Engine Emission Analysis and Performance Test with Ethanol-Gasoline Blended Fuel

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Abstract

Currently the automobiles of the world are largely driven by fossil gasoline. Facing depleting of crude oil reserves and air pollution problems, ethanol has been widely studied as a substitute for gasoline. Ethanol is a renewable fuel as it can be produced from biomass. The gasoline blended with ethanol is particularly promising since it is more readily incorporated into the existing fuel combustion system. This paper studies the engine performance using various ethanol−gasoline blends containing 0 to 20% ethanol. The engine under studied is a single cylinder, four strokes, and portable non−road engine. The engine performance is evaluated by two criteria, which are exhaust emission and fuel consumption. It is concluded that both CO and HC emission from exhaust gas show a reduction trend as the ethanol content increases. This is also true for the amount of fuel consumed.

Key words: Ethanol, gasoline, Robin engine, CG200 automotive emission analyzer.

1.0 Objective

This paper aims to investigate the performance of a robin engine performance using various ethanol−gasoline blended fuel. The exhaust emission by each blended fuel and the fuel consumption are measured and compared for different ethanol-gasoline blends.

2.0 Introduction

In recent years, the climate of the earth has changed greatly due to rising greenhouse gases concentration in the atmosphere, which subsequently leads to global warming (Huang and Wu, 2008). The major contributor to the global warming is CO_2, which is emitted by fossil fuel power plants, automobiles, and various industries. Huge amount of fossil fuel consumption also contributes to environmental pollution globally. Combustion of fossil fuel emits harmful gases such as carbon monoxide (CO), nitrogen oxides (NO_x), and unburned hydrocarbons (HCs). Since fossil fuel is currently dominating the energy generation scene, and is forecasted to continue this domination, it has become imperative to reduce the combustion of fossil fuel, while looking for alternative clean burning fuel.

The heavy dependence on fossil fuel has caused a drastic decrease in the fossil fuel reserve, which would take millions of years to regenerate. This has consequently led to the soaring price of crude oil. The local consumption of fossil fuels is expected to increase as the number of motor vehicles is expected to increase. Figure 1 shows the energy consumption by vehicles in Malaysia.

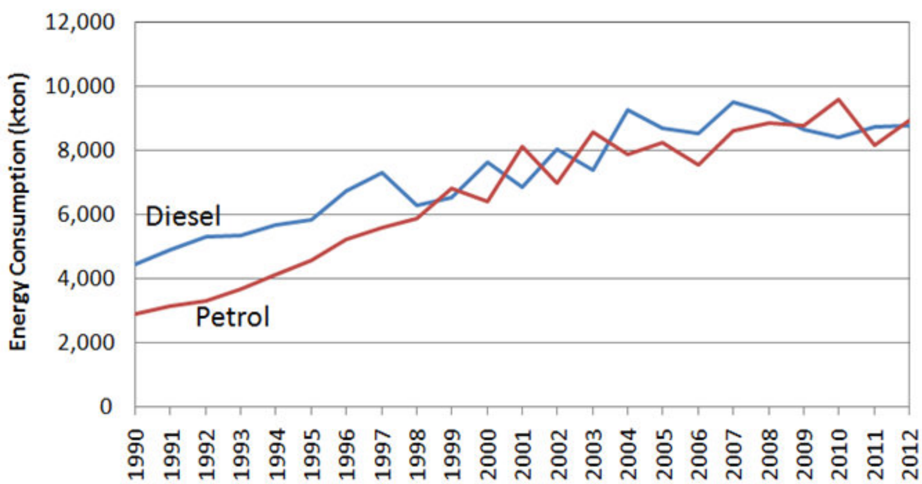

Figure 1: Energy use by transportation sector in Malaysia (kiloton oil equivalent) (NEB 2012, 2014)

Using ethanol as an alternative to substitute fossil fuel is one of the ways to reduce the pollution caused by excessive dependence on fossil fuel. Ethanol improves the efficiency of the engine because perfect combustion is more likely to occur. As a result, the engine emits less harmful gases (Anderson et al, 2012).

