showed that as an oxygenated fuel the addition of ethanol increases the engine torque and power by more complete combustion. However, the fuel consumption was significantly higher for ethanol-gasoline blends for lower heating value of ethanol than gasoline. On the other hand, CO, HC and NO<sub>x</sub> emissions were reduced for adding ethanol with gasoline. They also found ethanol-gasoline blends allow use of higher compression ratio (CR) without occurrence of knocking. Turner et al. (2011) have used different blending-ratios of bio-ethanol from 0 to 100% with gasoline on direct injection spark ignition engine. It is seen that, ethanol increase peak in-cylinder pressure slightly. However, the in-cylinder pressure decreases for ethanol because of lower adiabatic flame temperature of ethanol. Also, adding ethanol into gasoline reduces engine-out emissions such as CO, HC and NO<sub>x</sub> emission and improved engine efficiency. They attributed these benefits to addition of bio-ethanol, which modifies the evaporation properties of the fuel blends and presence of oxygen within bio-ethanol molecule.

Latey et al. (2004) experimentally investigated performance, combustion and emission on a motorcycle engine using 5% methanol with different volume of gasoline-ethanol blends (5%, 10%, 15% and 20% by volume with gasoline). Blend with 5% methanol, 20% ethanol and 75% gasoline shows better performance and combustion with lower emission compared to gasoline. Further, Hsieh et al. (2002) investigated engine performance and emission of different ethanol-gasoline blends (E0, E5, E10, E20, E30) under various throttle valve openings. They found improvement in engine torque for using ethanol with gasoline. In the term of engine exhaust emission, ethanol-gasoline

blends reduce CO and HC emission with the increase of CO<sub>2</sub> emission. NO<sub>x</sub> emission result was not stable with ethanol addition. Despite of all advantages of ethanol, ethanol-gasoline blended fuel consume more fuel than that of gasoline use. In another experiment, Al-Hasan (2003) found slightly different result on BSFC when ethanol-gasoline blends were tested in a gasoline engine. They found the decrease of BSFC with ethanol percentage increase up to 20%. Author explained, the higher latent heat of vaporization improve BTE as well as BSFC. However, ethanol reduce HC and CO emission with slightly increase of CO<sub>2</sub> emission.

Yücesu et al. (2006) used different ethanol-gasoline blend in a single cylinder gasoline engine on different compression ratio. In all compression ratios, the BSFC of ethanol-gasoline blends were higher than gasoline though using ethanol improve engine performance and reduces engine emission.

### **2.6.2 Butanol**

Increasing interest in butanol as a sustainable automobile fuel since the late 1990 s has led to a search for enhanced bio-butanol production processes that are more cost effective than petro-chemical production processes. Even though commercial butanol is currently produced exclusively by petrochemical routes, its production via microbial fermentation is not a new concept.

Butanol, a biofuel with the potential to solve many of the problems associated with ethanol. Butanol is better than ethanol in several ways: adding ethanol to gasoline reduces fuel mileage, but butanol has more energy than ethanol, meaning fewer more mileage. Butanol is less corrosive than ethanol, so more butanol can be blended in gasoline. And because butanol does not separate from gasoline in the presence of water,

it can be blended right at the refinery, while ethanol has to be shipped separately from gasoline and blended closer to the filling station (Abbasi, 2013).

Alasfour (1997a) compared engine performance of 30% butanol-gasoline blend and gasoline in a gasoline engine. They found lower BP, BTE and ExT for B30 than that of gasoline. They explained the lower heating value of iso-butanol is the reason of behind it. The exhaust gas temperature was reduced when the butanol-gasoline blend was used. This reduction is firstly due to alcohol's high latent heat of vaporization and secondly because of the low energy content per unit mass in the blend (energy contents: gasoline 43.5 MJ/kg; butanol 33.3 MJ/kg). Generally, lower exhaust gas temperature is an indication of a lower temperature through the entire engine cycle (Alasfour, 1997a).

In another experiment, Alasfour (1998) preheated the air 40 to 60°C to help vaporize the fuel mixture and used 30% iso-butanol-gasoline blend and gasoline as fuel. Significantly increase in BSFC and decrease in NO<sub>x</sub> emission was found for B30 than that of gasoline. In another study, Alasfour (1997b) found lower brake torque, IMEP and higher BSFC for B30 than gasoline. He explained higher LHV is the reason of better performance of gasoline than butanol blend. The maximum brake torque, IMEP and BSFC occurred with a slightly rich mixture and maximum BTE occurred on slightly lean mixture for both the gasoline and the butanol-gasoline blends. For lean mixtures, the alcohol-gasoline blends showed 11% low brake torque compared to pure gasoline.

Dernotte et al. (2009) used different butanol-gasoline blends on a port fuel-injection gasoline engine. HC emission was lower for lower concentrated butanol-gasoline blend (less than 40% butanol) and HC emission was significantly high for higher concentrated butanol-gasoline blend than that of gasoline. However, CO emission was high for butanol blended fuel. The oxidation of CO was difficult for butanol blended fuel. No

significant changes were observed in NO<sub>x</sub> emission when used butanol-gasoline blends instead of gasoline. Compared to gasoline, all butanol-gasoline blends increase SFC. Authors compared the SFC of butanol-gasoline with the SFC of ethanol-gasoline blend from literature and found that butanol consumed lower fuel than that of ethanol.

Butanol addition improves combustion stability by reducing the Coefficient of variation of Indicated Mean Effective Pressure (COV of IMEP). Analyzing in-cylinder pressure measurement has shown that butanol addition, even in small concentrations, reduced ignition delay by 2 CADs to 3 CADs and that the fully turbulent combustion phase (10%-90% MFB) was similar in duration for all blends and pure gasoline. Yang et al. (2011) optimize the spark timing for B35 fuel for better performance. They found higher torque and lower BSEC for B35 than that of gasoline. They found 48% reduction in HC emission, 22% reduction in CO emission and higher NO<sub>x</sub> emission for B35 than gasoline. As an oxygenated fuel, butanol has lower stoichiometric air fuel ration and make the combustion leaner.

Using 0% to 100% butanol in gasoline on a single cylinder PFI engine, Broustail et al. (2012) found decrease of HC for using butanol-gasoline blend than gasoline. Adding butanol with gasoline reduce maximum 30% of HC than that of gasoline. They explained, oxygen atom of in alcohol molecule favors the carbon oxidation process in CO and CO<sub>2</sub>, which reduce unburn HC. The NO<sub>x</sub> emission was slightly decreased for butanol-gasoline blends. However, the fuel consumption for butanol-gasoline blends was significantly lower than ethanol-gasoline blends. Gu et al. (2011) observed the emission characteristics of butanol-gasoline fuel in a gasoline engine with EGR. They found, butanol-gasoline blend reduce HC and CO emission than that of gasoline. However, the HC and CO emission for pure Butanol combustion was higher as because, the cylinder gas temperature dropped to evaporate pure butanol. Butanol reduces the NO<sub>x</sub> emissions, and this is due to the low adiabatic temperature and lower heating value

when engine operates with butanol. Alcohols require a considerable amount of heat to vaporize compared to gasoline. This high latent heat of vaporization leads to a significant reduction in combustion temperature inside the cylinder. That is why, 30% isobutanol blends produce lower NO<sub>x</sub> than gasoline.

Yasar (2010) found increase of HC emission for using butanol in low load but in high load, butanol reduces HC emission than that of gasoline. However, CO emission was lower for Butanol addition with gasoline as oxygenated fuel butanol give better combustion than gasoline. There were no significant trends of NO<sub>x</sub> for butanol addition with gasoline.

### **2.6.3 Propanol, pentanol and hexanol**

There have very few studies on propanol, pentanol or hexanol blended with gasoline for measuring performance and emission. However, higher carbon number alcohol can be a better alternative to fulfill the huge demand of ethanol. Some studies have been performed on multiple alcohol gasoline blends. Gravalos et al. (2013) used methanol, ethanol, propanol, butanol, pentanol with gasoline in a single cylinder gasoline engine. 1.9%, 3.5%, 1.5%, 1.1% of Methanol, propanol, butanol, pentanol were used respectively and ethanol percentage were varied so that there is a total 30% alcohol with gasoline. It was seen that, CO and HC emission were lower and NO<sub>x</sub> and CO<sub>2</sub> emission were higher for alcohol-gasoline blend than that of pure gasoline. In this study, higher-lower molecular mass alcohol gasoline blends were compared with ethanol gasoline blend as well. CO and HC emission were satisfactory for higher-lower molecular mass alcohol gasoline blend than ethanol gasoline blend. Yacoub et al. (1998) used methanol, ethanol, propanol, butanol and pentanol with gasoline to analyze performance and emission of a gasoline engine. In each blend, each alcohol was blended with gasoline

keeping oxygen content at 2.5% and 5%. Better BTE, knock resistance and emission with higher BSFC were found for alcohol gasoline blend than that of gasoline. However, alcohols having lower carbon content (e.g. C<sub>1</sub>, C<sub>2</sub>, C<sub>3</sub>) possess higher oxygen content, hence, relatively less amount of these are required to achieve the targeted oxygen percentage compared to higher carbon content alcohol (C<sub>4</sub>, C<sub>5</sub>). Neither alcohol percentage nor the properties were same or linear for each blend. For this reason, optimization considering oxygen content cannot give a proper comparison between different alcohol gasoline blends.

Gautam et al. (2000) prepared six blends with different proportion of methanol, ethanol, propanol, butanol, pentanol with gasoline having a total 10% alcohol in blend. All alcohol-gasoline blends produce lower brake specific CO, CO<sub>2</sub> and NO<sub>x</sub> emission than pure gasoline.

## CHAPTER 3: METHODOLOGY

### 3.1 Introduction

This chapter describes the research methodology and approaches for achieving objectives of current work. These include the selection of alcohols, characterization of different physicochemical properties, blend properties optimization, characterization of optimized blends, fuel blending for engine run, and engine emission and performance analysis. Figure 3.1 gives a brief summary of the implemented works of this research.

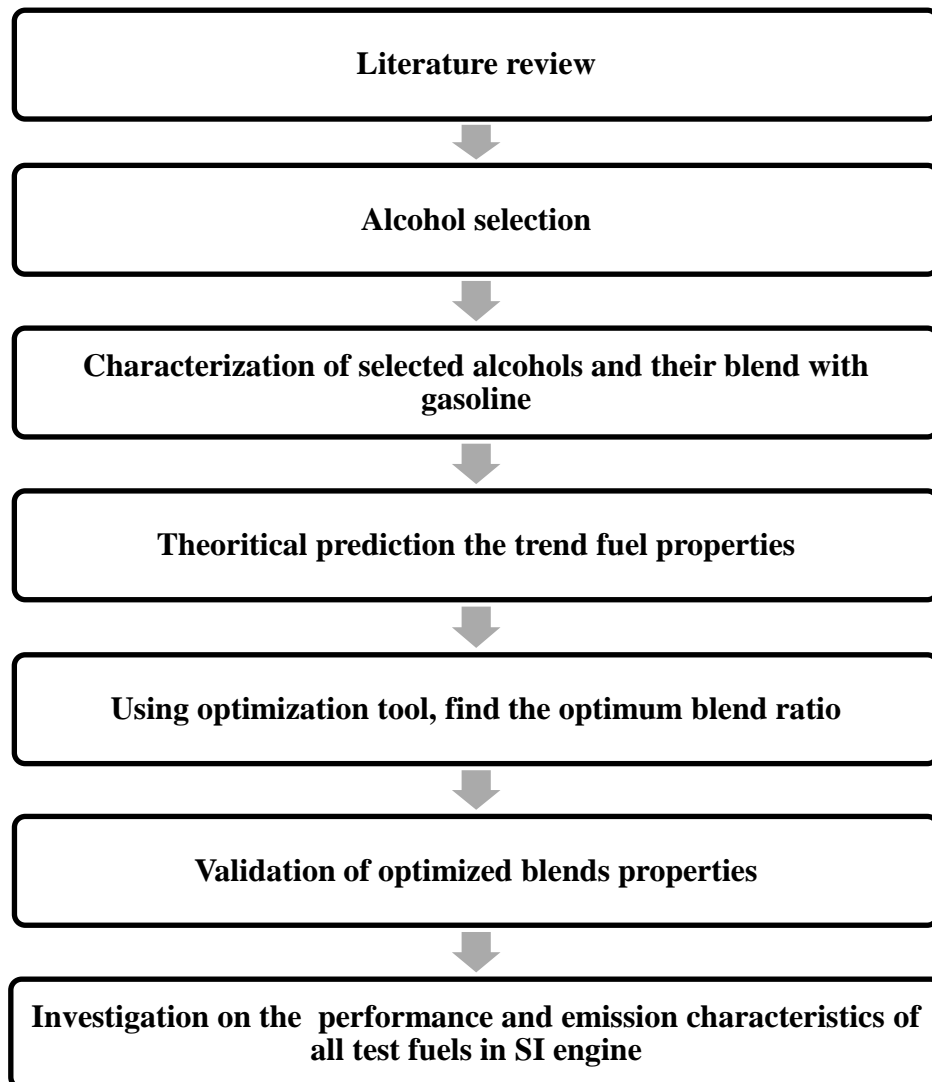


Fig 3.1: Flow chart of research methodology



### **3.2 Fuel selection**

In this study, we choose ethanol, propanol, butanol, pentanol and hexanol (99.8% purity). We utilized branched isomers of propanol, butanol and pentanol as they have higher octane numbers. However, straight isomer for hexanol was used due to its low cost compared to iso-hexanol (Moss et al., 2008). We procured the ethanol from Chemical Industries (Malaya) Sdn. Bhd., Malaysia and the other alcohols from QREC Chemical Company, Thailand. We obtained Primax 95 gasoline with research octane number 95 from PETRONAS, Malaysia as the base gasoline.

### **3.3 Measurement of fuel properties and equipment**

The quality of any fuel is expressed in terms of the fuel. In the evaluation of fuel, density, LHV, HoV, RON, and RVP are crucial to customer satisfaction, engine and legislative requirements, and the maintenance of industry standards. Thus, these fuel properties were compared in fuels containing volumetric amounts of different alcohols, including E15. In this experiment, fuel properties were measured using different apparatuses, as detailed in Table 3.1. Fuel RON was provided by the suppliers.

Table 3.1: Apparatus used for testing fuel properties

Property	Equipment	Manufacturer	Standard method
Density at 15°C	DM40 LiquiPhysics™ density meter	Mettler Switzerland	Toledo, ASTM D 4052
Lower Heating Value	C2000 basic calorimeter- automatic	IKA, UK	ASTM D240
Reid Vapor Pressure at 37.8°C	Setavap 2 Automatic Vapour Pressure Tester	Paragon Scientific Ltd, UK	ASTM D5191
Oxygen content	CE440 Elemental Analyzer	Exeter Analytical, Inc., US	
Latent Heat of Vaporization	Differential Scanning Calorimetry	METTLER TOLEDO, UK	

### 3.3.1 Density

Density is defined as the ratio of mass to volume of fuel. In this research work, the density of all fuel samples were measured using DM40 LiquiPhysics™ density meter according to ASTM D 4052 test method at 15°C temperature. In this equipment, both cells are filled in one cycle and the measurements are carried out simultaneously. After switching ON, the equipment initializes performing self-checks. After the indication sound it adjusts the temperature according to mode defined settings and prepares for test. To measure density at 15°C, the equipment mode was set at “M0: ASTM precise measurement”. After injection of sample and pressing of designated button it starts the measurement. During measurement, the equipment shows the deviation of the test results and prompts for new sample. After 2-3 subsequent measurements, the display shows the results with indication “RESULT VALID”. The average value of three repeated measurements is shown in the results section.

### 3.3.2 Lower heating value measurement

The heating value is the amount of heat produced by combustion of a unit quantity of a fuel. The lower heating value (LHV) is the amount of heat produced by the complete combustion of a unit quantity of fuel. The lower heating value is obtained when

- subtracting the latent heat of vaporization of the water vapor formed by the combustion.

The lower heating value of all the samples used in this research work was determined using IKA C 2000 bomb calorimeter. This equipment is used to determine the higher heating value of the solid and liquid fuel according to D240, D4809, D1929, D5468 and D5865. In this equipment, the whole bomb, pressurized with excess pure oxygen (at 30 atm) and containing a weighed mass of a sample (typically 0.5g to 0.6g) and a small fixed amount of water, is submerged under a known volume of water before the charge is electrically ignited. The weighed reactant put inside the steel container is then ignited. Energy is released by the combustion and heat flow from this crosses the stainless steel wall, thus raising the temperature of the steel bomb, its contents, and the surrounding water jacket. The temperature change in the water is then accurately measured with a thermometer. This reading, along with a bomb factor (which is dependent on the heat capacity of the metal bomb parts), is used to calculate the energy given out by the sample burn. The average value of three repeated tests per sample is presented in the results section.

### **3.3.3 Reid vapor pressure**

The Setavap 2 automatic vapor pressure tester was used for the measurement of gasoline, alcohols and other blends vapor pressure at 37.8°C temperature. All functions are accessed via a two button keypad and a rotary control. The digital display leads the operator through the test sequence, displays the instrument status and the test results. An audible prompt is sounded when an action is required from the operator. A sample is injected through a septum into a fixed volume chamber that is maintained at 37.8°C ± 0.1°C. The vapor to liquid ratio is 4:1. The pressure is automatically measured at one minute intervals until three readings are within 0.1 kPa, which determines the end of the test.

Results can be displayed as total pressure (P<sub>tot</sub>), dry vapor pressure equivalent (DVPE), EPA requirements, or Reid using pre-programmed correlation equations, and may be printed via the integral RS232 port and optional 81002-2 printer. A facility is included to allow two part tests to be conducted at 37.8 °C. All valve operations are automated including sample draining and chamber venting and purging. The valves utilize solvent resistant Kalrez seals. Calibration of temperature and pressure is automated and simple to carry out. The average value of three repeated tests per sample was collected.

### **3.3.4 Oxygen content**

In the CE440 Element Analyzer the oxygen content in fuel blends were determined. Combustion of the weighed sample (typically 1-3 mg; in certain cases up to 500 mg) occurs in pure oxygen under static conditions. With a conversion kit oxygen was analyzed. Before start of each run the entire system was flushed with helium at a high flow rate while the sample is in the cool zone. For oxygen analysis, the combustion

tube was replaced by a pyrolysis tube containing platinized carbon. The reduction tube is replaced by an oxidation tube containing copper oxide. The sample pyrolyzed in helium so that carbon monoxide is formed from oxygen in the sample. The CO is oxidized by the copper oxide to form carbon dioxide, which is detected and measured oxygen content. While the sample gas is displaced through the detectors, the output signals are recorded. At the end of the cycle, the exhaust valves were opened to allow the sample gases to escape to the atmosphere.

### **3.3.5 Latent heat of vaporization**

Differential scanning calorimetry (DSC) is a technique for measuring the energy necessary to establish a nearly zero temperature difference between a substance and an inert reference material, as the two specimens are subjected to identical temperature regimes in an environment heated or cooled at a controlled rate. It measures heat changes (enthalpy) as a function of temperature or time. The difference in heat flow is detected between an empty sample pan and a pan containing a sample. Samples may be solid or liquid but must not decompose or give off any volatiles during the test.