Despite the fact that ethanol produces carbon dioxide (CO_2) on complete combustion, its production holds at the promise of being carbon neutral because plant materials take up atmospheric CO_2 during their lifetime through photosynthesis. By burning ethanol fuel, the net carbon emission is significantly less than burning neat gasoline. This would alleviate the global warming problem, and at the same time enhance energy security.

Ethanol can be produced from a variety of agricultural products through fermentation process. Bioethanol is a formed of renewable energy produced from fermentation of biomass. In America, corn is widely used to produce bioethanol and in Brazil, sugarcane is extensively used (Luo et al, 2008). In Malaysia, there is small scale effort to use oil palm empty fruit bunch and sago as a source of bioethanol (Kamarudin et al, 2012; TCE, 2013). Blessed with an abundant supply of plant resources, Malaysia has the potential to develop the full scale production of bioethanol for fuel purpose (Azmi et al, 2013).

The fuel used in the engine plays a part in the fuel emission composition as well as the engine performance. In this research, Robin engine is used, as previous research mostly focused on an automotive engine. The Robin engine, being a non–road engine, might respond differently to ethanol fuel (Gravalos et al, 2013).

An engine which runs efficiently consumes less fuel for the same power output. The lesser the fuel consumed, the lesser the emission. Bioethanol is a potential solution to reduce the harmful emissions. The composition of the gasoline-ethanol blend is a factor to consider when evaluating the effects of ethanol on the emission and engine performance.

3.0 Literature Review

3.1 Ethanol

Ethanol is a liquid which is colorless, biodegradable with low toxicity. It is combustible and therefore can be used as a substitute for gasoline and diesel. Being renewable, it is able to reduce the dependency on fossil fuel. It can be produced through fermentation of plant and sugar (Parag and Raghavan, 2009). The fermentation produces hydrous ethanol, which must be dehydrated if it is to be blended with gasoline for motor fuel purpose (Kumar et al, 2010).

Any plant materials that are high in carbohydrates are suitable feedstocks for fermentation. Among the commonly used feedstocks are corn, sugarcane, cassava and sweet potato. Recent studies have shown tapping into using non–edible feedstock for bioethanol production, such as wood, wheat straw, corn stalk, etc. (Kumar et al, 2010).

3.2 Gasoline

Gasoline is a highly volatile flammable liquid HC mixture used as fuel for internal combustion engine. Gasoline is the primary fuel for automobiles worldwide.

Additives such as lead, oxygenates, and antioxidants, are mixed into gasoline to improve its operating characteristics. Antiknock additives are used to slow down the ignition and burning of gasoline (Agency for Toxic Substance and Disease Registry, 2012). This action helps prevent engine ping or knock (Knocking sound produced by abnormal and excessively rapid combustion). Leaded gasoline has lead antiknock additives. The lead results in a higher engine compression ratio in the combustion chamber and thereby prevents the fuel from igniting prematurely. Leaded gasoline is designed to be used in older vehicles that have little or no emission controls.

The fuel most commonly used is unleaded gasoline having a research octane number (RON) of 95, often called RON95. Unleaded gasoline does not contain leaded antiknock additives. The Parliament of Malaysia has enacted laws requiring all vehicles to meet strict emission levels (Ong et al, 2012). Leaded gasoline is totally banned by the United States Environmental Protection Agency (EPA) as lead emitted into the atmosphere is seriously harmful to living organisms (Surisetty et al, 2011).

The gasoline is combusted in the combustion chamber of an internal combustion engine. The gasoline is mixed with air and the gasoline enters the cylinder during the intake stroke. Next, it is compressed by a piston during the compression stroke and ignited by a spark plug. The expanding hot gas forced the piston up during the power stroke phase as the fuel is burned. Unburned gases are finally ejected from the cylinder during the exhaust stroke through an exhaust pipe (Gary et al, 2007).

In perfect combustion process, the oxygen in the air would chemically react with hydrocarbon releasing carbon dioxide and water vapor into atmosphere and providing energy to move the vehicle (Yepsen and Witoshkin, 1991). However, in reality a perfect combustion does not happen. Pollutants are emitted from the exhaust of the vehicle in the forms of unburned HCs, CO, and NO_x.

3.3 Pollutants in exhaust-CO and Unburned HCs

From incomplete combustion, CO is formed. This occurs especially when the combustion environment has oxygen deficiency.

Unburned HCs are the hydrocarbon unburned during combustion. When they are released through the exhaust pipe, these HCs end up polluting the atmosphere (Gary et al, 2007).

3.4 Bioethanol as a sustainable fuel

Bioethanol has emerged as a good alternative solution to replace the depleting global supply of fossil fuel. It has been used in Germany and France as early as 1894 by the then industrial internal combustion engines (Demirbas, 2005). Brazil has utilized bioethanol as a transportation fuel since 1970s, either in pure form or blend with gasoline (Alvarenga et al, 2013). To promote the use of bioethanol, Brazil Government has enforced a mandate that gasoline should contain a minimum of 22% ethanol. The price of bioethanol is cheaper than the gasoline, except during 2010–2012 when the sugarcane feedstock cost surged in a percentage higher than the crude oil cost (Ajanovic and Haas, 2014). In Brazil, flex–fuel cars, which are manufactured to run on any gasoline-ethanol blend, are becoming more common on the motorways.

The Thai Government has launched policies and programs to promote the production and consumption of bioethanol with an ultimate aim of establishing energy security. E20 vehicles that run on E20 ethanol–gasoline blend and E20 gasoline stations are on the increasing trend in Thailand due to the Government's effort (Silalertruksa, 2009).

Petroleum based fuel became more expensive to produce particularly after World War II. During 1970s oil crisis, studies on the optimum octane rating for new unleaded gasoline were carried out to replace the leaded fuel. This is because a higher octane rating will have a better efficiency in spark–ignited engine (Anderson et al, 2012).

Bioethanol has a higher octane number with broader flammability limit, higher flame speeds, and higher heats of vaporization than gasoline. As a result, it will lead to higher compression ratio, shorter burn time, and leaner burn (Dias de Oliveira et al, 2005). This sparks the interest of using bioethanol as a long term solution for transportation fuel.

Transportation fuel for vehicle can use pure bioethanol or it can be blended with gasoline. The most common blend is 10% ethanol and 90% petrol (E10) which is known as gasohol. Conventional gasoline-driven vehicles are able to run on up to 10% ethanol without any modification to the engine (Balat and Balat, 2009). Since the use of pure ethanol requires some modifications to the current internal combustion engine of motor vehicles, a blend of ethanol and gasoline is more feasible. In fact, in the last few years, gasoline with 5-10 %volume ethanol has been used in various parts of the world. In the USA, E10 gasohol is a very popular fuel for motor vehicles and is being dispensed by most of the gasoline stations (Turner et al, 2013).

The bioethanol is not considered widely applied as motor fuel in the world except in Brazil where 20% of the total energy consumed by the transportation sector is generated by bioethanol. In the US, bioethanol generates ca. 3% of the total transport energy. This figure is just 2% for the world (Ajanovic and Haas, 2014). International Energy Agency (IEA) predicts that future bioethanol development will be mainly driven by the demand from the transportation sector.

3.5 Global Bioethanol Production

The worldwide production of first generation ethanol is increasing in accordance with the rising demand. The largest producers of bioethanol are the US, Brazil, and China. The US is the largest producer with 4,450 million tons in 2012. The US and Brazil together contribute 87% of the world's bioethanol supply. The US has allocated vast areas of land for corn (maize) farming to produce bioethanol. Corn from US accounts for 40% of the global harvest. In Brazil, ethanol can be produced economically due to abundant sugarcane supply and support from the Government. Brazil is the largest producer of sugarcane with 27% of world's harvest (Kocar and Civas, 2013). In China, bioethanol is mainly produced from corn and wheat. A trial 10% mandate of ethanol-gasoline blend has been imposed in some regions of the People Republic (Yan and Lin, 2009).