## **3.4 Blend optimization**

### **3.4.1 Fuel properties prediction method**

To identify the optimum blend, we must determine the physicochemical properties of alcohol—gasoline blends in relation to engine operation. In the evaluation of fuel, density, LHV, HoV, RON, and RVP are crucial to customer satisfaction, engine and legislative requirements, and the maintenance of industry standards. Thus, these fuel

properties were compared in fuels containing volumetric amounts of different alcohols, including E15. Under basic assumptions regarding the mixture, we directly calculated some of these properties, including density, LHV, HoV, and oxygen content. These calculations remain straight forward regardless of the number of components in the blend because the properties of these components are linearly combined. Equation 3.1 is used to find the volumetric properties of a blend composed of n components with corresponding  $v$  volumetric concentration.

$$property_{blend} = \sum_{i=1}^n v_i \times property_i \quad (3.1)$$

The volumetric integration of alcohol with gasoline nonlinearly modifies octane number (Szybist et al., 2010). Therefore, Anderson et al. (2010) suggested molar alcohol concentration as a more appropriate measure to describe the dependence of RON and motor octane number on alcohol content. They simplify the calculation of RON by considering the molar fraction of alcohol in a blend. In Equation 3.2,  $x_{alc}$  is the molar fraction of alcohol in the blend.

$$ON_{blend} = (1 - x_{alc})ON_{base} + (x_{alc})ON_{alc} \quad (3.2)$$

The vapor pressure of the ethanol–gasoline blend is difficult to estimate because its solution is complex and non-ideal. To predict ethanol-gasoline blends vapor pressure, Reddy (2007) developed a model using the UNIFAC method. We apply this model in the current study. Equation 3.3 was used estimate the RVP of ethanol-gasoline blends.

$$RVP_{blend} = K_{gasoline}(V_{gasoline}/100)RVP_{gasoline} + K_{ethanol}(V_{ethanol}/100)RVP_{ethanol} \quad (3.3)$$

Here K and V represent the activity coefficient and volume respectively. K value of ethanol and gasoline were found out by using equation 3.4 and 3.5

$$K_{gasoline} = -7E-07(V_{ethanol})^3 + 0.0002(V_{ethanol})^2 + 0.0024V_{ethanol} + 1 \quad (3.4)$$

$$K_{ethanol} = 46.321(V_{ethanol})^{-0.8422} \quad (3.5)$$

For the alcohols with high carbon number (C<sub>3</sub>–C<sub>6</sub>), to predict RVP of alcohol-gasoline blends, Anderson et al. (2010) drawn the RVP curves based on experimental data and extrapolated in the alcohol–gasoline blend to predict the RVP in the blend.

### 3.4.2 Optimization tools

The blend properties were optimized using Microsoft Excel solver tools. This optimizer solves linear, non-linear, and integer programs within the spreadsheet. In the spreadsheet, the fuel volume concentrations were designated as decision variables, and volume concentration was changed to obtain the desired properties. The equations were used to predict the properties that inputted into Excel solver tools. The target values will be described in the next chapter. The three best fuel combinations among all the optimized combinations were considered those possess maximum heating value, RON, and petroleum displacement. Finally, the blends were prepared according to optimum blend ratio and tested the fuel properties in laboratory. The detail of optimization process is given in Appendix B.

### 3.4.3 Target properties for optimum blends

To evaluate the prospect of a substance as a fuel, it must first fulfill the desired properties. Hence, the total alcohol content of a multiple alcohol–gasoline blend must fall within a certain range. In this study, the fuel properties are considered energy content, octane number, oxygen content, petroleum displacement, and vapor pressure. Once these criteria and their target values are implemented, the properties of the multi-component blends are predicted and compared with those targets. We then examine the compositions of blends whose properties meet all of the target criteria. The trends are then identified and discussed in this paper.

The E10/E15 alternate scenario aims to identify multi-component blends that can be used in current engines and can enhance petroleum displacement, knock resistance, and/or energy content compared with E10/E15 while adhering to industry standards and consumer expectations. These blends contain adequate oxygen content to meet the EPA E15 waiver, a knock resistance equivalent to that of E10 or higher, vapor pressure that is within the standards of the American Society for Testing and Materials, a minimum energy content equal to that of E15, and petroleum displacement that is at least equal to that of E15. Table 3.2 summarizes these criteria and their values.

Table 3.2: Target value of optimum blends

Properties	Unit	Alternative fuel's target
LHV	MJ/kg	$\geq 41.65$
RON	--	$\geq 96.24$
RVP	kPa	34 to 62
Oxygen content	wt. %	$\leq 5.205$
Petroleum displacement	vol. %	$\geq 15\%$



### **3.5 Test fuel preparation**

Each test fuel blend (% vol.) was prepared prior to the engine test for every run. In this respect, all fuel components were mixed using a shaker machine (IKA®KS130 basic) by shaking it for 30 minutes at 400 rpm. As all alcohols and gasoline are evaporated in ambient temperature, fuel blend was done in closed bottle.

### **3.6 Engine test bed**

Experiment was done on a 1.6 L four-cylinder gasoline engine at the Engine Laboratory of the Mechanical Engineering Department in the University of Malaya (Figure 3.2). The detail of the engine is described in Table 3.3. The test engine was coupled with an eddy current dynamometer (Froude Hofmann model AG150, United Kingdom). The maximum power of used eddy current dynamometer is 150 kW.

We measured fuel flow using a KOBOLD ZOD positive-displacement type flow meter (Figure 3.3). The data were automatically collected using the CADET 10 data acquisition system. For combustion analysis a pressure sensor and a crank angle encoder (RIE-360) have been used. These two sensors together provide the in-cylinder pressure variation with crank angle. Digital data have been recorded in a computer using a software name DEWESoft Combustion Analyzer. In each test, performance, combustion and emission were measured in triplicate. These measurements were highly repeatable within the test series.

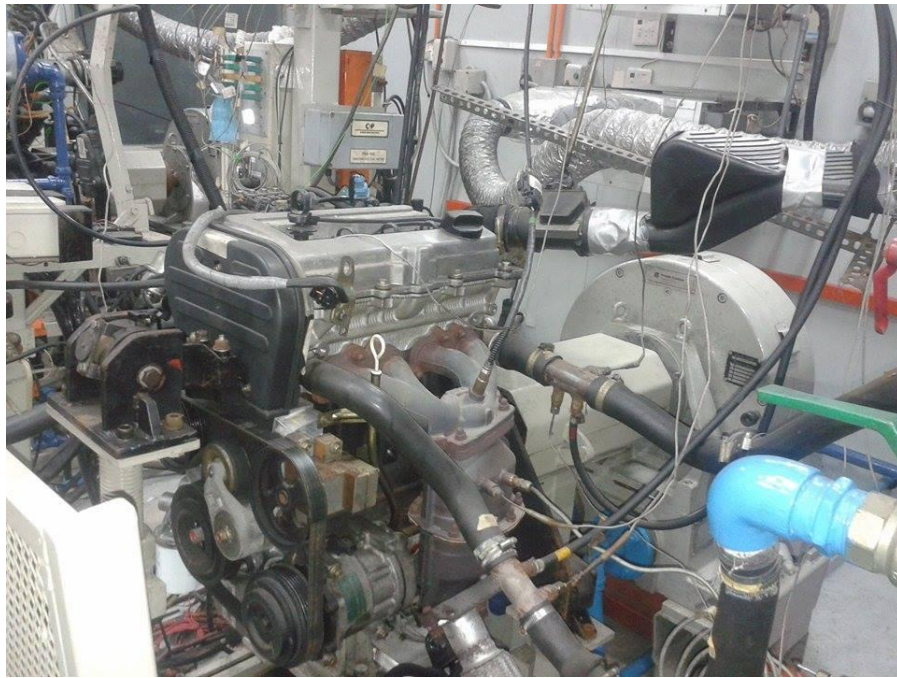


Figure 3.2: Proton Campro Engine test bed



Figure 3.3: Fuel tank with KOBOLD fuel flow meter

Table 3.3: Specification of the tested engine

Engine parameter	Value
Engine name	Proton Campro
Number of cylinder	4
Displacement volume	1596 cc
Bore	78 mm
Stroke	84 mm
Connecting rod length	131 mm
Compression ratio	10:1
Fuel system	Multi-point electric port fuel system
Max output	78kW at 6000rpm
Max torque	135N-m at 4000rpm

### 3.7 Engine exhaust gas analyzer

The exhaust emissions were measured using AVL DICOM 4000 exhaust gas analyzer. This analyzer incorporate automatic measurements with microprocessor control and self-test, auto calibration before every analysis and a high degree of accuracy in analysis of low concentrations of gases is found in engine fitted with the catalytic converter. Exhaust gas for the analysis was tapped from the exhaust pipe, approximately 2.0 meters from the exhaust valve. Emission results were taken for every speed step of the engine. However, for every engine speed, the engine was hold for 10 minutes in order to achieve the stability of exhaust gases before reading was taken. Details of the exhaust gas analyzer are given in Table 3.4. A pictorial view of the analyzer is shown in Figure 3.4.

Table 3.4: Specifications of the exhaust gas analyzer

	Measurement range	Resolution
CO	0-10% vol.	0.01 % vol.
CO <sub>2</sub>	0-20% vol.	0.1 % vol.
HC	0-20,000 ppm vol.	1 ppm
NO <sub>x</sub>	0-5,000 ppm vol.	1 ppm
O <sub>2</sub>	0-25 % vol.	0.01 % vol.



Figure 3.4: AVL DECOM 4000 emission analyzer

### 3.8 Engine performance and emission analysis

The schematic diagram of experimental setup is shown in Figure 3.5. Before taking data, the engine was first operated on gasoline for a few minutes to stabilize the operating condition. The fuel was then changed to the alcohol blend, when the sufficient amounts of the blend were consumed; data were acquired to ensure the removal of residual gasoline from the fuel line. Each test engine was again operated under gasoline to drain all of the blends in the fuel line. This procedure was followed for all the alcohol-gasoline blends. The engine was operated between 1000 rpm to 6000 rpm with a step of 1000 rpm at 100% load condition and 20N.m to 100N.m torque with step of 20N.m at 4000rpm engine condition. To convert the emission to g/kWh, the following equations were used which are described in 2002 SAE Handbook (Society of Automotive Engineers (SAE), 2002).

$$HC(g / kWh) = \frac{0.0287 \times HC_{conc} (ppm) \times \dot{m}_{exhaust} (kg / min)}{BP(kW)}$$

$$CO(g / kWh) = \frac{0.0580 \times CO_{conc} (ppm) \times \dot{m}_{exhaust} (kg / min)}{BP(kW)}$$

$$NOx(g / kWh) = \frac{0.0952 \times NOx_{conc} (ppm) \times \dot{m}_{exhaust} (kg / min)}{BP(kW)}$$

The engine performance is evaluated on torque, BSFC and BTE. The BSFC and BTE were calculated by following equations:

$$BSFC = \frac{\text{Fuel Consumption}}{\text{Output Power}}$$

$$BTE = \frac{3600 \times \text{Brake Power}}{\text{Fuel Consumption} \times LHV}$$

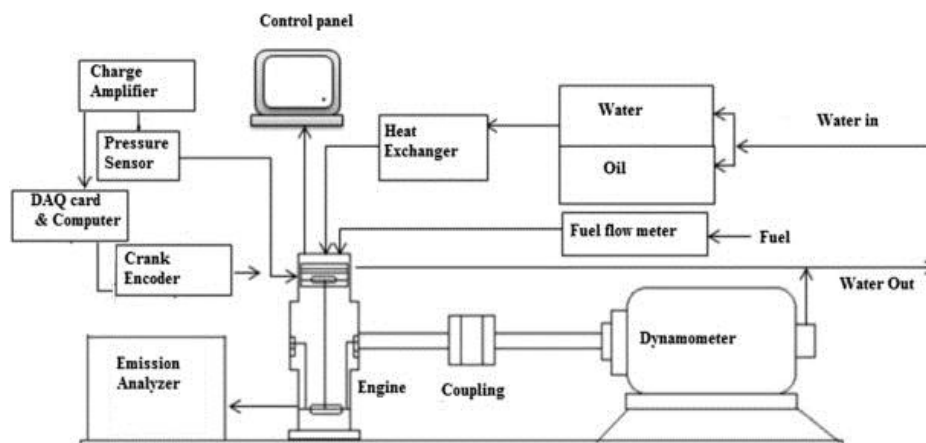


Figure 3.5: Schematic diagram of the engine test bed

### 3.9 Engine combustion analysis

For combustion analysis, the test system was equipped with necessary sensors. In-cylinder pressure was measured by using a Kistler 6058A type pressure sensor. It was installed in the spark plug port. Kistler 2614B4 type charge amplifier was used to amplify the charge signal outputs from the pressure sensor. A high precision Leine & Linde incremental encoder was used to acquire the top dead center (TDC) position and crank angle signal for every engine rotation. Simultaneous samplings of the cylinder pressure and encoder signals were performed by a computer with Dewe-30-8-CA data acquisition card. One hundred consecutive combustion cycles of pressure data were collected and averaged to eliminate cycle-to-cycle variation in each test. To reduce noise effects, Savitzky-Golay smoothing filtering was applied to the sampled cylinder pressure data.

Heat release rate (HRR) analysis is the most effective way to gather information for the combustion mechanism in SI engines. In the present study, different types of alcohol blended gasoline fuel were fueled in an identical spark ignition engine. Hence, HRR analysis is a significant parameter in understanding the combustion mechanism. Average in-cylinder pressure data of 100 consecutive cycles with a 0.1 crank angle (CA) resolution were used to calculate HRR. Analysis was derived from the first law of thermodynamics, as shown in Eq. (3.5), without taking into account heat loss through cylinder walls.

$$\frac{dQ}{d\theta} = \frac{V \frac{dP}{d\theta} + \gamma P \frac{dV}{d\theta}}{\gamma - 1} \quad (3.5)$$

Where,  $\frac{dQ}{d\theta}$  = rate of heat release (J/°CA), V = instantaneous cylinder volume (m<sup>3</sup>),

$\theta$  = crank angle ( $^{\circ}$ CA), P = instantaneous cylinder pressure (Pa),  $\gamma$ =specific heat ratio which is considered constant at 1.35 (Goering, 1998).

The input values are the pressure data and cylinder volume (with respect to crank angle). The V and  $\frac{dQ}{d\theta}$  terms are shown in the following equations:

$$V = V_c + A \times r \left[ 1 - \cos\left(\frac{\pi\theta}{180}\right) + \frac{1}{\lambda} \left\{ 1 - \sqrt{1 - \lambda^2 \sin^2\left(\frac{\pi\theta}{180}\right)} \right\} \right]$$

$$\frac{dV}{d\theta} = \left(\frac{\pi A}{180}\right) \times r \left\{ \sin\left(\frac{\pi\theta}{180}\right) + \frac{\lambda^2 \sin^2\left(\frac{\pi\theta}{180}\right)}{2 \times \sqrt{1 - \lambda^2 \sin^2\left(\frac{\pi\theta}{180}\right)}} \right\}$$

Here,  $\lambda = \frac{l}{r}$  and  $A = \frac{\pi d^2}{4}$ , where l = connecting rod length, r = crank radius =  $0.5 \times$  stroke, D = cylinder bore, and Vc = clearance volume.

### 3.10 Error analysis

Errors and uncertainties in the experiments can arise from instrument selection, condition, calibration, environment, observation, reading, and test planning. Uncertainty analysis was required to prove the accuracy of the experiments. The measurement range, accuracy and percentage uncertainties which associated with the instruments used in this experiment are listed in Table 3.5.

Table 3.5: List of measurement accuracy and percentage of uncertainties

Measurement	Measurement range	Accuracy	Measurement techniques	Uncertainty (%)
<b>Load</b>	±600 Nm	±0.1 Nm	Strain gauge type load cell	±0.25
<b>Speed</b>	0-10,000 rpm	±1 rpm	Magnetic pick up type	±0.1
<b>Time</b>		±0.1 s		±0.2
<b>Fuel flow measurement</b>	0.5-36 L/h	±0.04 L/h	Positive displacement gear wheel flow meter	±0.5
<b>Air flow measurement</b>	0.25-7.83 kg/min	±0.07 kg/min	Hot-wire air-mass meter	±2
<b>CO</b>	0-10% vol.	±0.01% vol.	Non-dispersive infrared	±1
<b>HC</b>	0-2000 ppm	±1 ppm	Heated flame ionization detector	±1
<b>NOx</b>	0-5000 ppm	±1 ppm	Electrochemical	±1.3
<b>CO<sub>2</sub></b>	0-20% vol.	±0.1% vol.	Non-dispersive infrared	±1.5
<b>Smoke</b>	0-100%	±0.1%	Photodiode detector	±1
<b>EGT sensor</b>	0-1200 °C	±0.3 °C	Type K thermocouple	±0.15
<b>Pressure sensor</b>	0-25,000 kPa	±10 kPa	Piezoelectric crystal type	±0.5
<b>Crank angle encoder</b>	2-12,000 rpm	±0.125°	Incremental optical encoder	±0.03
<b>Accelerometer</b>	±490 m/s <sup>2</sup>	±5 m/s <sup>2</sup>	Piezoelectric shear mode accelerometer	±1
<b>Computed</b>				
<b>BSFC</b>		±5 g/kWh		±1.5
<b>BTE</b>		±0.2		±1.5
<b>BSCO</b>		±0.05 g/kWh		±0.7
<b>BSHC</b>		±0.05 g/kWh		±0.7
<b>BSNOx</b>		±0.1 g/kWh		±2.5
<b>BSCO<sub>2</sub></b>		±0.1 g/kWh		±2.3

To compute the overall percentage uncertainty due to the combined effect of the uncertainties of various variables, the principle of propagation of errors is considered and can be estimated as ±3.88%. The overall experimental uncertainty was computed as follows (How et al., 2014):

$$\begin{aligned} \text{Overall experimental uncertainty} &= \text{Square root of } [(\text{uncertainty of speed})^2 + \\ &(\text{uncertainty of torque})^2 + (\text{uncertainty of BSFC})^2 + (\text{uncertainty of BTE})^2 + (\text{uncertainty} \\ &\text{of pressure sensor})^2 + (\text{uncertainty of crank angle encoder})^2 + (\text{uncertainty of BSCO})^2 + \\ &(\text{uncertainty of BSHC})^2 + (\text{uncertainty of BSNOx})^2 + (\text{uncertainty of BSCO}_2)^2] = \\ \text{Square root of } &[(0.1)^2 + (0.25)^2 + (1.5)^2 + (0.5)^2 + (0.03)^2 + (0.03)^2 + (0.7)^2 + (0.7)^2 + (2.5)^2 \\ &+ (2.3)^2] = 3.88\%. \end{aligned}$$



## **CHAPTER 4: RESULT AND DISCUSSION**

### **4.1 Introduction**

The results of all analysis done throughout the research is presented and discussed in this chapter. In the first section, physicochemical properties of all alcohols, gasoline along with their blends is shown. Then the optimized fuels properties are discussed. The improvement on fuel properties by optimization also will be discussed on this section. Finally, engine performance, emission and combustion characteristics of optimized blends are addressed and compared with gasoline and traditional alcohol-gasoline blend.

### **4.2 Physico-chemical properties of alcohols**

The fuel properties have been considered as one of the main factors influencing engine performance. Quality of fuel is assessed through the determination of physicochemical properties. In this research, physicochemical properties were measured using the equipment and methods mentioned in Section 3.3. The physicochemical properties of gasoline, ethanol, iso-propanol, iso-butanol, iso-pentanol and n-hexanol are presented in Table 4.1.

Table 4.1: Properties of alcohols and gasoline

Property	Unit	Gasoline	Ethanol	Iso-Propanol	Iso-Butanol	Iso-Pentanol	n-Hexanol
<b>Oxygen</b>	wt. %	0	34.7	26.6	21.6	18.1	15.7
<b>Density</b>	kg/m <sup>3</sup>	736.8	794.3	789.4	806	812.5	822.2
<b>LHV</b>	MJ/kg	43.919	28.793	32.947	35.689	37.622	38.968
<b>RON</b>		95	107.4	112.5	105.1	98.8	69.3
<b>RVP (at 37.8°C)</b>	kPa	63.9	19.1	13.8	6.6	2.9	2.8
<b>Latent heat of vaporization</b>	kJ/kg	349	923	761	683	621	484
<b>Specific gravity</b>		0.7375	0.795	0.7899	0.8067	0.8132	0.8229

Figure 4.1 shows the LHV of the neat fuels as a function of alcohol percentage. LHV linearly decreases with increasing alcohol content in the blend. An alcohol with a higher carbon number has more carbon-carbon bonds that are broken during combustion. An increase in the number of chemical bonds in addition to a lower weight percentage of oxygen increases the change in enthalpy during combustion which results in a higher energy content (M. B. Smith, 2013).

All of the alcohols have significantly lower energy content than gasoline. Also shown in Figure 4.1 is the percent decrease in energy content of the alcohols from gasoline. The alcohol with the highest LHV, n-hexanol, is only an 11.3% decrease from gasoline. The lowest LHV alcohol, ethanol, is a 34.5% decrease. The remaining alcohols have a LHV between ethanol and hexanol which amounts to a decrease of around 25% for propanol, 19% for butanol and 15% for pentanol relative to gasoline.

As can be clearly seen, increasing oxygen content of the alcohol almost linearly reduces the lower heating value from 43.9 MJ/kg for gasoline to 28.8 MJ/kg for ethanol. This almost 40% reduction in mass-specific energy content can be reduced with longer-chain alcohols such as butanol with a LHV penalty compared to gasoline of approximately 18% or hexanol with a respective penalty of only 11%. However, due to

their oxygen content the energy per unit mass is still significantly reduced compared to the gasoline baseline. However, lower LHV is the reason of higher BSFC for a fuel and also it effects on engine performance and emission (Ozsezen et al., 2009).