In Southeast Asia, Thailand is the major bioethanol producer with 500 million liters in 2011 (Kumar et al, 2013). This figure is expected to grow rapidly in the coming years in line with the nation's interest of sustainable energy. The raw materials used are sugarcane and cassava which can be acquired abundantly locally at low costs. The country boasts of its relatively advanced development in bioethanol conversion technology as compared to other Southeast Asian countries.

The large scale production of bioethanol is feeding on edible feedstocks. Cultivation of these feedstock crops creates a food–fuel competition issue and threatens food security especially in highly populated countries such as the US and China. The cultivation of agricultural crops for either food or energy shares the same production resources such as land, water, and labor. High bioethanol demand in the future may increase the prices of these energy crops. The public access to these foodstuffs will then be hampered by the price hikes. Realizing the gravity of this issue, the Chinese Government has moved to marginal lands for energy crops plantation (Ge et al, 2014). Sweet sorghum and cassava are indentified as the potential energy crops. The former is rich in sugar while the later in starch. Both crops can grow on barren lands where other food crops do not.

The total global fuel bioethanol demand is expected to grow exceeding 12.5 billion liters by year 2020 (Demirbas, 2008).

3.6 Greenhouse Gas (GHG) Emission

According to IEA, sugarcane bioethanol produced by a well–integrated production plant can reduce the well-to-wheels CO_2 emission as much as 90% as compared to fossil fuels (IEA, 2007). In Yu and Tao's experiment (2009), it showed that bioethanol fuel emits less CO_2 and volatile organic compounds (VOCs) than conventional gasoline during its lifecycle. A study on the potential of biomass and bio-energy in Southeast Asia between 1990 and 2005 showed that the carbon emission reduction associated with using woody biomass instead of fossil fuels for energy was between 202 and 336.7 Tg carbon per year (Sasaki et al, 2009).

However, bioethanol does not necessarily result in negative carbon emission. Over the entire life cycle, bioethanol may result in positive GHG emission. The life cycle of carbon emission is evaluated from cradle to grave, i.e. from soil treatment, seeding, harvesting to the retailing and eventual combustion of bioethanol fuel. The life cycle of GHG emission depends on feedstock, agricultural technology, conversion technology, etc. (Yan and Lin, 2009). Alvarenga and De Wulf (2013) found that the net life−cycle of carbon emission for hydrous ethanol fuel is 0.21 kg CO_2 eq/kg; and this value rises to 2.03 kg CO_2 eq/kg for E22 blend. With supports from the governments, the bioethanol technology at the cultivation and production phases can be further improved in terms of yield and cost. This can further lower the overall GHG emission and potentially achieve carbon neutrality. Blending gasoline with ethanol is a positive step in mitigating GHG emissions. Though it cannot give negative carbon emission cradle-to-grave, it significantly reduces the GHG emission by the fossil fuel.

The bioethanol conversion technology based on second generation feedstock, which is non−edible biomass, is currently not profitable for mass production. Development is under way for second generation bioethanol. The success of it will serve a three-fold purpose, which are addressing energy concern, avoiding direct competition with food, and advancing closer to carbon neutrality (Kumar et al, 2013; Ajanovic and Haas, 2014).

3.7 Ethanol in Gasoline

The addition of ethanol to gasoline will alter the properties of the fuel. Ethanol has desirable properties when it is blended with gasoline and strengthens the quality of the resultant fuel (Wen et al, 2010).

Ethanol has higher octane number and higher heat of vaporization than typical gasoline as shown in Table 1. Therefore, gasoline–ethanol blends have higher octane numbers and higher heats of vaporization than gasoline. The higher the octane number, the more compression the fuel can stand before igniting. Research shows that a higher octane number, equivalent to a low self-ignition tendency, yields higher engine efficiency (Heywood, 1988).

Table 1: Properties of gasoline and ethanol (Anderson et al, 2012)

Properties	**Gasoline**	**Ethanol**
Kinematic Viscosity (mm^2/s)	0.5–0.6	1.2–1.5
Density (kg/m^3 at 20°C)	718.33	789.67
Research Octane number	91−100	108.61−110
Heat of Vaporization (kJ/kg)	380−400	900−920
Reid vapor pressure (kPa) (at 37.8°C)	55.2−103.4	15.8
Stoichiometric air/fuel ratio (by weight)	14.2−15.1	8.97
Lower heating value (MJ/kg)	44.0	26.9

3.8 Previous Works

The effects of ethanol blended gasoline on emissions and catalyst conversion efficiencies were investigated by He et al (2003). The engine under study was a spark ignition engine with an electronic fuel injection (EFI) system. The fuel containing 30% ethanol produced emissions with lower HC, CO and NO_x emissions but higher unburned ethanol and acetaldehyde emissions. The engine-out Pt/Rh catalyst was effective in reducing acetaldehyde emissions but not unburned ethanol. They also suggested that blended fuels can decrease brake specific energy consumption.

Dufey (2006) proved that engines running on biofuel or biofuel blend with fossil fuel tend to have lower particulate, CO and HC emissions as compared to neat fossil fuel. He attributed it to the clean burning characteristics of biofuel. Since transport sector is one major contributor to air pollution, blending ethanol with gasoline looks promising to alleviate the pollution.

Schifter et al (2011) investigated the effect of using gasoline-ethanol fuel on engine performance and exhaust emissions on a single cylinder engine, spark ignited and DOHC controlled. CO and HC emissions decreased while NO_x increased. At constant mass fuel rate, gasoline blended with 10% ethanol has marginal effect in combustion rates relative to the reference fuel. However, for 20% ethanol, the combustion process slowed down and increased cyclic dispersion in proportion to the burning rate reduction as an enleanment consequence.

Turner et al (2011) used a direct injection engine to test the combustion performance of bioethanol−blended gasoline. Spark timing and injection methods were varied to study their effects. The results obtained were reduced combustion initiation duration and faster combustion because of higher flame velocity. In addition, CO emission was reduced while NOx was minimally decreased. The authors suggested that fuel injection strategies could modify the combustion and emission characteristics.

Gravalos et al (2013) blended gasoline with lower−higher molecular mass alcohol (propanol, butanol and pentanol) and studied the emissions of CO, CO_2, HC and NO. They found that the CO and HC emissions reduced while the CO_2 and NO emissions increased with ethanol content. The CO and HC emissions were higher than those from ethanol−gasoline blends.

Masum et al (2013) studied NOx emission with a spark ignited engine. They investigated the effects of engine load, engine compression ratio, and engine speed on NOx emissions. It was found that higher flame speed of ethanol helped achieve complete combustion of rich mixtures attained during higher engine loads or speeds. This resulted in higher NOx emission for ethanol–gasoline blends than that of gasoline.

4.0 Materials and Apparatus

4.1 Materials

The materials are gasoline (RON 95) obtained from a local gas station and ethanol purchased from chemicals store. The specifications of ethanol are as shown in Table 2.

Table 2: Specifications of ethanol

Characteristics	Specifications
Assay	99.98% v/v at $20^oC/20^oC$
Specific Gravity	0.7906 at $20^oC/20^oC$
Acidity	0.00163% w/v
Solubility	Complies with B.P. requirement
Clarity	Not more than 10 hazen
Identification	Complies with B.P. requirement
Water content	0.1400% w/w

4.2 Instruments/Engine

Two main pieces of instrument/engine in this study are Robin engine and an automotive emission analyzer (CG200 Automotive Emission Analyzer). The Robin engine used in this research is a portable engine, commonly used around the world under all kinds of environment, to generate electricity for various machines and equipment. This engine is not only economical but also reliable and convenient to use. The Robin engine runs on gasoline and emits waste gases through an exhaust pipe during its operation. The characteristics and specification of Robin engine are shown in Table 3.

The analyzer is equipped with a non−dispersive infrared (NDIR) module for CO and HC. This model comes with digital display and is able to measure the carbon monoxide and hydrocarbon content continuously. The specifications are as shown in Table 4. The sample line of the analyzer is fitted to the exhaust pipe 400mm away to provide adequate mixing to the emission gases.