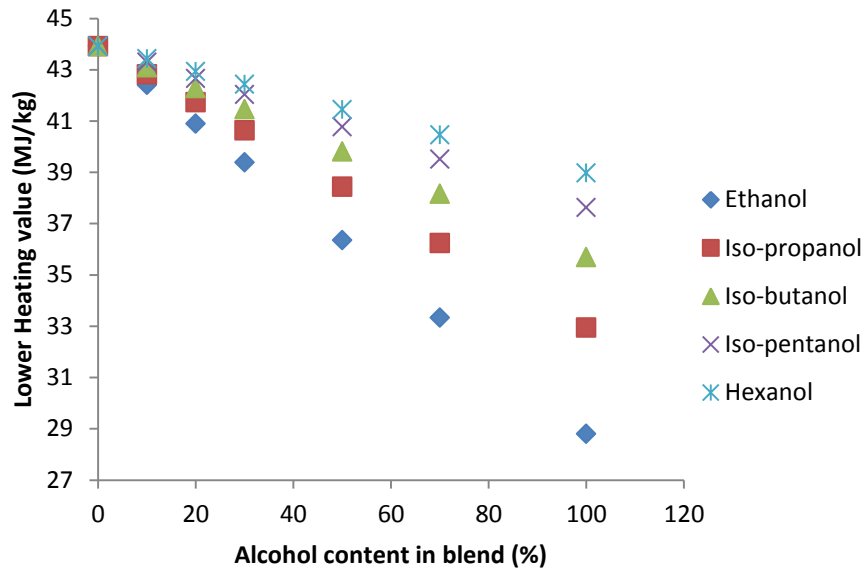


Figure 4.1: Effect of alcohol-gasoline blend on LHV

Spark-ignition engine fuels are classified based on Research Octane Number (RON) according to ASTM D2699 and Motor Octane Number (MON) according to ASTM D2700. Octane number indicates the anti-knock properties of a fuel. For choosing a gasoline fuel, the values of octane number are still a commonly used benchmark for fuel characterization. Both, RON and MON are determined by comparing a fuel's knock behavior to that of a mix of primary reference fuels using an engine. Figure 4.2 shows the measured RON values for a range of gasoline fuels as well as several alcohols. Ethanol, propanol, butanol and pentanol have 13%, 18%, 14% and 11% higher RON value compared gasoline respectively. Alcohol fuels span a wide range of Research Octane Numbers with a general trend of decreasing RON with decreasing oxygen content. It is also worth noting that Research Octane Numbers do not scale linearly when blending gasoline and alcohols as shown in (Kasseris & Heywood, 2012).

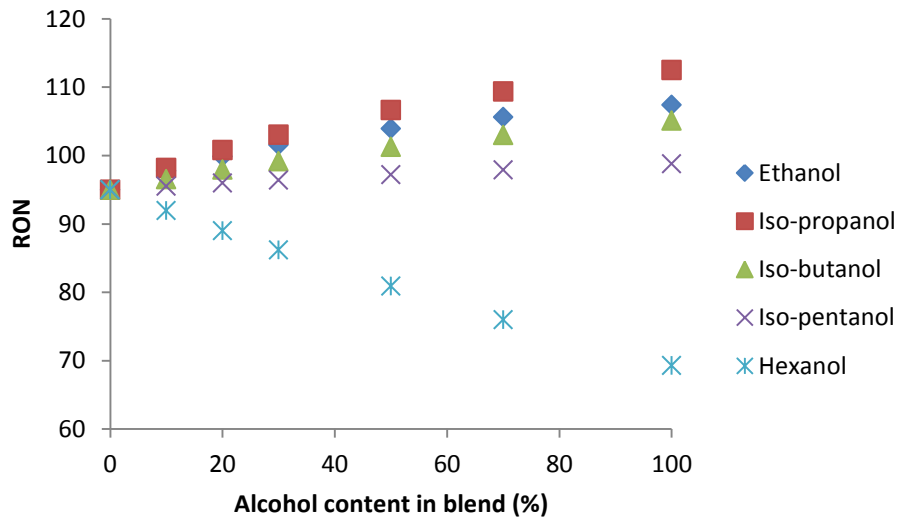


Figure 4.2: Effect of alcohol-gasoline blend on RON

Vapor pressure is used to determine the volatility of gasoline and other spark ignition engine fuels. The RVP values of gasoline and other alcohols are shown in Figure 4.3. The result shows a clear trend of decreasing RVP with increasing the carbon number of alcohol fuels, while all tested alcohols display RVP values significantly below those of gasoline. While lower RVP is desirable from an evaporative emissions point of view, too low an RVP can cause cold start issues and related increase in hydrocarbon emissions (Kito-Borsa et al., 1998).

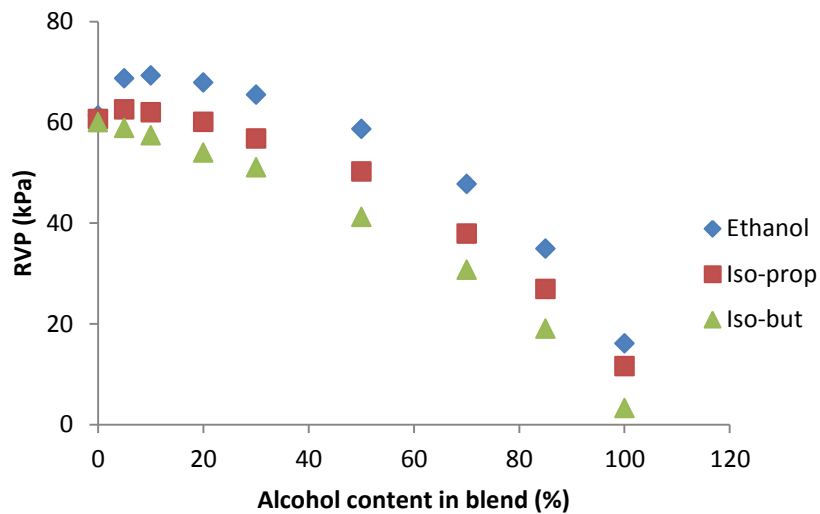


Figure 4.3: Effect of alcohol-gasoline blend on RVP

Latent heat of vaporization is another critical factor influencing in-cylinder mixture preparation in engines. Heat of vaporization results in a temperature reduction inside the engine intake system for port fuel injection and in-cylinder for direct-injection engines since energy taken from the intake air is required to evaporate the fuel. Increased heat of vaporization is desirable particularly for direct injection engines because it can significantly reduce in-cylinder process temperatures thus reducing NO<sub>x</sub> emissions formation as well as knock propensity. As shown in Figure 4.4, latent heat of vaporization decreases with increasing carbon number of alcohols. The differences in heat of vaporization within a group of alcohols are limited compared to the significant differences between different chain length alcohols. The energy needed to evaporate 1 kg of ethanol (923 kJ) is almost double that of n-hexanol (484 kJ). For comparison, the latent heat of vaporization of gasoline is around 300 kJ/kg.

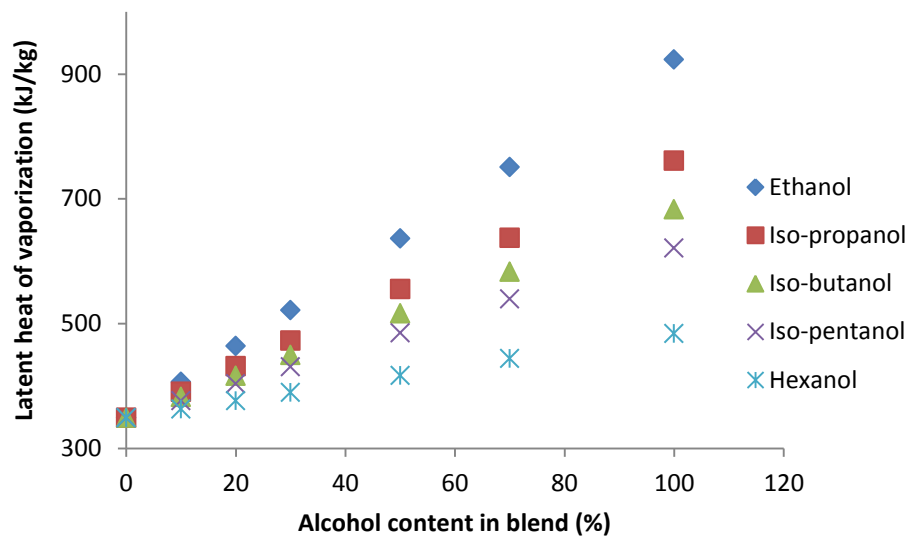


Figure 4.4: Effect of alcohol-gasoline blend on latent heat of vaporization

Fuel density plays an important effect on the performance of engine (Sera et al., 2009). It influences the fuel efficiency of fuel atomization and combustion characteristics as well. In Figure 4.5, the density of different alcohols and gasoline are displayed. It is

seen that density are increasing for higher carbon number alcohols. However, alcohols density is higher than that of gasoline.

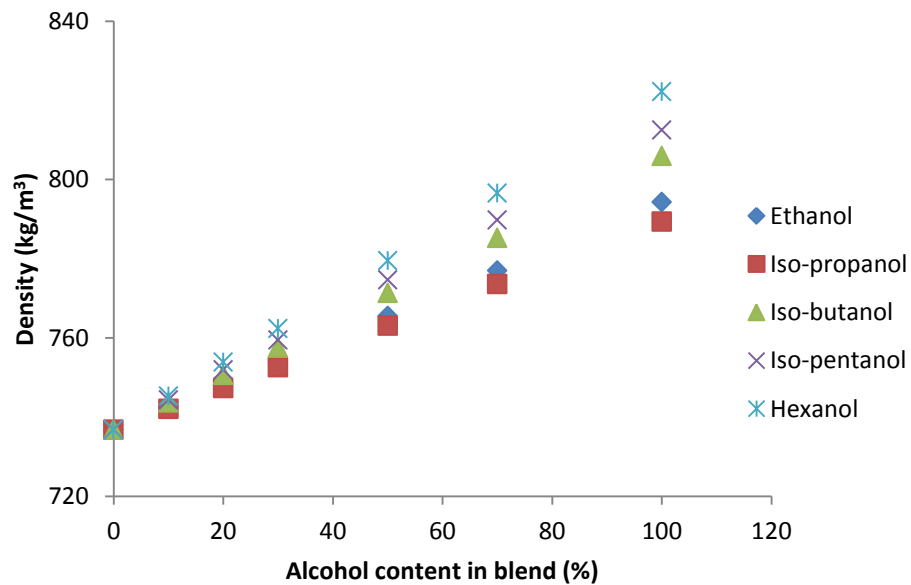


Figure 4.5: Effect of alcohol-gasoline blend on density

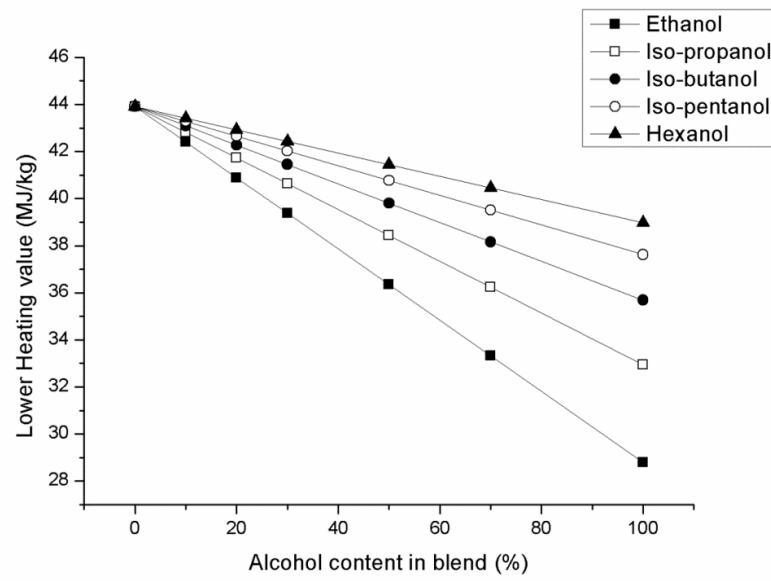
### 4.3 Validation of blend properties prediction analysis

In chapter 3.4.1, fuels properties prediction method of alcohol-gasoline blends were discussed. In this chapter, those prediction methods are compared or validated with experimental data. Based on equation 3.1, equation 4.1, 4.2 and 4.3 are developed and used to predict the LHV, density and oxygen content respectively. Here, a blend composed of n components with corresponding v volumetric concentration. From Figure 4.6, it is seen that LHV, density and oxygen content related straight forward with the volumetric concentration of each component in blend. Many researchers found from their experiment that LHV, density and oxygen content vary linearly with the volumetric ratio on the blend.

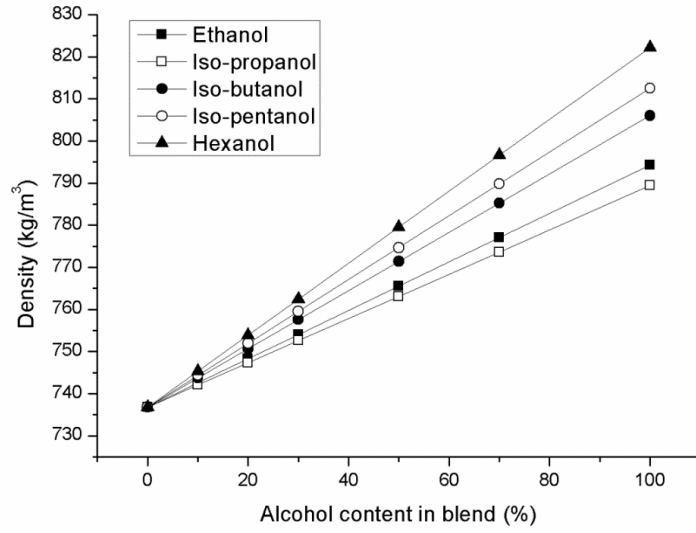
$$LHV_{blend} = \sum_{i=1}^n v_i \times LHV_i \quad (4.1)$$

$$Density_{blend} = \sum_{i=1}^n v_i \times Density_i \quad (4.2)$$

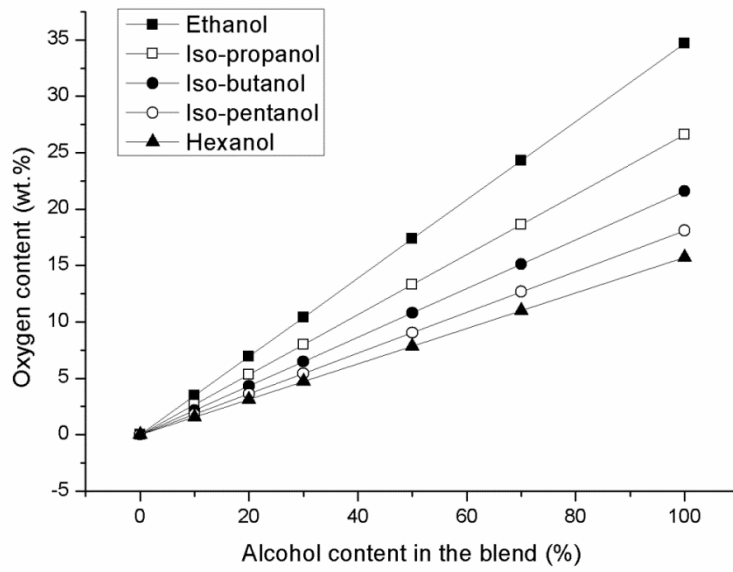
$$Oxygen_{blend} = \sum_{i=1}^n v_i \times Oxygen_i \quad (4.3)$$



(a)



(b)



(c)

Figure 4.6: Estimated gasoline-alcohol blend (a) LHV, (b) density and (c) oxygen content



Applying Equation 3.4 with the blending octane number assumption to predict the RON of two-component blends of gasoline with each of the alcohols yields the curves shown in Figure 4.7.

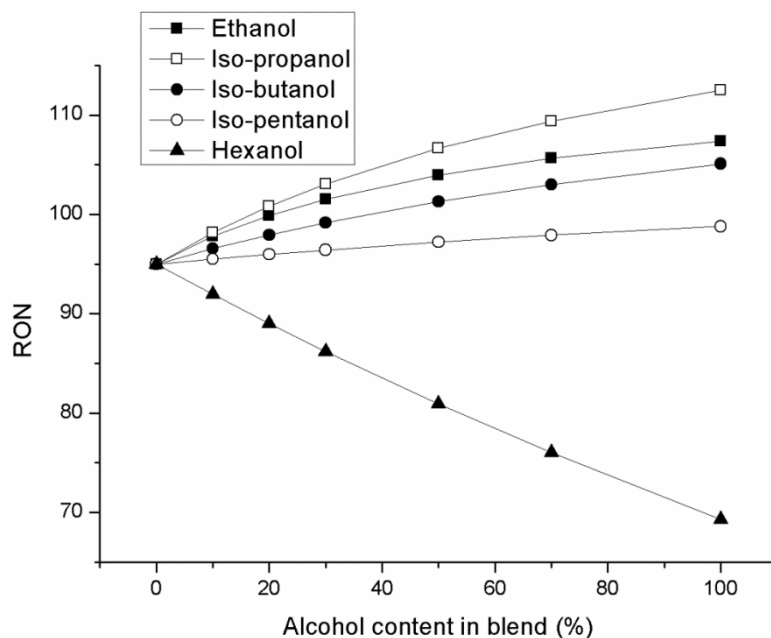


Figure 4.7: Estimated gasoline-alcohol blend RON

The RVP of a fuel blend is complicated to predict because of the azeotropic behavior of some of the alcohols. Methanol and ethanol have very pronounced peaks in RVP when mixed with a blendstock around 5 vol.% while this behavior diminishes with increased alcohol chain length. It was also found that with increasing the ethanol content, the Reid vapor pressure of the blended fuels initially increases to a maximum at 10% ethanol addition, and then decreases. Experimental data of the effect on blend RVP when more than one alcohol is mixed with a blendstock are not available for all possible combinations of alcohols, therefore a method to predict this behavior had to be developed. Figure 4.8 displays the estimated and experimental vapor pressures of different alcohol—gasoline blends.

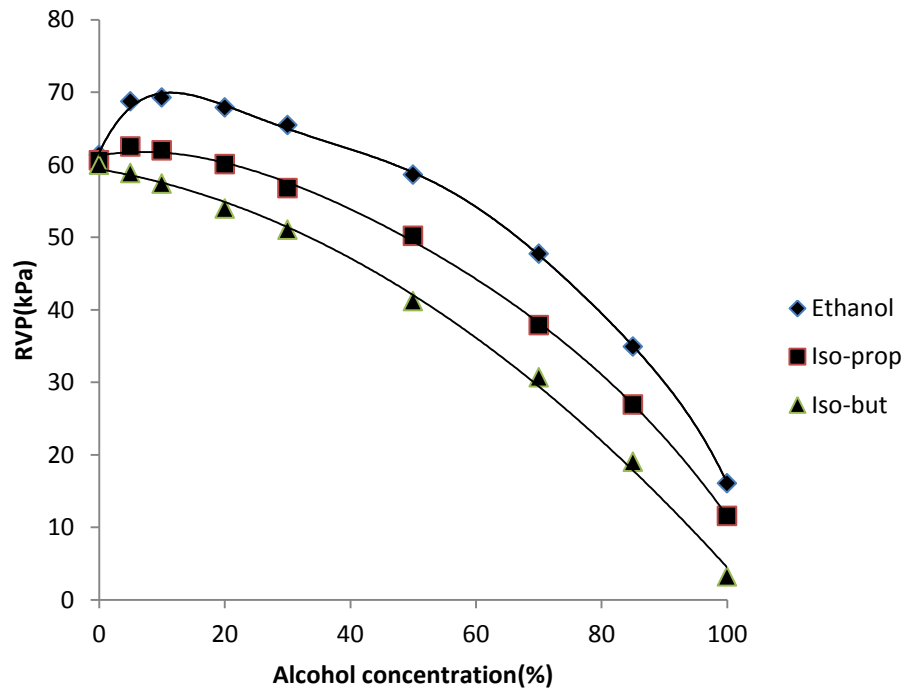


Figure 4.8: Estimated gasoline-alcohol blend RVP

#### 4.4 Optimum blend properties

Confirming the target values described in Table 3.2, properties prediction equations (described in section 2.2) were used in an optimization tool of Microsoft Excel to find the optimum fuel blend ratio. The three blend ratio was selected by focusing on maximum LHV, RON, and petroleum displacement and denoted by MaxHV, MaxRON, and MaxPD, respectively. Table 4.2 and Figure 4.9 depict the blend ratio of these suitable blends. The properties of these three blends were measured experimentally and results are given in Table 4.3. It is seen that all three blends met the targeted alternative fuel properties as described in Table 3.2. Compared with the target value, the MaxRON blend improves RON by 4.65%, improves LHV by 0.29% and displace 30.47% more gasoline than E15. MaxHV blend, which focuses to improve fuel LHV, improves LHV by 1.92% than E15 with met all other fuel properties target values. MaxPD blend

improves 32.27% petroleum displacement with improving 0.35% RON and 0.36% LHV than target values.