Table 3: Specifications of Robin engine

Characteristics	**Specifications**
Engine type	Single cylinder, four stroke, air cooled gasoline engine
Continuous output	2.24 kW/3000 min^{-1} (3 HP/3000 rpm) 2.61 kW/3600 min^{-1} (3.5 HP/3600 rpm)
Maximum power	3.73 kW/4000 min^{-1} (5 HP/4000 rpm)
Dry weight	16 kg
Fuel tank capacity	3.8 liters
Starting system	Recoil starter
Spark plug	NGK B−6HS
Dimension (length x width x height)	318 x 332 x392 mm

Table 4: Specifications of the CG200 Automotive Emission Analyzer

Emission	**Measuring range**	**Accuracy**	**Resolution**
CO	0–9.99% volume	±0.006%	0.01%
HC	0–9999ppm	±12ppm	1 ppm

5 Experimental Procedures

5.1 Preparation of Enthanol-Gasoline Fuel

The biofuel is produced by blending gasoline with pure ethanol. Four types of ethanol-gasoline fuels are prepared, with each blend containing a designated percentage by volume of ethanol. The blends containing 5%, 10%, 15% and 20% of ethanol are prepared, named respectively as E05, E10, E15, and E20. The gasoline RON95 is to be used as the control fuel.

5.2 Emission Analysis and Fuel Consumption Test

The engine is started and left to warm up for 30 minutes. Before filling in a new ethanol gasoline fuel, sufficient time is allowed for the engine to consume the leftover fuel from the previous experimental run. The engine is set at 3000rpm throughout this study. Once the displayed readings of the analyzer become steady, the values are taken. For each fuel blend, three runs are carried out to obtain average values.

For this performance test, the amount of fuel consumed for a period of 30 minutes is recorded. All five fuel ethanol-gasoline fuel types i.e. RON95, E5, E10, E15 and E20 - are used during the test. For each ethanol-gasoline fuel type, three runs are carried out to obtain the average values.

6. Results and Discussion

6.1 Emission Analysis

6.1.1 CO Emission

CO emission is one of the indicators of combustion efficiency. Figure 2 shows the percentage of CO in the flue gas from the Robin engine. The amount of CO emission decreases as the amount of ethanol in the fuel increases. RON95 fuel records the highest CO percentage at 2.36%, followed by E05, E10, E15, and E20 which recorded 1.98%, 1.68%, 1.55% and 1.29% respectively.

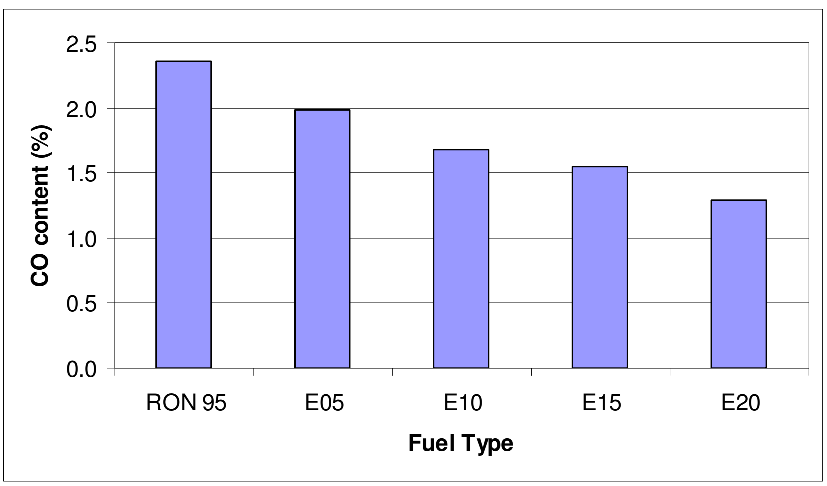

Figure 2: Percentage CO content in the exhaust emission

RON95 produces the most CO. This can be attributed to insufficient air or oxygen supply during combustion. In contrast, E20 produces the least emission. The result is consistent with the findings from Chen et al (2010) who tested ethanol–gasoline fuel with motorcycle engines. CO emission is almost directly related to the air–fuel mixture ratio. Ethanol, being an oxygenated fuel with 34.7% oxygen content, needs less air for combustion, when compared with gasoline (Kumar et al, 2010). Having a higher octane number, ethanol increases the octane number of the fuel blend and hence increases the compression ratio. Thus, combustion has higher efficiency.