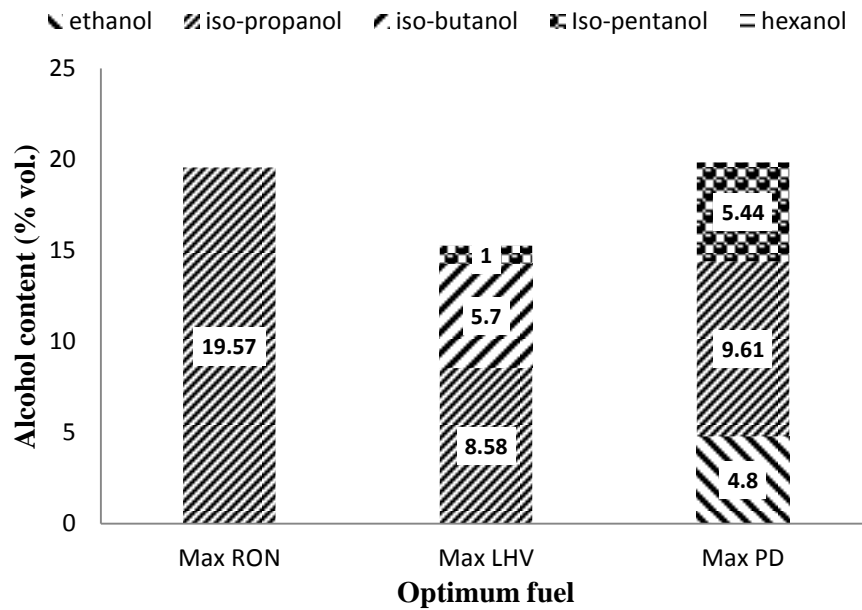


Figure 4.9: Composition of the optimum fuels

Table 4.2: Composition of the optimum fuels

Blend name	Blend specialty	Composition
<b>MaxRON</b>	Blend with maximum RON	19.57% Propanol 80.43% Gasoline
<b>MaxHV</b>	Blend with maximum LHV	8.58% Propanol 5.7% Butanol 1% Pentanol 84.72% Gasoline
<b>MaxPD</b>	Blend with maximum Petroleum displacement	4.8% Ethanol 9.61% Propanol 5.44% Pentanol 80.15% Gasoline

Table 4.3: Properties of optimum fuels and improvement over target

	<b>Expected value</b>	<b>Blend #1</b>	<b>Blend#2</b>	<b>Blend #3</b>
		<b>Max RON</b>	<b>Max LHV</b>	<b>Max Petr. displacement</b>
<b>RON</b>	≥96.24	<b>100.71</b>	96.24	96.58
		<b>(+4.65%)</b>	<b>(0%)</b>	<b>(+0.35%)</b>
<b>LHV (MJ/kg)</b>	≥41.65	41.77	<b>42.45</b>	41.8
		<b>(+0.29%)</b>	<b>(+1.92)</b>	<b>(+0.36)</b>
<b>Petroleum displacement (vol. %)</b>	≥15	19.57	15.28	<b>19.85</b>
		<b>(30.47%)</b>	<b>(+1.8)</b>	<b>(+32.27)</b>

#### 4.5 Engine performance and emission

This section describes the effect of different fuel on engine performance, combustion and emission. Performance parameters include engine torque, engine brake power, brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) and exhaust gas temperature; emission parameters include brake specific carbon monoxide (BSCO), brake specific hydrocarbon (BSHC), brake specific carbon dioxide (BSCO<sub>2</sub>) and brake specific nitrogen-oxide (BSNO<sub>x</sub>) emission; and combustion parameters include in-cylinder pressure and heat release rate (HRR). To carry out initial comparison, engine performance and emission test was carried out at constant load (100%) and varying speed condition. To compare the fuels further, performance, emission and combustion analysis was carried out at constant engine speed (4000rpm) and varying torque condition with test fuels.

##### 4.2.1 Torque

Torque is a turning force produced by the pressure from the crankshaft of the piston. Engine torque depends on engine stroke length, charge condition, and average effective

cylinder pressure (Baker, 2014). Under a constant engine condition, torque varies given different fuels as a result of the fuel properties and the effective pressure generated. Figure 4.10 compares the engine torque outputs at different engine speeds in full load condition for the test fuels. It can be seen that engine torque increases steadily up to 4000 rpm then decreases for all fuels. The maximum engine torque recorded at 4000 rpm for gasoline, E15, MaxRON, MaxPD, MaxHV were 129.3 Nm, 131.5 Nm, 130.9 Nm, 129.5 Nm and 131.5 Nm respectively. On average, in full load condition, alcohol-gasoline blends increase torque 1.9%, 1.82%, 1.13% and 2.57% for MaxRON, MaxPD, MaxHV and E15 fuel respectively than that of gasoline. The increased torque may be attributed to the high latent heat of vaporization (HoV). Fuel vaporizes in the intake manifold and in the combustion chamber. As the HoV of alcohols are higher, charge temperature is decreased as the alcohol evaporates. Furthermore, charge density increases. Engine torque is also enhanced by associated fuel mass at the same air–fuel ratio. This result is consistent with those obtained by other researchers (Feng et al., 2013; Schifter et al., 2013). Moreover, the incorporation of oxygenated alcohol produces a lean mixture that burns more efficiently than gasoline (Koç et al., 2009). Balki & Sayin (2014) explained higher flame speed of alcohol is the reason of better torque of alcohol-gasoline blend. The increase in the total number of molecules and the oxygen molecules would speed up the combustion process. So the burning rate and combustion efficiency of alcohol–gasoline blend are higher than that of gasoline (Feng et al., 2013). However, among all blends, E15 obtained the highest torque, though it has lowest LHV than that of other blends. This improved torque may be attributed to the enhanced RON of E15 (Campos-Fernandez et al., 2012). MaxRON also produced nearly the same torque as E15. Hence, engine torque decreases after it is maximized by engine acceleration.

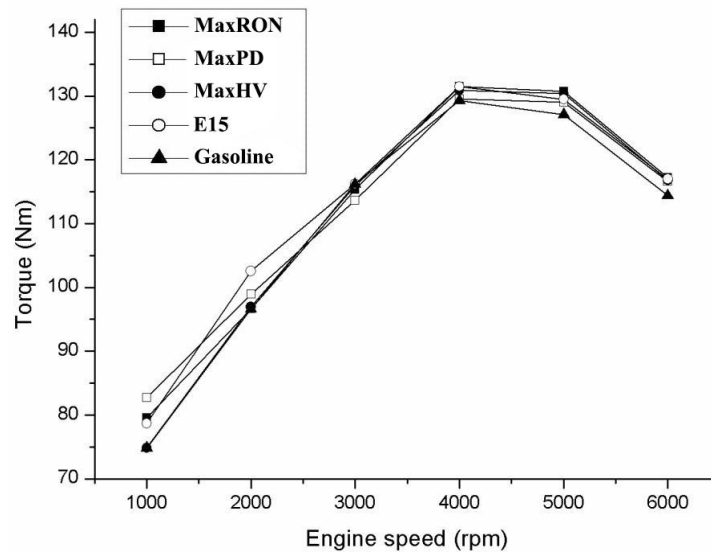


Figure 4.10: Variation of torque for the test fuels with engine speed at 100% load

#### 4.2.2 Brake power

Engine brake powers at full throttle, considering gasoline and other alcohol-gasoline blends, are plotted in Figure 4.11. The engine speed ranging from 1000 rpm to 6000 rpm is charted on the horizontal axis. It can be seen that, brake power for all alcohol-gasoline blends are slightly higher than that of gasoline fuel. Among all alcohol gasoline blend, E15 shows the highest brake power, though it has lowest LHV than that of other blends. The maximum brake powers are available in 6000 rpm engine speed. On average, 1.86%, 1.16%, 1.52% and 2.12% brake power were increased for MaxRON, MaxPD, MaxHV and E15 respectively than that of gasoline respectively. This result may be explained by using latent heat of vaporization of fuel. The vaporization of the blend can occur in the intake manifold or in the combustion chamber. The evaporation in intake manifold increases the charge density and associated fuel mass for the same air fuel ratio, which in turn results in more brake power. A similar result is obtained by other researchers (Feng et al., 2013; Schifter et al., 2013). The addition of oxygenated alcohol produces a lean mixture that makes the

burning more efficient than gasoline, which can be added as another reason (Koç et al., 2009). The improved anti knock behavior of alcohol-gasoline blend allowed a more advanced timing that results in higher torque as well as better brake power (Najafi et al., 2009).

The engine brake power increased with engine speed for all test fuels. The engine brake power of all the three fuels increase as engine speed increases. Faster burning rate can lead to more constant volume combustion in SI engines, which has positive effect on the increase of engine output power (Wei et al., 2014).

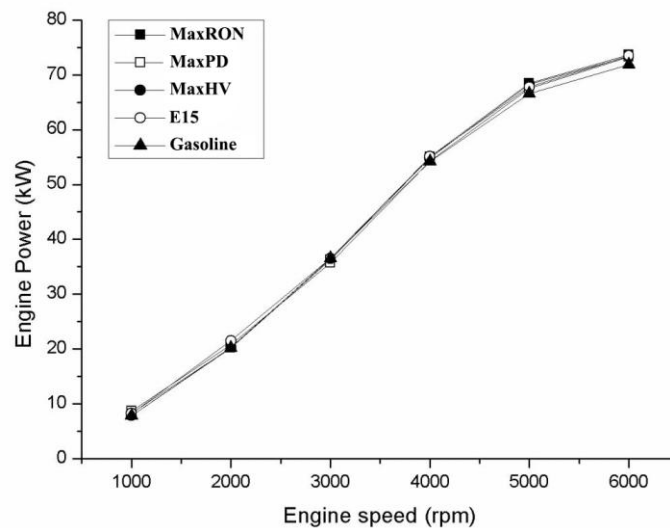


Figure 4.11: Variation of Brake Power with engine speed

### 4.2.3 Brake specific fuel consumption

#### (a) Constant load and varying engine speed condition

Figure 4.12(a) depicts the influence of test fuels on BSFC at different engine speeds at full engine load condition. Figure 4.12(a) indicates that BSFC decreases steadily from 1000 rpm to 5000 rpm then increases up. Gasoline shows the lowest BSFC compared to

other alcohol-gasoline blended fuel on the entire engine speed at full engine load. It was attained that the value of minimum BSFC for gasoline is 345.3 g/kWh at 5000 rpm. On average, the BSFC values for the use of E15, MaxRON, MaxPD and MaxHV were higher than that of gasoline by 5.1%, 2.1%, 4.76% and 2.5%, respectively. This result is typically ascribed the lower energy content of the alcohols, which enhances engine BSFC (Balki et al., 2014). Therefore, increased amounts of fuel are required to produce the same level of engine power as that generated by higher LHV fuel. The high BSFC of alcohol may also be induced by higher density of alcohol (Koç et al., 2009). Nonetheless, the BSFC of MaxRON is closer to gasoline. Furthermore, MaxRON, MaxHV and MaxPD displayed 3.01%, 1.05% and 2.46% lower BSFC values, respectively, than that of E15. With displacing more than 15% gasoline, optimized blends were showed lower BSFC than that of E15. This is because of the better fuel properties (e.g. LHV in case of BSFC) of optimized blend than that of E15.

For all fuels tested, BSFC is found to decrease with increase in the engine speed. Al-Hasan (2003) explained, this is due to the decreases in equivalence air-fuel ratio. A further increase in engine speed results in increasing BSFC, since the equivalence air-fuel ratio increases.

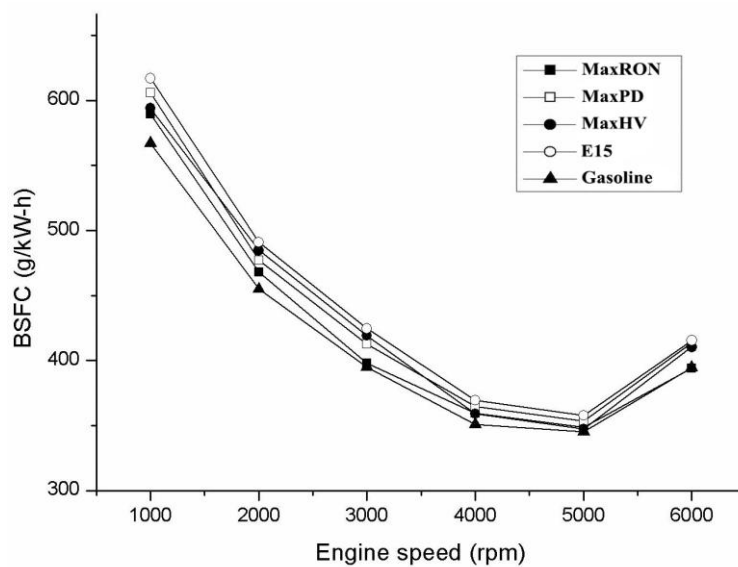
#### **(b) Constant engine speed and varying engine torque condition**

Figure 4.12 (b) depicts the influence of test fuels on BSFC at different engine speeds at full engine load condition. It can be seen that BSFC first decrease steadily from 20 Nm to 80 Nm then increases up from 80 Nm to 120 Nm. It is seen that gasoline shows the lowest BSFC compared to other alcohol gasoline blends on the entire engine load. The lower BSFC was found for gasoline fuel at 80 Nm torque and it was is 341.9 g/kWh. This result is typically ascribed to the low energy content of the alcohols, which

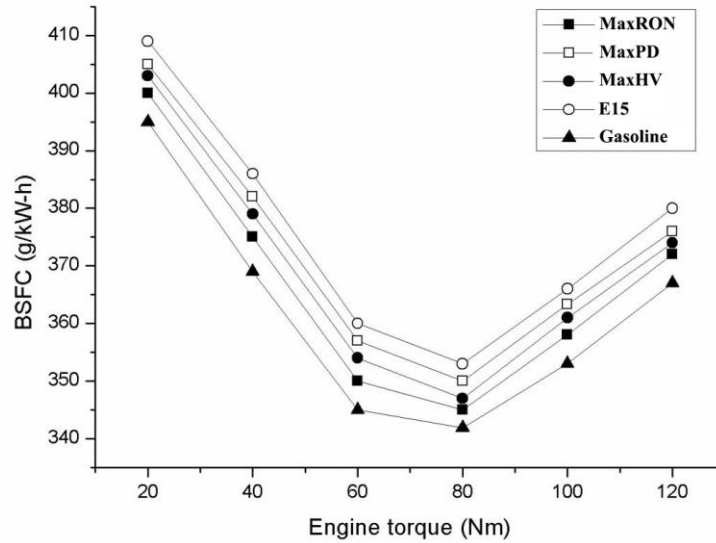


enhances engine BSFC (Balki et al., 2014). Therefore, increased amounts of fuel are required to produce the same level of engine power as that generated by higher LHV fuel. The high BSFC of alcohol may also be induced by high density of alcohol (Koç et al., 2009). Furthermore, MaxRON, MaxHV and MaxPD displayed BSFC values 2.5%, 0.93% and 1.7% lower, respectively, than that of E15. With displacing more than 15% gasoline, optimized blends were showed lower BSFC than that of E15. This is because of better fuel properties (e.g. LHV in case of BSFC) of optimized blend than that of E15.

For all fuels tested, brake specific fuel consumption is found to decrease with increase in the load. This is due to the higher percentage increase in brake power with load as compared to the increase in fuel consumption (Ramadhas et al., 2005). However, after a certain load limit, BSFC start increase because rich air-fuel mixture needs to gain that engine load.



(a)



(b)

Figure 4.12: Variation of BSFC for the test fuels with (a) engine speed at 100% load and (b) engine torque at 4000 rpm

#### 4.2.4 Brake thermal efficiency

##### (a) Constant load and varying engine speed condition

Thermal efficiency indicates the ability of the combustion system to accept the experimental fuel, and provides comparable means of assessing how efficient the energy in the fuel was converted to mechanical output (Hulwan & Joshi, 2011). Figure 4.13(a) displays the variation of BTE values with engine speed at full engine load. Brake thermal efficiency increased with engine speed until 5000rpm and the maximum brake thermal efficiency was 24.53%, 24.38%, 24.09%, 24.17% and 23.74% when MaxRON, MaxPD, MaxHV, E15 and gasoline were used as fuel respectively. Alcohol—gasoline blends show slightly higher BTE than that with gasoline. This condition can be attributed to the fact that alcohols contain oxygen where gasoline has no oxygen. As a

result, combustion is improved, thereby enhancing thermal efficiency (Campos-Fernandez et al., 2013). Moreover, fuel is vaporized in the compression stroke when latent HoV is high. Given that fuel absorbs heat from the cylinder during vaporization, the air—fuel mixture is compressed more easily, thus improving thermal efficiency for alcohol-gasoline blend than that of gasoline. Balki et al. (2014) noted that the HoV and oxygen content of alcohol enhances BTE in alcohol—gasoline blends. They also explained that alcohol fuels have a faster stoichiometric flame speed than that of gasoline. Higher stoichiometric flame speed causes to comparatively faster and more complete combustion of fuel in the engine cylinder, which decreases heat losses from the cylinder walls thus increasing BTE. Compared with E15, optimized blends improve engine BTE slightly in full load condition. Specially, MaxRON blend improve 2.8% BTE than E15 blend.

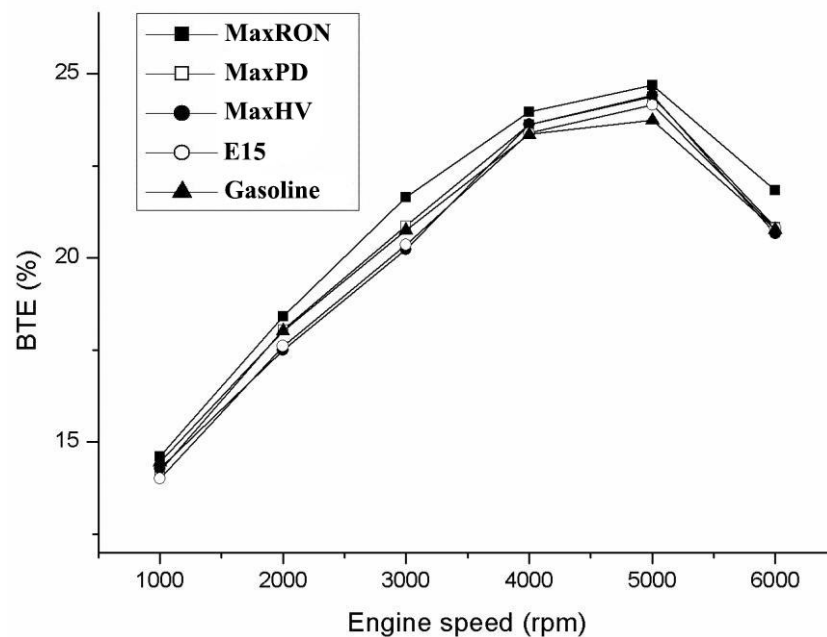
From figure 4.13 (a), it is also seen that BTE increases with engine speed. Krishna et al. (2008) also found the same result. They explained, thermal efficiency marginally increased with increase of engine speed, due to increase of turbulence of combustion, though friction power increased with an increase of speed.

#### **(b) Constant engine speed and varying engine torque condition**

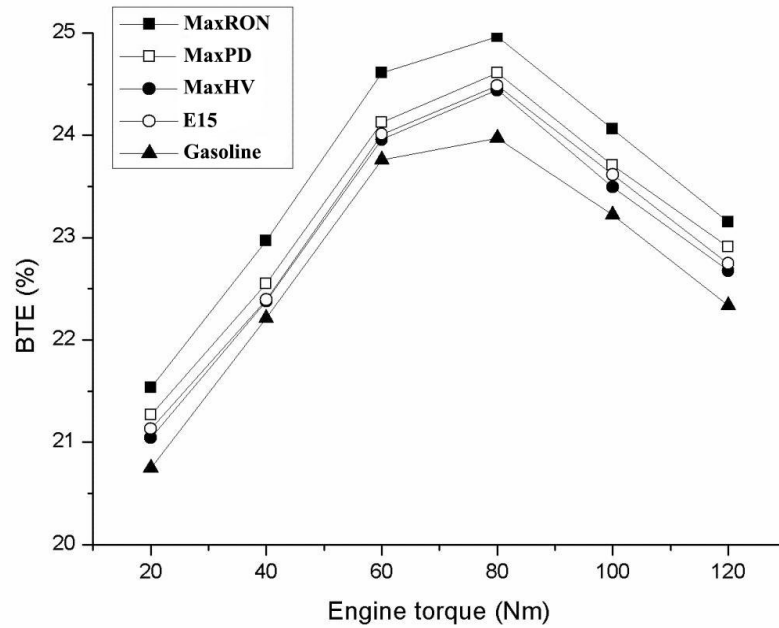
Figure 4.13 (b) displays the variation of BTE values with engine torque at constant engine speed. Brake thermal efficiency increased with engine speed until 80Nm and the maximum brake thermal efficiency was 24.97%, 24.61%, 24.44%, 24.49% and 24.00% when MaxRON, MaxPD, MaxHV, E15 and gasoline were used as fuel respectively. Alcohol—gasoline blends show slightly higher BTE than that with gasoline. This condition can be attributed to the fact that alcohols contain oxygen where gasoline has no oxygen. As a result, combustion is improved, thereby enhancing thermal efficiency

(Campos-Fernandez et al., 2013). Moreover, fuel is vaporized in the compression stroke when latent HoV is high. Given that fuel absorbs heat from the cylinder during vaporization, the air—fuel mixture is compressed more easily, thus improving thermal efficiency for alcohol-gasoline blend than that of gasoline. Balki et al. (2014) noted that the HoV and oxygen content of alcohol enhances BTE in alcohol—gasoline blends. They also explained that alcohol fuels have a faster stoichiometric flame speed than that of gasoline. Higher stoichiometric flame speed causes to comparatively faster and more complete combustion of fuel in the engine cylinder, which decreases heat losses from the cylinder walls thus increasing BTE. Compared with E15, optimized blends improve engine BTE in full load condition. Specially, MaxRON blend improve 2.06% BTE than E15 blend.

In all cases, brake thermal efficiency has the tendency to increase with increase in applied load. This is due to the reduction in heat loss and increase in power developed with increase in load (Ramadhas et al., 2005).



(a)



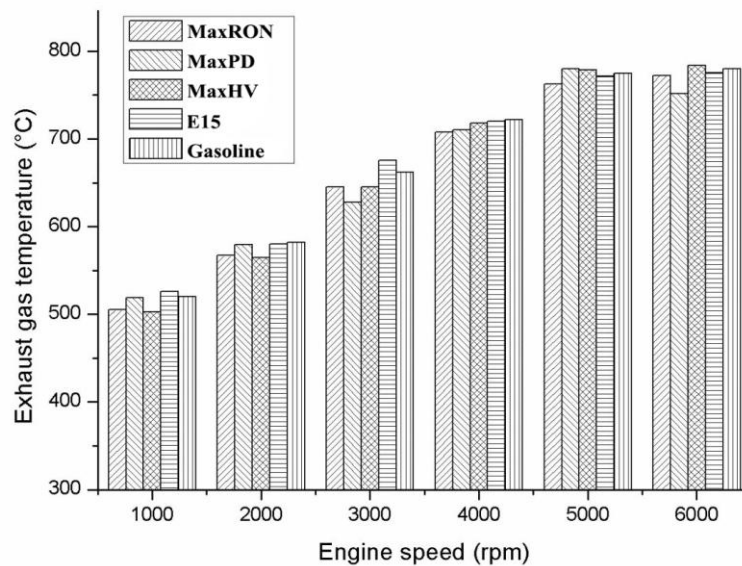
(b)

Figure 4.13: Variation of BTE for the test fuels with (a) engine speed at 100% load and (b) engine torque at 4000 rpm

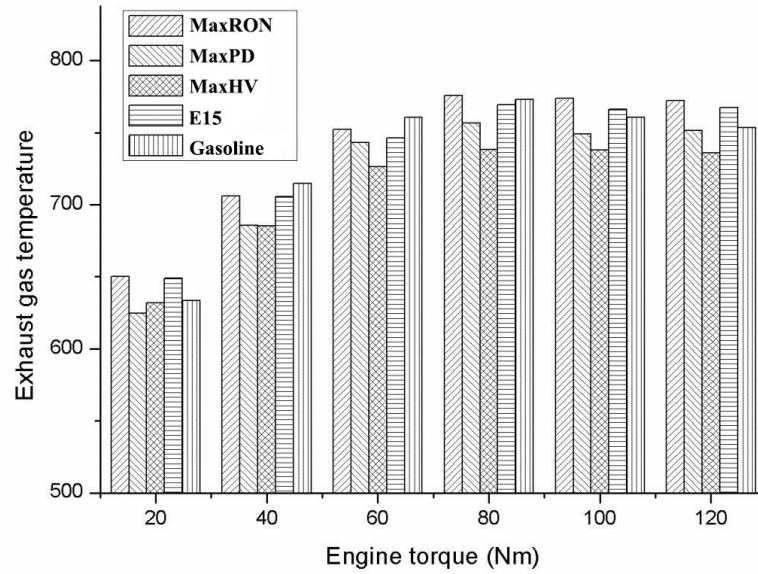
#### 4.2.5 Exhaust gas temperature

Figure 4.14 presents the effect of test fuels on the EGT of the test engine, which is a significant indicator of cylinder temperature. EGT can also be used to analyze exhaust emission, especially of NO<sub>x</sub> because NO<sub>x</sub> formation often depends on temperature (Rizwanul Fattah et al., 2014). In this figure, the addition of alcohol to gasoline reduces EGTs. In overall engine condition, EGTs reduced 4.3%, 1.9%, 3.6%, and 2.2% for using MaxRON, MaxPD, MaxHV, and E15 respectively than that of using gasoline. The reason of this EGTs reduction is that lower LHV of alcohol. Karabektas & Hosoz (2009) explained, the lower energy content of fuel results in lower EGTs. Few other researches (Topgöl et al., 2006; Yücesu et al., 2006) explained, higher RON of alcohol

starts in-cylinder combustion earlier that assist utilize more heat of combustion and decreases EGTs than gasoline. In all fuels, EGTs increase with engine speed. Moreover, EGT and combustion temperature increase as increased amounts of fuel burn at high engine speeds. However, lower EGT is also an advantage of a fuel to use in the engine. Lower EGT indicates the higher utilization of heat in the engine. Lower EGT also reduces exhaust manifold cost.



(a)



(b)

Figure 4.14: Variation of exhaust gas temperature for the test fuels with (a) engine speed at 100% load and (b) engine torque at 4000 rpm

#### 4.2.6 In-cylinder gas pressure

We can compare the combustion characteristics of different fuels based on cylinder gas pressure and heat release rate. Figure 4.15 compares the cylinder gas pressures of all of the test fuels at an engine in full throttle load at a speed of 5000 rpm. All of the fuels displayed similar inlet and exhaust pressure curves because throttle angle was almost constant. Furthermore, the maximum pressures for all test fuels were close to the top dead center (TDC). As observed in the figure, cylinder gas pressure started to increase earlier in alcohol—gasoline blends than in pure gasoline. Furthermore, this pressure was higher for alcohol-gasoline blend than pure gasoline. According to Melo et al., (2012), the increase in alcohol enhanced timing and prevented knocking, thus maximizing the pressure obtained using alcohol. Balki et al.

(2014) added that high latent HoV and oxygen content in alcohols increases cylinder gas pressure. Moreover, Figure 4.15 shows that the addition of alcohol shortens combustion duration compared with that of gasoline. This finding is attributed to high laminar flame speed and RON by Balki et al. (2014).

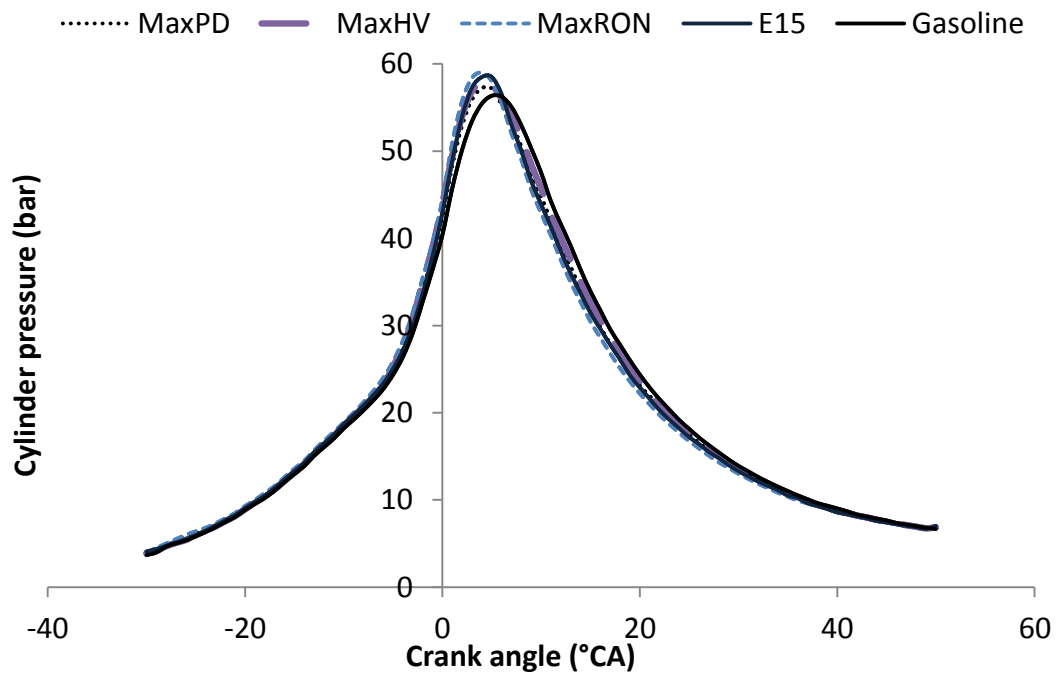


Figure 4.15: Comparison of in-cylinder pressure for the test fuels at 5000rpm

#### 4.2.7 Heat release rate

Figure 4.16 illustrates the effect of blends on the rate of heat release to the crank angle at an engine speed of 5000 rpm. At high rates, alcohol accelerates combustion flame speed, particularly in the MaxRON combustion. According to Siwale et al. (2014), flame burned more quickly in alcohol–gasoline blends than in pure gasoline. Moreover, the peak release rate of location heat is higher in the alcohol–gasoline blend than in pure gasoline. Eyidogan et al. (2010) explained that the oxygen content in alcohols



improves combustion; thus, much fuel burns near TDC. This condition enhances the peak release rate of location heat in alcohol.

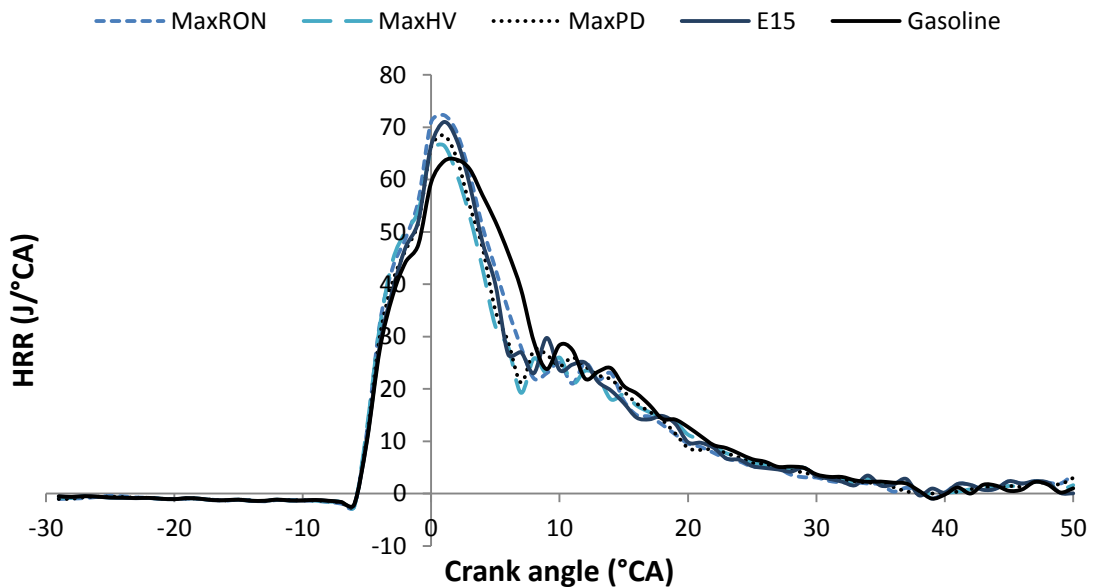


Figure 4.16: Comparison of heat release rate for the test fuels at 5000rpm

#### 4.2.8 BSCO emission

##### (a) Constant load and varying engine speed condition

CO emission represents a loss in the chemical energy that is not fully utilized in the engine. It is a product of incomplete combustion given either an insufficient amount of air in the air–fuel mixture or the interruption of combustion cycle time (Bayindir et al., 2010). Figure 4.17 (a) shows, the variation of BSCO exhaust emission in relation to the engine speed. In overall engine speed range, BSCO is significantly lower for alcohol—gasoline blends than that of gasoline fuel. The average decrease of BSCO emission for E15, MaxRON, MaxHV and MaxPD than that of gasoline is 8.1%, 12.1%, 15.9% and

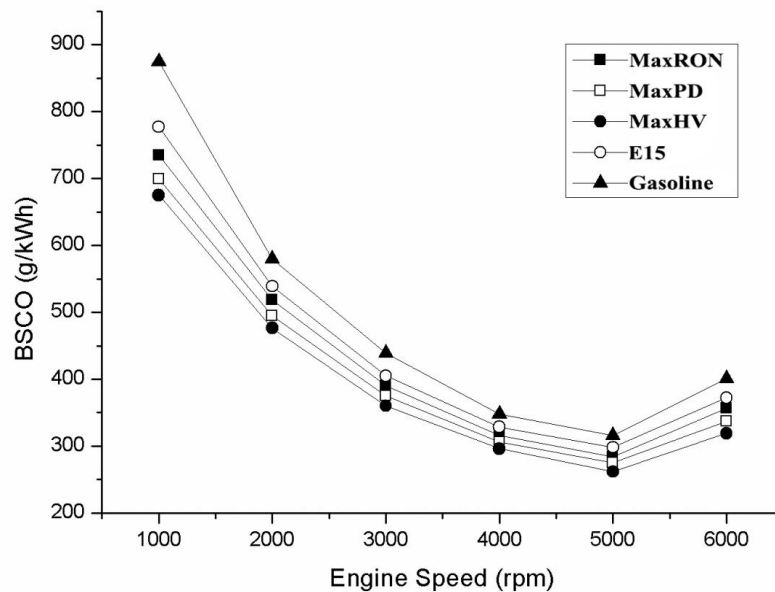
19.3% respectively. Alcohols are oxygenated fuels; therefore, they enhance oxygen content in fuel for combustion. This process generates the “leaning effect”, which sharply reduces CO emission (Canakci et al., 2013). This result can also be attributed by the higher flame speed of alcohol that assists to complete the combustion (Feng et al., 2013; Pechout et al., 2012). As a result of this increased flame speed in alcohol, alcohol—gasoline blends complete combustion earlier and emit less CO. It was observed that the minimum BSCO emissions obtained from the gasoline, E15, MaxRON, MaxHV and MaxPD fuels were 316.04 g/kWh, 298.22 g/kWh, 262 g/kWh, 275.5 g/kWh and 284.15 g/kWh respectively, and were achieved at 5000rpm engine speed. Comparing all alcohol-gasoline blends, it is seen that optimized blends results slightly lower BSCO than E15. Using MaxRON, MaxHV and MaxPD reduce BSCO than E15 by averages of 4.4%, 9.66%, 8.52% and 12.1%, respectively. Higher LHV of MaxHV blend accelerates the combustion process that results in low CO emission. Gravalos et al. (2013) also found lower CO emission for lower-higher molecular mass alcohol-gasoline fuel blends than that of lower molecular mass alcohol/gasoline blend.

#### **(b) Constant engine speed and varying engine torque condition**

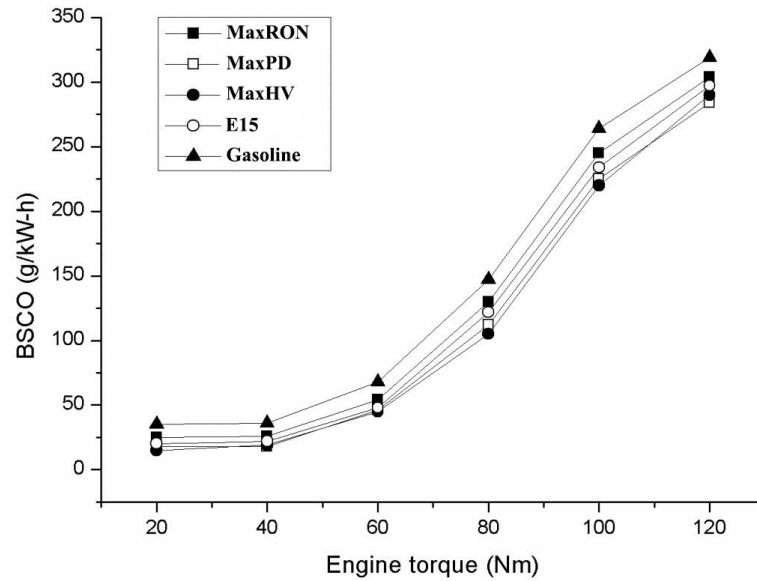
Figure 4.17 (b) shows, the variation of BSCO exhaust emission in relation to the engine torque in 4000 rpm. In overall engine speed range, BSCO is significantly lower for alcohol—gasoline blends than that of gasoline fuel. The average decrease of BSCO emission for E15, MaxRON, MaxHV and MaxPD than that of gasoline is 14.4%, 9.8%, 20.1% and 19.0% respectively. Alcohols are oxygenated fuels; therefore, they enhance oxygen content in fuel for combustion. This process generates the “leaning effect”, which sharply reduces CO emission (Canakci et al., 2013). This result can also be attributed by the higher flame speed of alcohol that assists to complete the combustion

(Feng et al., 2013; Pechout et al., 2012). As a result of this increased flame speed in alcohol, alcohol—gasoline blends complete combustion earlier and emit less CO. Comparing all alcohol-gasoline blends, it is seen that optimized blends results slightly lower BSCO than E15. Using MaxRON, MaxHV and MaxPD reduce BSCO than E15. Higher LHV of MaxHV blend accelerates the combustion process that results in low CO emission. Gravalos et al. (2013) also found lower CO emission for lower-higher molecular mass alcohol-gasoline fuel blends than that of lower molecular mass alcohol/gasoline blend.

On the other hand, CO emission increases with the rising of wheel power. This is typical with all internal combustion engines since the air–fuel ratio decreases with increase in load. CO emission is the ideal emission product assessor. The CO emissions increase as the fuel–air ratio becomes greater than the stoichiometric value (Ramadhas et al., 2005).