6.1.2 HC Emission

Low HC emission is an indication of efficient combustion. Figure 3 shows the HC content in ppm in the exhaust gas from the engine. The HC content decreases as the ethanol content increases. RON95 records the highest HC content at 181ppm. This is followed by E05, E10, E15 and E20, which respectively recorded 164ppm, 156ppm, 136ppm, and 135ppm. The HC emission becomes nearly constant from E15 to E20. These findings echo those results from Al-Hasan (Al-Hasan, 2003), who studied the exhaust emission from a four-cylinder and four-stroke automotive engine using bioethanol. A high amount of HC emitted indicates incomplete combustion. Ethanol can be burnt more efficiently than gasoline because it is an oxygenated fuel with 34.7wt% oxygen that promotes high combustion temperature and its higher flame speed promotes complete combustion (Masum et al, 2013).

For complete combustion, the stoichiometric air-fuel ratio for gasoline is 1.6 times that of ethanol (Masum et al, 2013). A blend of ethanol and gasoline is therefore able to reduce the required air for complete combustion.

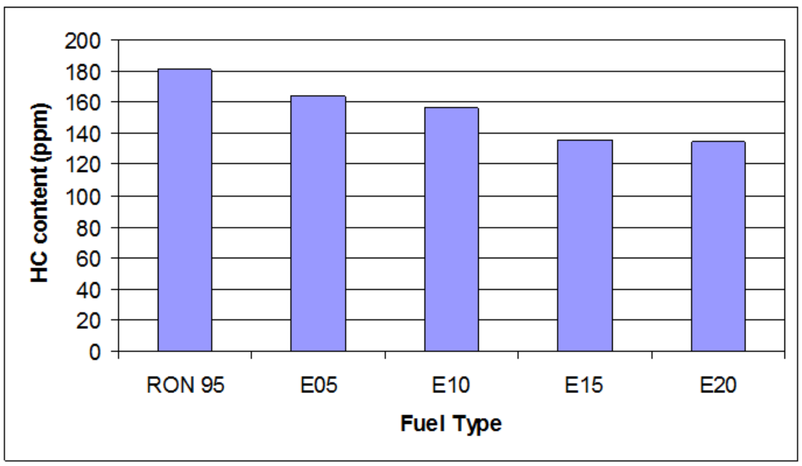

Figure 3: HC content in exhaust emission

6.1.3 Percentage Reduction of CO and HC

As shown in the results in Fig. 2 and 3, adding ethanol into gasoline is one possible way since it successfully reduces the CO and HC emissions. Figure 4 shows the percentage reduction of CO and of HC against the control fuel RON95. CO and HC emissions are primary indicators of combustion efficiency of the engine. They are closely related to many design and operating variables. Combustion chamber and ignition system design are two important design variables; while air-fuel ratio, speed and load are main operating variables (Gravolos et al, 2013). High combustion efficiency has reduced CO and HC emissions. Since ethanol can increase the combustion efficiency, ethanol-gasoline fuel yields reduced CO and HC emissions. However, the results from Fig. 4 shows that for the same blend ratio, the percent reduction of CO emission is more than the percent reduction of HC emission. This implies that CO emission has a higher degree affected by fuel properties such as air-fuel ratio. Meanwhile, the fuel has a more limited effect on HC emission. This limited effect comes to a halt at E15 blend and above. This indication is shown in Fig. 3 and Fig. To further reduce the HC emission content below 135 ppm, the engine system such as the combustion chamber and ignition system has to be re-designed.