(a)



(b)

Figure 4.17: Variation of BSCO emission for the test fuels with (a) engine speed at 100% load and (b) engine torque at 4000 rpm

#### 4.2.9 BSHC emission

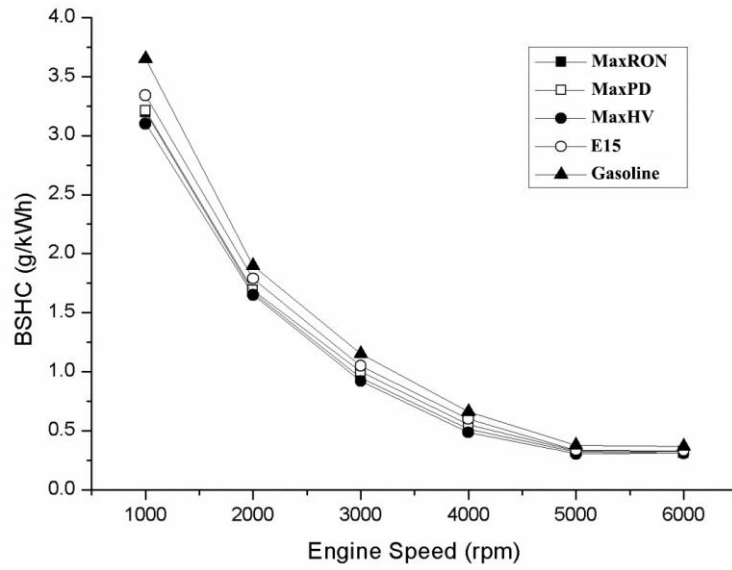
##### (a) Constant load and varying engine speed condition

Emissions of unburned HC are primarily caused by unburned mixtures induced by improper mixing and incomplete combustion. These emissions are a main contributor to photochemical smog and ozone pollution (Kaiser et al., 1991). Figure 4.18 (a) exhibits the emissions of BSHC by all test fuels at speeds ranging from 1000 rpm to 6000 rpm. These emissions were slightly lower in all alcohol—gasoline blends than in pure gasoline. On average, emissions of BSHC by E15, MaxRON, MaxPD and MaxHV decreased by 5.49%, 1.0%, 9.8% and 9.3%, respectively. This result may be attributed to the leaning effect and the oxygen content in the alcohol (Koç et al., 2009). At the

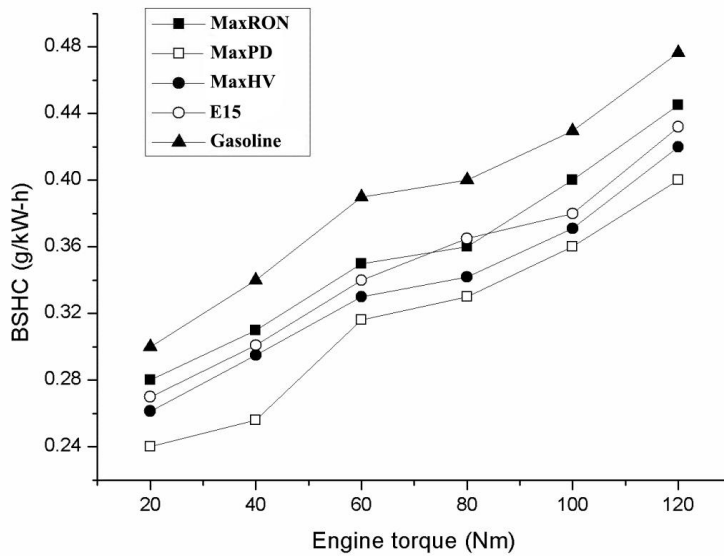
same time, laminar flame speed of alcohol is higher than gasoline (Sayin, 2010). That may assist complete combustion of alcohol-gasoline blend as well as lower HC emission. Moreover, these emissions decrease as engine speed increase in all blends. At high speeds, the air—fuel mixture homogenizes to increase in-cylinder temperature. This condition in turn enhances combustion efficiency. Thus, BSHC emission was lower at high engine speeds than at low speeds. This conclusion is consistent with that of Koç et al. (2009). In overall speed range, for all alcohol-gasoline blends, BSHC were quit similar. BSHC emission of optimized blends varies 5% to 9% than E15 blend.

#### **(b) Constant engine speed and varying engine torque condition**

Figure 4.18 (b) exhibits the emissions of BSHC by all test fuels at engine torque ranging from 20 Nm to 120 Nm at 4000 rpm. These emissions were slightly lower in all alcohol—gasoline blends than in pure gasoline. On average, emissions of BSHC by E15, MaxRON, MaxPD and MaxHV decreased by 10.7%, 8.36%, 18.5% and 13.6%, respectively. This result may be attributed to the leaning effect and the oxygen content in the alcohol (Koç et al., 2009). At the same time, laminar flame speed of alcohol is higher than gasoline (Sayin, 2010). That may assist complete combustion of alcohol-gasoline blend as well as lower HC emission. Moreover, these emissions decrease as engine speed increase in all blends. At high speeds, the air—fuel mixture homogenizes to increase in-cylinder temperature. This condition in turn enhances combustion efficiency. Thus, BSHC emission was lower at high engine speeds than at low speeds. This conclusion is consistent with that of Koç et al. (2009). On average, for all alcohol-gasoline blends, BSHC were quit similar.



(a)



(b)

Figure 4.18: Variation of BSHC emission for the test fuels with (a) engine speed at 100% load and (b) engine torque at 4000 rpm

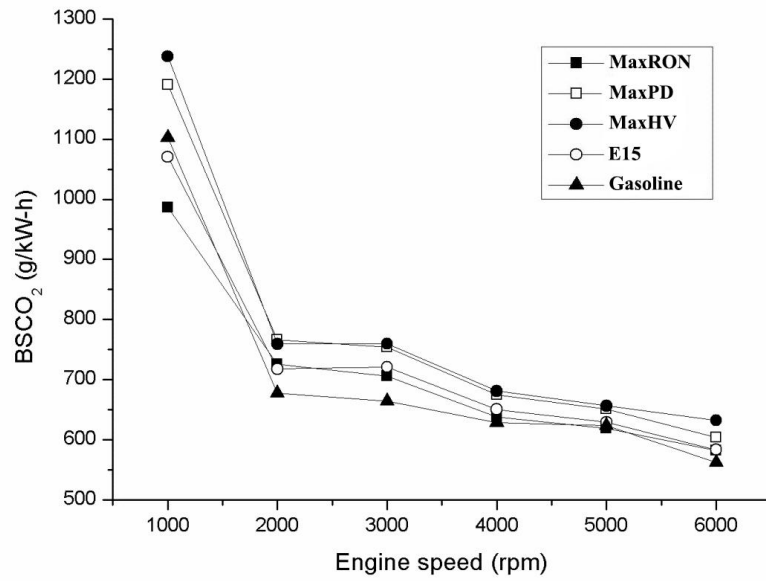
#### **4.2.10 BSCO<sub>2</sub> emission**

##### **(a) Constant load and varying engine speed condition**

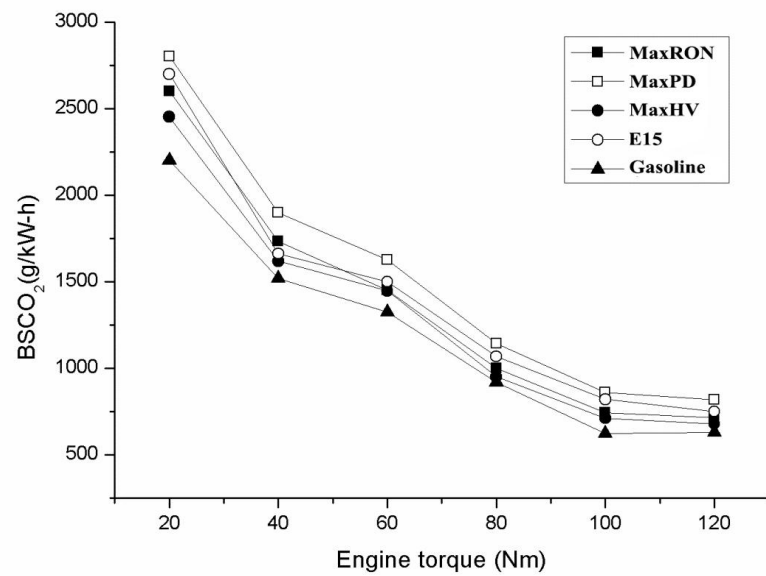
CO<sub>2</sub> is a GHG produced by the complete combustion of hydrocarbon fuel. Its formation is affected by the carbon–hydrogen ratio in fuel. Stoichiometrically, hydrocarbon fuel combustion should generate only CO<sub>2</sub> and water (H<sub>2</sub>O). Figure 4.19 (a) presents the variation in CO<sub>2</sub> emission across different fuels. As per the study results, CO<sub>2</sub> emission is higher for alcohol–gasoline blends than in pure gasoline; on average, CO<sub>2</sub> emissions by E15, MaxRON, MaxPD and MaxHV are 6.22%, 3.7%, 10.6% and 11.8% significantly higher. This finding can be attributed to carbon flow rate. To attain a certain level of engine power given a constant throttle position, the amount of alcohol–gasoline blended fuel consumed must be higher than that of gasoline. Therefore, the carbon flow rates of the alcohol–gasoline blends are higher than those of gasoline (Melo et al., 2012). The oxygen ratio in alcohols also enhances the combustion efficiency of alcohol–gasoline blends, which enhances CO<sub>2</sub> emission in alcohol—gasoline blends.

##### **(b) Constant engine speed and varying engine torque condition**

Figure 4.19 (b) presents the variation in CO<sub>2</sub> emission across different fuels at variable torque at 4000rpm. As per the study results, CO<sub>2</sub> emission is higher for alcohol–gasoline blends than in pure gasoline; on average, CO<sub>2</sub> emissions by E15, MaxRON, MaxPD and MaxHV are 17.7%, 14.1%, 26.6% and 8.8% higher. This finding can be attributed to carbon flow rate. Therefore, the carbon flow rates of the alcohol–gasoline blends are higher than those of gasoline (Melo et al., 2012). The oxygen ratio in alcohols also enhances the combustion efficiency of alcohol–gasoline blends, which enhances CO<sub>2</sub> emission in alcohol—gasoline blends.



(a)



(b)

Figure 4.19: Variation of BSCO<sub>2</sub> emission for the test fuels with (a) engine speed at 100% load and (b) engine torque at 4000 rpm



#### **4.2.11 BSNOx emission**

##### **(a) Constant load and varying engine speed condition**

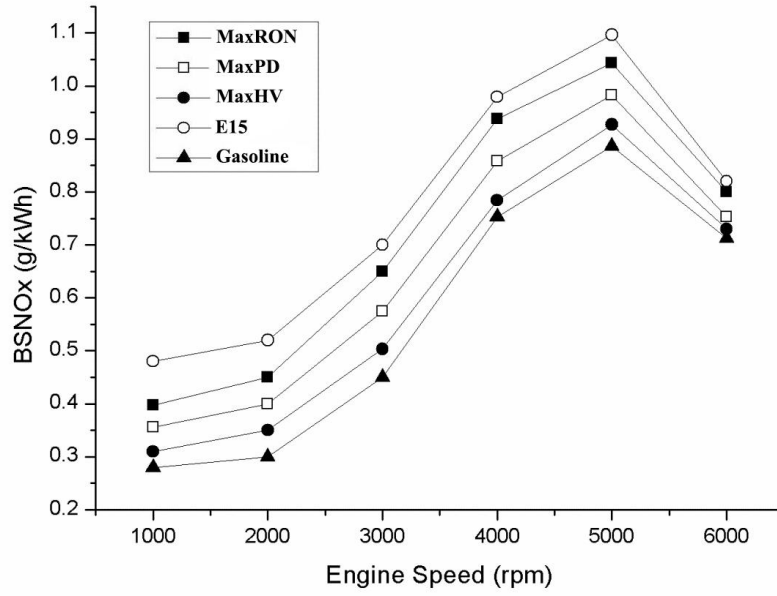
During combustion at high temperature, nitrogen in the air oxidizes to form NO<sub>x</sub>. Thus, the generation of NO<sub>x</sub> in an engine is closely related to combustion temperature, oxygen concentration, and residence time of the combustion chamber (Palash et al., 2013). Figure 4.20 (a) exhibits the variation in BSNO<sub>x</sub> emission in different engine speeds at WOT condition. As per the study result, NO<sub>x</sub> emission is higher for alcohol-gasoline blends than that of pure gasoline. It is seen that E15 produced the highest NO<sub>x</sub> emission. The highest BSNO<sub>x</sub> was observed at 5000rpm and it was 1.04 g/kWh, 0.98 g/kWh, 0.92 g/kWh, 1.1 g/kWh and 0.89 g/kWh for MaxRON, MaxPD, MaxHV, E15 and gasoline, respectively. In general, NO<sub>x</sub> emission depends on the peak in-cylinder temperatures and oxygen concentration of fuel (Gravalos et al., 2013). Alcohol-gasoline blends result higher peak in-cylinder pressure than gasoline (in Figure 4.14) that indicates higher peak in-cylinder temperatures for alcohol-gasoline blends. And also higher oxygen concentration of alcohols might be the reason for higher NO<sub>x</sub> emission for using alcohol-gasoline blend (Xing-cai et al., 2004). However, optimized blends emit lower BSNO<sub>x</sub> as compared to the E15. Higher BSFC together with higher torque of E15 increases the in-cylinder temperature as well as more BSNO<sub>x</sub> emission than that of other fuels.

BSNO<sub>x</sub> increases with the engine speed, for all test fuels. Some researchers (Al-Farayedhi et al., 2000; Najafi et al., 2009) have reported that in higher engine speed, more fuel burn and in-cylinder temperature become high that results higher NO<sub>x</sub> in higher speed.

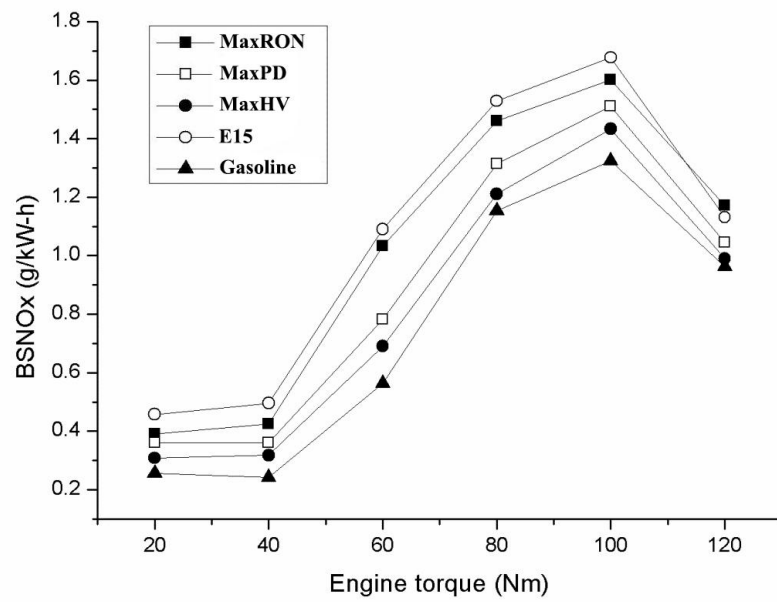
### **(b) Constant engine speed and varying engine torque condition**

Figure 4.20 (b) exhibits the variation in BSNO<sub>x</sub> emission at 4000rpm and at different engine torques. As per the study result, NO<sub>x</sub> emission is higher for alcohol–gasoline blends than that of pure gasoline. It is seen that E15 produced the highest NO<sub>x</sub> emission. The highest BSNO<sub>x</sub> is observed at 120 Nm torque and it was 1.60 g/kWh, 1.51 g/kWh, 1.43 g/kWh, 1.68 g/kWh and 1.33 g/kWh for MaxRON, MaxPD, MaxHV, E15 and gasoline respectively. In general, NO<sub>x</sub> emission depends on the peak in-cylinder temperatures and oxygen concentration of fuel (Gravalos et al., 2013). Alcohol-gasoline blends result higher peak in-cylinder pressure than gasoline (in Figure 5) that indicates higher peak in-cylinder temperatures for alcohol-gasoline blends. And also higher oxygen concentration might be the reason for higher NO<sub>x</sub> emission for using alcohol gasoline blend (Bahattin Celik, 2008). However, optimized blends emit lower BSNO<sub>x</sub> as compared to the use of E15. Higher BSFC together with higher torque of E15 increases the in-cylinder temperature as well as more BSNO<sub>x</sub> emission than that of other fuels.

For all test fuel, BSNO<sub>x</sub> were increasing with increasing load. More fuel or a richer mixture is needed to increase the engine load, which results in a higher in-cylinder temperature as well as higher NO<sub>x</sub> formation (Sarin, 2012). However, in 120 N.m torque, NO<sub>x</sub> emission falls suddenly. In highest load, faster combustion lower the combustion duration as well as nitrogen get shorter time to form NO<sub>x</sub> (Sarin, 2012).



(a)



(b)

Figure 4.20: Variation of BSNOx emission for the test fuels with (a) engine speed at 100% load and (b) engine torque at 4000 rpm

## CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusions

The main objective of this study was to improve the energy content, knock resistance, and/or petroleum displacement using multi alcohol-gasoline blend compared to traditional ethanol blends such as E10/E15 while maintaining specified fuel properties. The performance, combustion and emission characteristics were measured for those multi-alcohol gasoline blends and compared with gasoline and E15 blend. Based on experimental observation the following conclusion can be made:

- Among all multi alcohol-gasoline fuel combination, three optimum blends were selected on the basis of maximum LHV, maximum RON and maximum petroleum displacement and these optimized fuels improved LHV, RON and petroleum displacement by 1.92%, 4.65% and 32.27%, respectively.
- Optimized blends improved engine torque and brake power than gasoline. Specially, optimized blends improve BTE and reduce BSFC than E15 blend. Among all alcohol-gasoline blends, MaxRON blend shows better engine performance that improved 2.8% BTW and reduced 5.1% BSFC than E15 in engine full throttle condition.
- All alcohol gasoline blends emitted significantly lower BSCO and BSHC emission than that of gasoline. In terms of NO<sub>x</sub> emission, the BSNO<sub>x</sub> of optimized blends were lower than E15. However, MaxHV blend emitted lowest CO, HC and NO<sub>x</sub> compared to all other blends.

The overall results showed that optimized blends have improved fuel properties and shows better performance and emission in gasoline engine without any modification. Thus optimized blends as well as multi-alcohol-gasoline blends can be used with better engine performance and emission than that of E15 fuel with more petroleum fuel displacement.

## **5.2 Recommendations**

Based on the conclusion, the following recommendations can be drawn:

- Further research is required to study the feasibility of commercial use of multi alcohol-gasoline fuels in SI engine. More research also necessary on mass production of higher carbon number alcohols from renewable sources as it perform well in gasoline engine.
- This research work only focusses on immediate effect of engine performance and emission for multi-alcohol-gasoline blends. Other engine tests are also important; such as tribological effect etc.

## REFERENCES

- Abbasi, J. (2013). The fuel that could be the end of Ethanol. Retrieved from <http://fortune.com/2013/04/12/the-fuel-that-could-be-the-end-of-ethanol/>
- Abbasi, T., & Abbasi, S. A. (2011). Decarbonization of fossil fuels as a strategy to control global warming. *Renewable & Sustainable Energy Reviews*, 15(4), 1828-1834.
- Al-Baghdadi, M. A. S. (2003). Hydrogen-ethanol blending as an alternative fuel of spark ignition engines. *Renewable Energy*, 28(9), 1471-1478.
- Al-Farayedhi, A. A., Al-Dawood, A., & Gandhidasan, P. (2000). Effects of blending crude ethanol with unleaded gasoline on exhaust emissions of SI engine: SAE Technical Paper.
- Al-Hasan, A. (2003). Effect of ethanol-unleaded gasoline blends on engine performance and exhaust emission. *Energy Conversion and Management*, 44(9), 1547-1561.
- Al-Hasan, M. (2003). Effect of ethanol-unleaded gasoline blends on engine performance and exhaust emission. *Energy Conversion and Management*, 44(9), 1547-1561.
- Alasfour, F. (1997a). Butanol—a single-cylinder engine study: availability analysis. *Applied Thermal Engineering*, 17(6), 537-549.
- Alasfour, F. (1997b). Butanol—a single cylinder engine study: engine performance. *International journal of energy research*, 21(1), 21-30.
- Alasfour, F. (1998). NO<sub>x</sub> Emission from a spark ignition engine using 30% Iso-butanol-gasoline blend: Part 1—Preheating inlet air. *Applied thermal engineering*, 18(5), 245-256.
- Alasfour, F. N. (1998). NO<sub>x</sub> Emission from a spark ignition engine using 30% Iso-butanol-gasoline blend: Part 1—Preheating inlet air. *Applied Thermal Engineering*, 18(5), 245-256.
- Aleklett, K. (2009). *Fossil motor fuels around 2050*. Paper presented at the The Royal Swedish Academy of Sciences International Energy Symposium, Sweden.
- Ammar, E. M. (2013). *Metabolic Engineering of Propionibacteria for Enhanced Propionic Acid and n-Propanol Fermentative Production*. The Ohio State University.
- Andersen, V. F., Anderson, J., Wallington, T., Mueller, S., & Nielsen, O. J. (2010). Vapor pressures of alcohol-gasoline blends. *Energy & Fuels*, 24(6), 3647-3654.