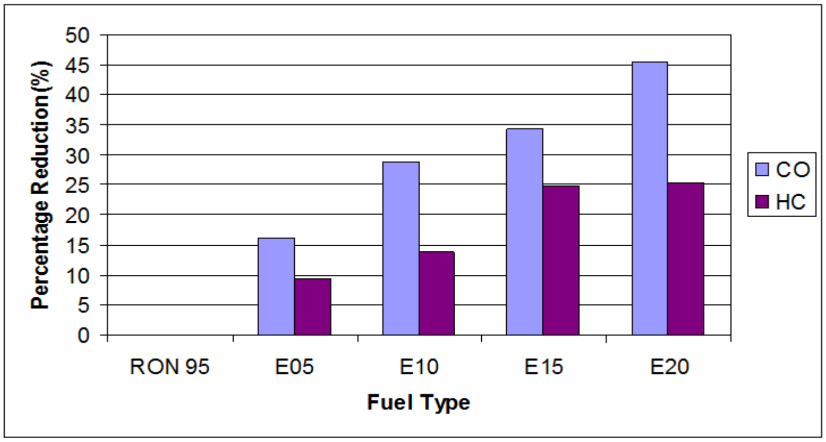

Figure 4: Percentage of reduction of CO and HC

6.2 Fuel Consumption Test

The results of fuel consumption test are shown in Fig. 5. It is noted that E20 consumes the least fuel, while the control fuel - RON 95 consumes the most. The fuel volumes consumed for RON95, E05, E10, E15, and E20 are 157.83ml, 157.67ml, 157.00ml, 154.17ml, and 153.17ml respectively.

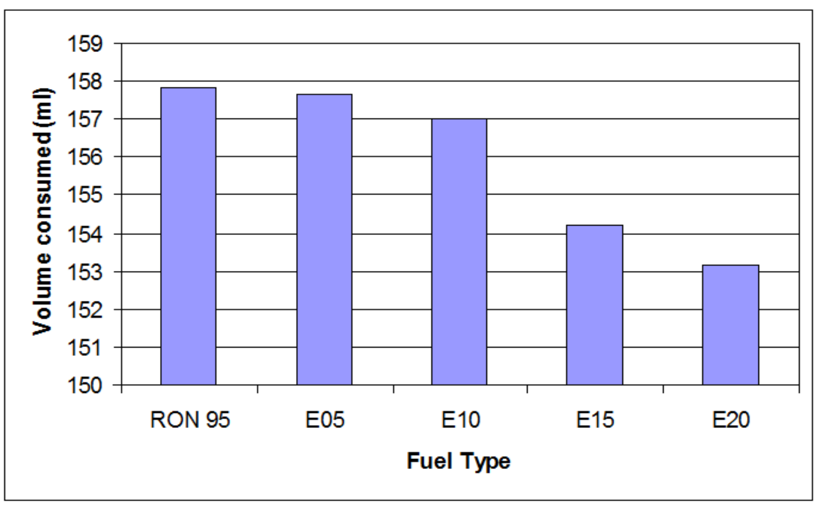

Figure 5: Fuel consumption for various ethanol-gasoline fuels

The increasing ethanol content in the fuel successfully reduces the volume consumed, though the volume reduction is small. This might be attributed to the higher compression ratio with higher ethanol content. Higher compression ratio leads to increase of engine performance with reduced knocking and increased combustion efficiency (Turner et al, 2011). Since less fuel is consumed, from a mass balance point of view, it may be inferred that the emissions are less than that from neat gasoline.

7.0 Conclusion

In the emission analysis, it is found that the emissions of CO and HC are reduced as the ethanol concentration in the ethanol-gasoline blend increases. 45.33% reduction of CO and 25.41% reduction of HC are respectively recorded for E20 fuel. Using the same fuel blend ratio, the drop in CO content in the exhaust gas is more than the drop in HC content. The fuel has a more limited effect on reducing HC emission content compared to reducing CO emission content. Change of either engine load or speed or engine redesign is required to further reduce HC emission.

For the fuel consumption test, the fuel consumed is the least for E20, which is 153.17ml. The fuel consumed by the control fuel-RON95 is the most, which is 157.83ml. Engine efficiency is enhanced by the addition of ethanol owing to higher compression ratio, reduced knocking, and enhanced combustion efficiency.

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