- Anderson, J., DiCicco, D., Ginder, J., Kramer, U., Leone, T., Raney-Pablo, H., & Wallington, T. (2012). High octane number ethanol–gasoline blends: Quantifying the potential benefits in the United States. *Fuel*, *97*, 585-594.
- 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.
- Azadi, H., de Jong, S., Derudder, B., De Maeyer, P., & Witlox, F. (2012). Bitter sweet: How sustainable is bio-ethanol production in Brazil? *Renewable and Sustainable Energy Reviews*, *16*(6), 3599-3603.
- Bailey, B. K. (1996). Performance of ethanol as a transportation fuel. *See Ref, 1*, 37-58.
- Baker, C. J. (2014). Why diesels make so much torque. Retrieved from <http://www.bankspower.com/techarticles/show/27-why-diesels-make-so-much-torque>
- Balamurugan, T., & Nalini, R. (2014). Experimental investigation on performance, combustion and emission characteristics of four stroke diesel engine using diesel blended with alcohol as fuel. *Energy*(0).
- Balat, M., & Balat, H. (2009). Recent trends in global production and utilization of bio-ethanol fuel. *Applied Energy*, *86*(11), 2273-2282.
- Balki, M. K., & Sayin, C. (2014). The effect of compression ratio on the performance, emissions and combustion of an SI (spark ignition) engine fueled with pure ethanol, methanol and unleaded gasoline. *Energy*, *71*, 194-201.
- Balki, M. K., Sayin, C., & Canakci, M. (2014). The effect of different alcohol fuels on the performance, emission and combustion characteristics of a gasoline engine. *Fuel*, *115*(0), 901-906.
- Bayindir, H., Yücesu, H. S., & Aydin, H. (2010). The Effects of  $\lambda$  and  $\epsilon$  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.
- Broustail, G., Halter, F., Seers, P., Moreac, G., & Mounaim-Rousselle, C. (2012). Comparison of regulated and non-regulated pollutants with iso-octane/butanol and iso-octane/ethanol blends in a port-fuel injection Spark-Ignition engine. *Fuel*, *94*(1), 251-261.
- Brown, G. (2008). Review of fuel ethanol impacts on local air quality.
- Bureau, U. S. C. (2011). International Data Base World Population: 1950-2050 Retrieved 28.03.2015, 2015, from International Data Base World Population: 1950-2050

- Campos-Fernández, J., Arnal, J. M., Gómez, J., & Dorado, M. P. (2012). A comparison of performance of higher alcohols/diesel fuel blends in a diesel engine. *Applied Energy*, 95(0), 267-275.
- 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*.
- 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.
- Cecrle, E., Depcik, C., Duncan, A., Guo, J., Mangus, M., Peltier, E., . . . Zhong, Y. (2012). Investigation of the Effects of Biodiesel Feedstock on the Performance and Emissions of a Single-Cylinder Diesel Engine. *Energy & Fuels*, 26(4), 2331-2341.
- Celik, M. B. (2008). Experimental determination of suitable ethanol-gasoline blend rate at high compression ratio for gasoline engine. *Applied Thermal Engineering*, 28(5), 396-404.
- 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.
- Chandra, R., Takeuchi, H., & Hasegawa, T. (2012). Methane production from lignocellulosic agricultural crop wastes: A review in context to second generation of biofuel production. *Renewable & Sustainable Energy Reviews*, 16(3), 1462-1476.
- Chefurka, P. (2007). World Energy to 2050. Retrieved from <http://www.paulchefurka.ca/WEAP2/WEAP2.html>
- Chen, R. H., Chiang, L. B., Wu, M. H., & Lin, T. H. (2010). Gasoline displacement and NOx reduction in an SI engine by aqueous alcohol injection. *Fuel*, 89(3), 604-610.
- Chong, J. J., Tsolakis, A., Gill, S. S., Theinnoi, K., & Golunski, S. E. (2010). Enhancing the NO2/NOx ratio in compression ignition engines by hydrogen and reformat combustion, for improved aftertreatment performance. *International Journal of Hydrogen Energy*, 35(16), 8723-8732.
- Cohn, D. R., Heywood, J. B., & Bromberg, L. (2013). Fuel management system for variable ethanol octane enhancement of gasoline engines: Google Patents.
- Colton, W. M. (2011). The Outlook for Energy a view to 2030. *ExxonMobil*.
- Cooper, C., & Alley, F. (1994). *Air Pollution Control: A Design Approach*. Boston (1986): PWS Inc.
- Costa, R. C., & Sodre, J. R. (2010). Hydrous ethanol vs. gasoline-ethanol blend: Engine performance and emissions. *Fuel*, 89(2), 287-293.



- Costa, R. C., & Sodre, J. R. (2011). Compression ratio effects on an ethanol/gasoline fuelled engine performance. *Applied Thermal Engineering*, 31(2-3), 278-283.
- Demirbas, A. (2007). Progress and recent trends in biofuels. *Progress in Energy and Combustion Science*, 33(1), 1-18.
- Demirbas, A. (2009). Biofuels securing the planet's future energy needs. *Energy Conversion and Management*, 50(9), 2239-2249.
- 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.
- European Commission. (2006). World Energy Technology Outlook (WETO H2).
- Eyidogan, M., Ozsezen, A. N., Canakci, M., & Turkcan, A. (2010). Impact of alcohol-gasoline fuel blends on the performance and combustion characteristics of an SI engine. *Fuel*, 89(10), 2713-2720.
- 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 H<sub>2</sub>O addition. *Energy Conversion and Management*, 74(0), 192-200.
- Fluent Inc. (2001). Prompt NO<sub>x</sub> Formation. Retrieved from [http://combust.hit.edu.cn:8080/fluent/Fluent60\\_help/html/ug/node582.htm](http://combust.hit.edu.cn:8080/fluent/Fluent60_help/html/ug/node582.htm)
- 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.
- Gautam, M., Martin, D. W., & Carder, D. (2000). Emissions characteristics of higher alcohol/gasoline blends. *Proceedings of the Institution of Mechanical Engineers Part a-Journal of Power and Energy*, 214(A2), 165-182.
- Goering, C. E. (1998). Engine heat release via spread sheet. *Transactions of the Asae*, 41(5), 1249-1253.
- 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.
- Grotkjaer, T., Christensen, B., Regueira, T. B., Joergensen, S. T., & Berry, A. (2011). Recombinant N-propanol and Isopropanol Production: Google Patents.
- Gu, X., Huang, Z., Cai, J., Gong, J., Wu, X., & Lee, C.-f. (2011). Emission characteristics of a spark-ignition engine fuelled with gasoline n-butanol blends in combination with EGR. *Fuel*.

- Gürü, M., Artukoğlu, B. D., Keskin, A., & Koca, A. (2009). Biodiesel production from waste animal fat and improvement of its characteristics by synthesized nickel and magnesium additive. *Energy Conversion and Management*, 50(3), 498-502.
- Hansen, A. C., Zhang, Q., & Lyne, P. W. (2005). Ethanol-diesel fuel blends -- a review. *Bioresour Technol*, 96(3), 277-285.
- Hardenberg, H. O. (1992). *Samuel Morey and His Atmospheric Engine*: Society of Automotive Engineers.
- Heywood, J. B. (1988). *Internal combustion engine fundamentals* (Vol. 930): Mcgraw-hill New York.
- Heywood, J. B. (1995). The role of preparation in low-emission combustion. *Engineering for Gas Turbines and Power, ASME*, 117, 617-654.
- 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(0), 749-759. doi: DOI 10.1016/j.energy.2014.03.070
- 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.
- Hulwan, D. B., & Joshi, S. V. (2011). Performance, emission and combustion characteristic of a multicylinder DI diesel engine running on diesel-ethanol-biodiesel blends of high ethanol content. *Applied Energy*, 88(12), 5042-5055.
- Ilkic, C., & Behcet, R. (2010). The Reduction of Exhaust Emissions from a Diesel Engine by Using Biodiesel Blend. *Energy Sources Part a-Recovery Utilization and Environmental Effects*, 32(9), 839-850.
- International Energy Agency (IEA). (2011). *Technology Roadmaps - Biofuels for Transport*.
- Jain, R., & Yan, Y. (2011). Dehydratase mediated 1-propanol production in metabolically engineered Escherichia coli. *Microb Cell Fact*, 10(97), 97.
- Jayed, M. H., Masjuki, H. H., Kalam, M. A., Mahlia, T. M. I., Husnawan, M., & Liaquat, A. M. (2011). Prospects of dedicated biodiesel engine vehicles in Malaysia and Indonesia. *Renewable & Sustainable Energy Reviews*, 15(1), 220-235.
- Kaiser, E. W., Siegl, W. O., Henig, Y. I., Anderson, R. W., & Trinker, F. H. (1991). Effect of Fuel Structure on Emissions from a Spark-Ignited Engine. *Environmental Science & Technology*, 25(12), 2005-2012.
- Karabektas, M., & Hosoz, M. (2009). Performance and emission characteristics of a diesel engine using isobutanol-diesel fuel blends. *Renewable Energy*, 34(6), 1554-1559.

- Kasseris, E., & Heywood, J. (2012). Charge cooling effects on knock limits in SI DI engines using gasoline/ethanol blends: part 1-quantifying charge cooling: SAE Technical Paper.
- 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.
- Komonkiat, I., & Cheirsilp, B. (2013). Felled oil palm trunk as a renewable source for biobutanol production by *Clostridium* spp. *Bioresource technology*, 146, 200-207.
- Krishna, M. M., & Kishor, K. (2008). Performance of copper coated spark ignition engine with methanol-blended gasoline with catalytic converter. *International Journal of Scientific and Technology Research*, 67, 543-548.
- Kumar, S., Cho, J. H., Park, J., & Moon, I. (2013). Advances in diesel-alcohol blends and their effects on the performance and emissions of diesel engines. *Renewable and Sustainable Energy Reviews*, 22, 46-72.
- Kumar, S., Singh, N., & Prasad, R. (2010). Anhydrous ethanol: A renewable source of energy. *Renewable & Sustainable Energy Reviews*, 14(7), 1830-1844.
- Lan, E. I., & Liao, J. C. (2013). Microbial synthesis of *n*-butanol, isobutanol, and other higher alcohols from diverse resources. *Bioresource technology*, 135, 339-349.
- Latey, A., Bhatti, T., Das, L., & Babu, M. G. (2004). Experimental Investigations on Ethanol 5%+ Methanol-Gasoline Mixtures Operated Single Cylinder SI Engine: SAE Technical Paper.
- Lawyer, K., Ickes, A., Wallner, T., Ertl, D., Williamson, R., Miers, S., & Naber, J. (2013). Blend Ratio Optimization of Fuels Containing Gasoline Blendstock, Ethanol, and Higher Alcohols (C3-C6): Part I-Methodology and Scenario Definition: SAE Technical Paper.
- Liu, F. J., Liu, P., Zhu, Z., Wei, Y. J., & Liu, S. H. (2011). 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.
- Manzetti, S., & Andersen, O. (2015). A review of emission products from bioethanol and its blends with gasoline. Background for new guidelines for emission control. *Fuel*, 140(0), 293-301. doi: 10.1016/j.fuel.2014.09.101
- Mekhilef, S., Siga, S., & Saidur, R. (2011). A review on palm oil biodiesel as a source of renewable fuel. *Renewable & Sustainable Energy Reviews*, 15(4), 1937-1949.

- Melo, T. C., Machado, G. B., Belchior, C. R., Colaço, M. J., Barros, J. E., de Oliveira, E. J., & de Oliveira, D. G. (2012). Hydrous ethanol–gasoline blends–Combustion and emission investigations on a Flex-Fuel engine. *Fuel*, *97*, 796-804.
- Moss, J. T., Berkowitz, A. M., Oehlschlaeger, M. A., Biet, J., Warth, V., Glaude, P. A., & Battin-Leclerc, F. (2008). An experimental and kinetic modeling study of the oxidation of the four isomers of butanol. *J Phys Chem A*, *112*(43), 10843-10855.
- 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.
- Niven, R. K. (2005). Ethanol in gasoline: environmental impacts and sustainability review article. *Renewable & Sustainable Energy Reviews*, *9*(6), 535-555.
- Normann, F., Andersson, K., Leckner, B., & Johnsson, F. (2009). Emission control of nitrogen oxides in the oxy-fuel process. *Progress in Energy and Combustion Science*, *35*(5), 385-397.
- Olson, E. S., Sharma, R. K., & Aulich, T. R. (2004). *Higher-alcohols biorefinery*. Paper presented at the Proceedings of the Twenty-Fifth Symposium on Biotechnology for Fuels and Chemicals Held May 4–7, 2003, in Breckenridge, CO.
- Ong, H. C., Mahlia, T. M. I., & Masjuki, H. H. (2011). A review on energy scenario and sustainable energy in Malaysia. *Renewable & Sustainable Energy Reviews*, *15*(1), 639-647.
- Otto, N. A. (1877). Improvement in Gas-motor engines: Google Patents.
- Ozsezen, A. N., & Canakci, M. (2010). The emission analysis of an IDI diesel engine fueled with methyl ester of waste frying palm oil and its blends. *Biomass & Bioenergy*, *34*(12), 1870-1878.
- Ozsezen, A. N., Canakci, M., Turkcan, A., & Sayin, C. (2009). Performance and combustion characteristics of a DI diesel engine fueled with waste palm oil and canola oil methyl esters. *Fuel*, *88*(4), 629-636.
- Palash, S., Kalam, M., Masjuki, H., Masum, B., Rizwanul Fattah, I., & Mofijur, M. (2013). Impacts of biodiesel combustion on NOx emissions and their reduction approaches. *Renewable and Sustainable Energy Reviews*, *23*, 473-490.
- Pechout, M., Mazac, M., & Vojtisek-Lom, M. (2012). Effect of higher content n-butanol blends on combustion, exhaust emissions and catalyst performance of an unmodified SI vehicle engine. *Training*(2012-01-1594).
- Ramadhas, A. S., Muraleedharan, C., & Jayaraj, S. (2005). Performance and emission evaluation of a diesel engine fueled with methyl esters of rubber seed oil. *Renewable Energy*, *30*(12), 1789-1800.

- Reddy, S. R. (2007). *A Model for Estimating Vapor Pressures of Commingled Ethanol Fuels*. Paper presented at the SAE Technical Paper. <http://papers.sae.org/2007-01-4006/>
- Report Rabobank. (2012). The Future of Ethanol - Brazilian and U.S. Perspectives. Retrieved from <http://www.prnewswire.com/news-releases/rabobank-report-the-future-of-ethanol---brazilian-and-us-perspectives-141054333.html>
- Rizwanul Fattah, I. M., Masjuki, H. H., Kalam, M. A., Mofijur, M., & Abedin, M. J. (2014). Effect of antioxidant on the performance and emission characteristics of a diesel engine fueled with palm biodiesel blends. *Energy Conversion and Management*, 79(0), 265-272. doi: 10.1016/j.enconman.2013.12.024
- Sarin, A. (2012). *Biodiesel: production and properties*: Royal Society of Chemistry.
- Sayin, C. (2010). Engine performance and exhaust gas emissions of methanol and ethanol–diesel blends. *Fuel*, 89(11), 3410-3415.
- Schifter, I., Diaz, L., Gómez, J. P., & Gonzalez, U. (2013). Combustion characterization in a single cylinder engine with mid-level hydrated ethanol–gasoline blended fuels. *Fuel*, 103(0), 292-298
- Sera, M. A., Bakar, R. A., Leong, S. K., & Malaysia, F. K. M. U. T. (2009). Effect of fuel density on the performance of a CNG fuelled engine. *Dept. of Mechanical Engineering, University Technology Malaysia*, 81310.
- Siwale, L., Kristóf, L., Bereczky, A., Mbarawa, M., & Kolesnikov, A. (2014). Performance, combustion and emission characteristics of n-butanol additive in methanol–gasoline blend fired in a naturally-aspirated spark ignition engine. *Fuel Processing Technology*, 118, 318-326.
- Smith, J. L., & Workman, J. P. (1980). *Alcohol for motor fuels*: Colorado State University Extension Service.
- Smith, M. B. (2013). *March's advanced organic chemistry: reactions, mechanisms, and structure*: John Wiley & Sons.
- Society of Automotive Engineers (SAE). (2002). 2002 SAE Handbook. Retrieved from
- Sundar, R. C., & Saravanan, G. (2011). Influence of hexanol-diesel blends on constant speed diesel engine. *Thermal Science*, 15(4), 1215-1222.
- Szybist, J., Foster, M., Moore, W., Confer, K., Youngquist, A., & Wagner, R. (2010). Investigation of knock limited compression ratio of ethanol gasoline blends. *SAE Technical Paper*, 01-0619.
- Thurber, M. C., Grisch, F., Kirby, B. J., Votsmeier, M., & Hanson, R. K. (1998). Measurements and modeling of acetone laser-induced fluorescence with implications for temperature-imaging diagnostics. *Appl Opt*, 37(21), 4963-4978.

- Topgül, T., Yücesu, H. S., Cinar, 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.
- Tunison, M. E. (2011). The Outlook for Energy a view to 2030. Retrieved from
- Turner, D., Xu, H. M., Cracknell, R. F., Natarajan, V., & Chen, X. D. (2011). Combustion performance of bio-ethanol at various blend ratios in a gasoline direct injection engine. *Fuel*, 90(5), 1999-2006.
- U.S. Environmental Protection Agency (EPA). (1994). Automobile Emissions: An Overview. Retrieved from
- Veloo, P. S., & Egolfopoulos, F. N. (2011). Studies of n-propanol, iso-propanol, and propane flames. *Combustion and Flame*, 158(3), 501-510.
- Venugopal, T., Sharma, A., Satapathy, S., Ramesh, A., & Gajendra Babu, M. (2012). Experimental study of hydrous ethanol gasoline blend (E10) in a four stroke port fuel-injected spark ignition engine. *International Journal of Energy Research*.
- Wald, M. L. (2010). A Bit More Ethanol in the Gas Tank. Retrieved from [http://www.nytimes.com/2010/10/14/business/energy-environment/14ethanol.html?\\_r=0](http://www.nytimes.com/2010/10/14/business/energy-environment/14ethanol.html?_r=0)
- Wei, L., Cheung, C. S., & Huang, Z. (2014). Effect of n-pentanol addition on the combustion, performance and emission characteristics of a direct-injection diesel engine. *Energy*, 70(0), 172-180.
- Xing-cai, L., Jian-Guang, Y., Wu-Gao, Z., & Zhen, H. (2004). Effect of cetane number improver on heat release rate and emissions of high speed diesel engine fueled with ethanol–diesel blend fuel. *Fuel*, 83(14), 2013-2020.
- Yacoub, Y., Bata, R., & Gautam, M. (1998). The performance and emission characteristics of C1-C5 alcohol-gasoline blends with matched oxygen content in a single-cylinder spark ignition engine. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 212(5), 363-379.
- Yang, J., Wang, Y., & Feng, R. (2011). The performance analysis of an engine fueled with butanol-gasoline blend. *SAE Technical Paper*, 01-1191.
- Yasar, A. (2010). Effects of Alcohol-Gasoline Blends on Exhaust and Noise Emissions in Small Scaled Generators. *Metalurgija*, 49(4), 335-338.
- Yeung, C., & Thomson, M. (2012). Experimental and kinetic modeling study of 1-hexanol combustion in an opposed-flow diffusion flame. *Proceedings of the Combustion Institute*.
- Yücesu, H. S., Topgül, T., Cinar, C., & Okur, M. (2006). Effect of ethanol–gasoline blends on engine performance and exhaust emissions in different compression ratios. *Applied Thermal Engineering*, 26(17), 2272-2278.

- Yücesu, H. S., Topgül, T., Çınar, 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.
- Yunoki, S., & Saito, M. (2009). A simple method to determine bioethanol content in gasoline using two-step extraction and liquid scintillation counting. *Bioresour Technol*, 100(23), 6125-6128.
- Wei, H., Feng, D., Shu, G., Pan, M., Guo, Y., Gao, D., & Li, W. (2014). Experimental investigation on the combustion and emissions characteristics of 2-methyl furan gasoline blend fuel in spark-ignition engine. *Applied Energy*, 132(0), 317-324.
- Zhuang, Y., & Hong, G. (2013). Primary investigation to leveraging effect of using ethanol fuel on reducing gasoline fuel consumption. *Fuel*, 105(0), 425-431.

## APPENDIX A

### Publications

#### Journal papers

1. **Masum, B. M.**, Masjuki, H. H., Kalam, M. A., Rizwanul Fattah, I. M., M. Palash, S., & Abedin, M. J. (2013). Effect of ethanol–gasoline blend on NO<sub>x</sub> emission in SI engine. *Renewable and Sustainable Energy Reviews*, 24, 209-222. [ISI indexed, Q1].
2. **Masum, B. M.**, Masjuki, H. H., Kalam, M. A., Palash, S. M., Wakil, M. A., & Imtenan, S. (2014). Tailoring the key fuel properties using different alcohols (C<sub>2</sub>–C<sub>6</sub>) and their evaluation in gasoline engine. *Energy Conversion and Management*, 88(0), 382-390. [ISI indexed, Q1].
3. **Masum, B. M.**, Kalam, M. A., Masjuki, H. H., Rahman, S. M. Ashrafur, & Daggig, E. E. (2014). Impact of denatured anhydrous ethanol–gasoline fuel blends on a spark-ignition engine. *RSC Advances*, 4(93), 51220-51227. [ISI indexed, Q1].

#### Conference papers

1. **Masum, B. M.**, Masjuki, H. H., Kalam, M. A., Rizwanul Fattah and Sajjad, H. Optimization of fuels containing C<sub>2</sub>-C<sub>6</sub> alcohols and gasoline and their effect on engine performance. 4th International Conference on Environment Science and Engineering, 2014, Erzurum, Turkey.
2. **Masum, B. M.**, Masjuki, H. H., Kalam, M. A. and Palash, M. S. "Study on the Effect of Adiabatic Flame Temperature on NO<sub>x</sub> Formation Using Ethanol Gasoline Blend in Si Engine." **The 2013 International Forum on Mechanical and Material Engineering**, 2013, Guangzhou, China.



## APPENDIX B

### Introduction of Solver tools

The major PC-based spreadsheets used today, Lotus, Excel and Quatro, all have built-in optimizers. These optimizers allow linear, non-linear and integer programs to be solved within the spreadsheet. If the Data tab doesn't have the choice "Solver" available then follows Figure 1 to install it. After install "Solver" it will be available on tab as shown in Figure 2.

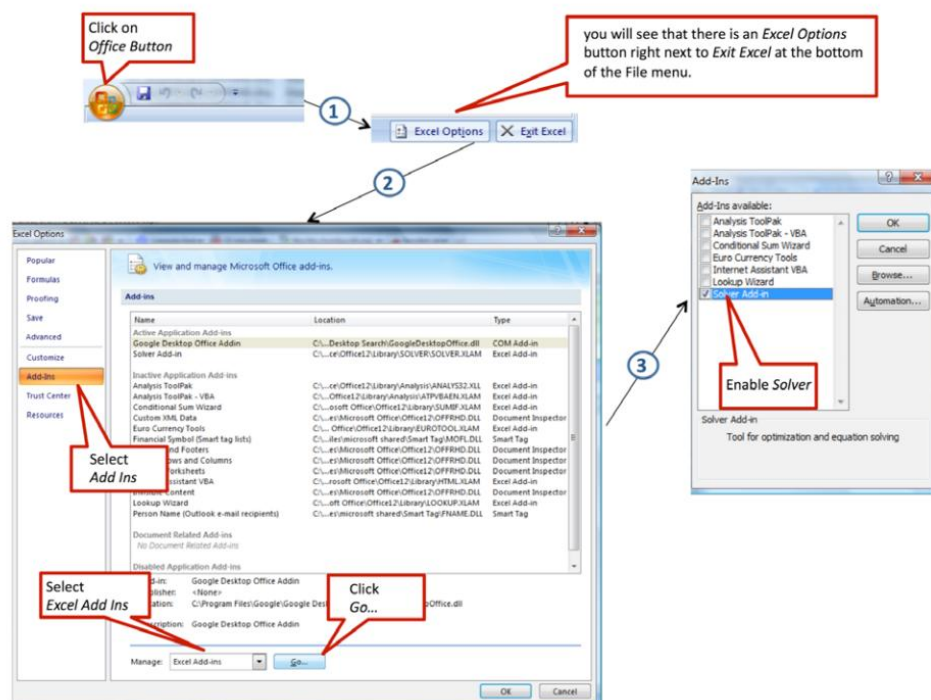
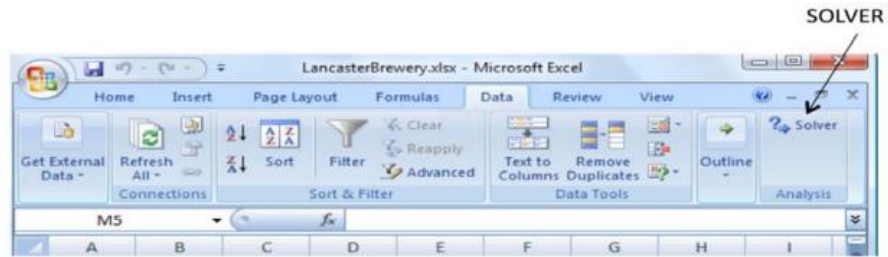


Figure 1



**Figure 2**

### **Creating a spreadsheet model**

In this chapter, one example will be shown how to find optimum blend ratio. Method of finding the blend with maximum heating value (MaxHV) with fulfilling all the conditions (conditions were described in Chapter 3.4.2) are shown here as an example.

First of all, a spreadsheet needs to create to calculate the properties of the fuel blends. Figure 3 show the beginning of the spreadsheet. In Column B to Column G are specified for different fuels, Row 5 shows the concentration of each fuels in percentage and Row 6 to Row 9 show the fuel properties. Column I represent the sum to total fuel blend. Here, B6 to F6 indicate the RON of each alcohol-gasoline blends depending on alcohols concentration. The RON of each blend is calculated by using Equation 3.4. The formula for the RON of ethanol gasoline blend **B6** is  $= (1-B4)*95+B4*107$ . The formula of resultant RON of the blend **I6** =  $AVERAGEIFS(B6:F6,B5:F5,">0")$ . As LHV works linearly, the LHV of blend are calculated by using Equation 4.1 and the formula in the spreadsheet is **I7** =  $SUMPRODUCT(B5:G5,B7:G7)/100$ . Here, B8 to F8 indicate the RVP of each alcohol-gasoline blends depending on alcohols concentration. The RVP of each blend is calculated by using Equation 3.3. The formula for the RVP of ethanol-gasoline blend **B8** =  $= (-7*10^{-7}*B5^3+0.0002*B5^2+0.0024*B5+1)*(100-B5)*0.61+(46.321*B5^{-0.8422})*B5*0.174$ . The formula of resultant RVP of the blend **I8** =  $AVERAGEIFS(B8:F8,B5:F5,">.9")$ . B9 to F9 indicate the oxygen content of

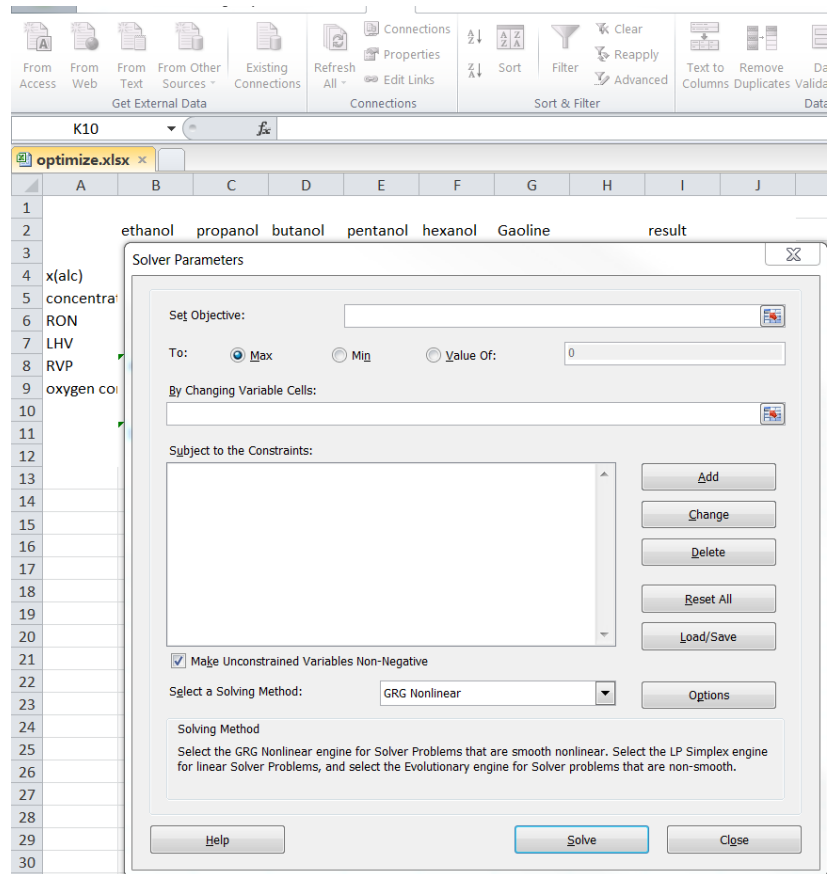
each alcohol-gasoline blends and it is calculated by using Equation 4.3. The formula for the oxygen content of ethanol-gasoline blend  $B9 = 34.7 * B5 / 100$  and the formula of resultant oxygen content of the blend  $I9 = SUM(B9:G9)$ . Here, I5 indicates the sum of the concentration of each fuel and its formula is  $I5 = SUM(B5:G5)$ .

	ethanol	propanol	butanol	pentanol	hexanol	Gaoline	result
concentra	1	10	5.00	1	2	81	100
RON	95.30791	98.1704	95.80582	95.05295	94.37916	95	95.74325
LHV	28.799	32.947	35.689	37.622	38.968	43.919	42.09711
RVP	68.60683	60.4	59.176	50.248	50.349		57.75597
oxygen co	0.347	2.66	1.08	0.181	0.314	0	4.582

Figure 3

### Specifying the objective function:

With all of formulas entered in the spreadsheet, the next step is to invoke optimizer i.e. “Solver” which is available in the “Analysis” group on the “Data” tab. This bring up the “Solver parameters” dialog box shown in Figure 4. Notice that the cursor is initially positioned in the in the box “Set objective”, which is Excel’s term for “objective function”. For this optimization, the object is to miximize LHV, which is computed in the cell I6. Type or use the mouse to highlight cell I6. Note that the target cell is specified as “Max” for the maximum value of I6.



**Figure 4**

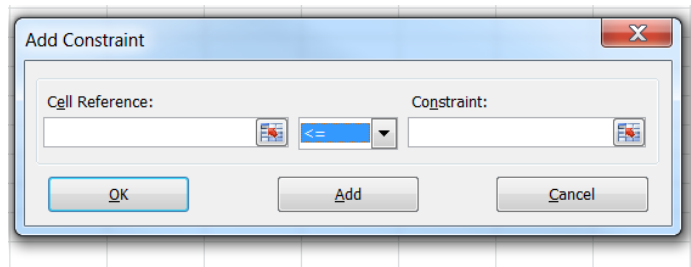
### **Specifying the decision variables**

In this optimization, a optimized blend ratio will be found that contain maximum LHV. So, the concentration of fuel B9 to G9 are cllid changing cells in Excel. Use the mouse to the box lebeled “ By Changing Variable cells” in the “Solver Parameter” dialog box. Then type B4:G4.

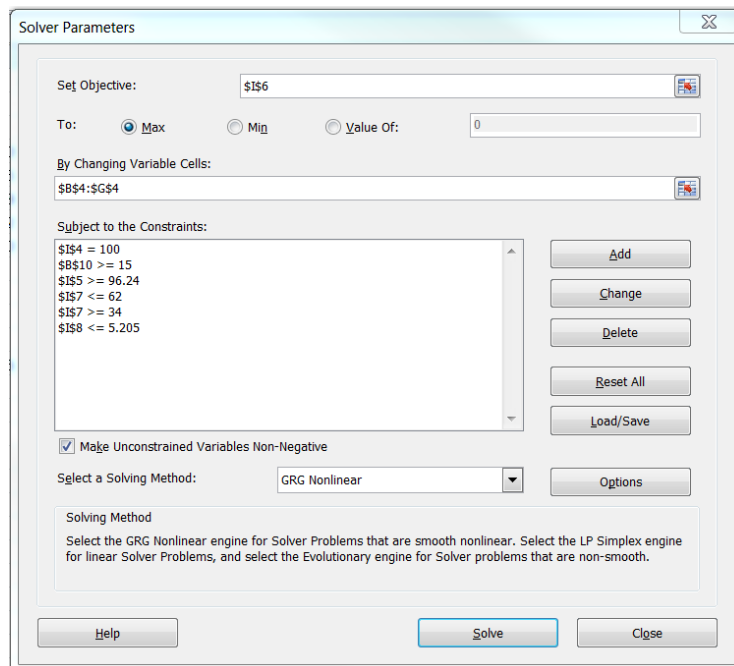
### **Specifying the constraints and the model type**

The next step is to specify the nonnegativity constraints. Set this boundary condition is important to reach on the target values of blend properties. That is, it need to guarantee that the optimal values in the cell B4:G4 are nonnegative. Use the mouse to click on the “Add” button that brings up the “Add Constrain” dialog box shown in Figure 5. Here,

all the target values condition are set those are mentioned in Chapter 3.4.2. As an example, the condition of oxygen concentration limit has been show that's value will be lower than or equal to 5.205. In the “Cell Reference” part of the “Add Constraint” dialog box, I9 has selected as I9 denotes the oxygen content of blend. Next select the down arrow and choose “<=”. In the “Constraint” box write 5.205 and then press “OK”. This equation indicate, the value of I9 will be less than or equal to 5.205. In the same way, all the conditions or target values set and shown in Figure 6.



**Figure 5**



**Figure 6**

It is ready now to find the blend ratio of maximum LHV. To active optimizer, use the mouse to click the “Solve” button. After few seconds, the “Solver Result” dialog box

should appear. Since the default is “Keep Solver Solution” clicking on “OK” will close the dialog box as shown in Figure 7. Reveal the optimal solution as illustrated in Figure 8.

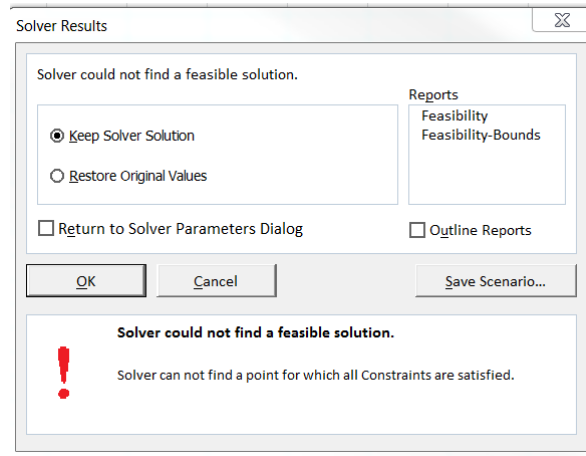


Figure 7

	A	B	C	D	E	F	G	H	I	J	K
1		ethanol	propanol	butanol	pentanol	hexanol	Gaoline		result		
2											
3	x(alc)										
4	concentration	0	8.58	5.70E+00	1	0	84.72		100		
5	RON	95	97.75549	95.91462	95.05295	95	95		96.24102		
6	LHV	28.799	32.947	35.689	37.622	38.968	43.919		42.44552		
7	RVP		60.47232	59.04468	52.5544	52.61112			57.35713		
8	oxygen content	0	2.28228	1.2312	0.181	0	0		3.69448		
9											
10											
11											
12											

Figure 8

## APPENDIX C

### Engine emission data on variable engine speed at 100% throttle condition

#### Exhaust mass flow

Engine speed	Max R	MaxD	MaxH	E15	Gasoline
rpm	Kg/min				
1000	2.319671	2.314888	2.320467	2.310611	2.317754
2000	2.785379	2.773899	2.780801	2.78003	2.791771
3000	3.855208	3.847126	3.852299	3.861234	3.865179
4000	4.110962	4.107551	4.107303	4.105761	4.11697
5000	4.656719	4.650707	4.650469	4.648098	4.657103
6000	5.487103	5.466717	5.48772	5.48472	5.491832

#### CO emission

Engine Speed	Max R	MaxD	MaxH	E15	Gasoline
rpm	% vol.				
1000	9.28	9.61	8.72	8.86	9.92
2000	10.98	11.02	10.64	10.73	11.40
3000	12.22	12.44	12.61	12.31	12.71
4000	9.68	10.32	10.61	9.94	10.97
5000	9.23	9.65	9.78	9.37	10.06
6000	10.26	10.6	10.74	10.45	10.95

#### HC emission

Engine Speed	MaxR	MaxD	MaxH	E15	Gasoline
rpm	ppm				
1000	632	620	596	636	649
2000	669	650	627	685	699
3000	651	638	621	678	682
4000	408	393	365	371	431
5000	303	290	248	268	315
6000	282	285	249	267	297

## CO<sub>2</sub> emission

Engine Speed	Max R	MaxD	MaxH	E15	Gasoline
rpm	% vol.				
1000	3.9	4.9	3.5	4.2	4.8
2000	5.8	6.3	5.4	6.2	5.2
3000	7.3	7.8	6.9	7.6	6.8
4000	9.6	9.9	9.5	9.8	8.9
5000	10.2	10.6	9.9	10.3	9.4
6000	8.8	8.9	8.3	8.9	8.1

## NO<sub>x</sub> emission

Engine Speed	MaxR	MaxD	MaxH	E15	Gasoline
rpm	ppm				
1000	26	13	10	38	28
2000	44	30	27	54	35
3000	62	39	46	76	50
4000	111	71	92	124	79
5000	140	116	131	148	119
6000	126	99	117	137	112

## Engine emission data on variable engine torque at 4000rpm

### Exhaust mass flow

Torque	Max R	MaxD	MaxH	E15	Gasoline
N.m	Kg/min				
20	2.269658	2.2708	2.27052	2.271817	2.2694
40	2.6832	2.685983	2.684727	2.685025	2.68152
60	3.694492	3.69994	3.699775	3.7012	3.6942
80	3.89495	3.8981	3.896773	3.899417	3.892874
100	4.409609	4.411435	4.410589	4.414851	4.405729
120	5.180695	5.184035	5.179178	5.187783	5.176907



## CO emission

Torque	MaxR	MaxD	MaxH	E15	Gasoline
<b>N.m</b>			<b>% vol.</b>		
<b>20</b>	0.157	0.141	0.128	0.131	0.184
<b>40</b>	0.151	0.141	0.238	0.134	0.577
<b>60</b>	0.407	0.543	0.701	0.444	1.0316
<b>80</b>	1.536	1.606	2.887	1.559	2.601
<b>100</b>	3.64	3.89	4.732	3.919	5.221
<b>120</b>	4.844	4.997	5.655	4.961	6.669

## HC emission

Torque	MaxR	MaxD	MaxH	E15	Gasoline
<b>N.m</b>			<b>ppm</b>		
<b>20</b>	44	22	47	35	57
<b>40</b>	54	46	68	54	94
<b>60</b>	75	75	93	74	108
<b>80</b>	89	94	114	86	126
<b>100</b>	103	106	135	110	143
<b>120</b>	109	119	136	111	161

## CO<sub>2</sub> emission

Torque	Max R	MaxD	MaxH	E15	Gasoline
<b>N.m</b>			<b>% vol.</b>		
<b>20</b>	11.73	8.66	9.98	9.71	11.3
<b>40</b>	11.95	10.4	11.21	11.23	11.82
<b>60</b>	11.87	10.28	10.97	10.72	10.79
<b>80</b>	10.82	10.81	9.82	10.09	10.03
<b>100</b>	9.04	8.82	8.82	8.81	8.28
<b>120</b>	8.71	8.22	8.47	8.68	7.64

## NOx emission

<b>Torque</b>	<b>MaxR</b>	<b>MaxD</b>	<b>MaxH</b>	<b>E15</b>	<b>Gasoline</b>
<b>N.m</b>			ppm		
<b>20</b>	15	14	12	18	10
<b>40</b>	28	24	21	32	16
<b>60</b>	72	56	50	78	40
<b>80</b>	132	119	110	138	104
<b>100</b>	161	150	143	168	133
<b>120</b>	119	106	99	115	98