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Experimental Study on the Effects of Methanol and Ethanol on Gasoline Engine Performance and Exhaust Emissions

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ABSTRACT

Increasing demands of energy sources in automotive sector have led to depletion of fossil fuels. In solving the problem of fuel supply, researchers have rapidly raised intentions on alternative fuels since the late 20th century, in which it is highly favourable over gasoline fuel due to its cost-efficiency and environmental friendly. This paper presented the effects of various alcohol-gasoline blends on engine performance and exhaust emissions. Four fuel blends; M5 (methanol 5% + pure gasoline 95%), M15 (methanol 15% + pure gasoline 85%), E5 (ethanol 5% + pure gasoline 95%) and E15 (ethanol 15% + pure gasoline 85%) were tested on a 4-cylinder, 4-strokes, 1.6L natural aspirated spark ignition (SI) engine under condition of wide open throttles and engine speed varied from 1000-4000 rpm. The results showed that methanol and ethanol fuels provide air-fuel charge cooling to increase the density of the charge. Thus, the fuel blends produced higher engine brake power than that of pure gasoline. In relation to brake specific fuel consumption (BSFC), E15 presented the highest result due to the lower energy content compared to that of other blends. Brake thermal efficiency

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(BTE) produced by M15 was the highest, obtaining 5.17% increment from pure gasoline compared to other fuel blends which were 1.6%, 1.16% and 2.47% for M5, E5 and E15, respectively. The fuel blends emitted lower exhaust emissions of carbon monoxide (CO) and hydrocarbon (HC) gases due to the addition of oxygenated fuel that promoted better combustion process and reduced exhaust emissions of CO and HC. However, the blends have resulted in increase of NOx emissions in comparison to that of pure gasoline which can be attributed to the higher flame temperature of alcohol. Optimized blend ratios for methanol and ethanol with gasoline were found to be better than pure gasoline fuel in terms of fuel properties, combustion behaviour, engine performance and exhaust emissions with E15 producing the highest engine brake power of 60.3 kW and emitting the lowest CO and HC emissions at high engine speed with 0.566% and 114.2 ppm, respectively. Meanwhile, M15 provided the most thermal efficient fuel blend at all operating conditions.

Keywords: *Ethanol, Methanol, Engine Performance, Exhaust Emissions, Gasoline Engine*

Nomenclature:

BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CO	Carbon monoxide
HC	Hydrocarbon
NO_x	Nitrogen oxide
LHV	Lower heating value
rpm	revolutions per minute
ppm	parts per million
SI	Spark ignition
CH_3OH	Methanol
C_2H_5OH	Ethanol
M5	Methanol 5% - gasoline 95%
M15	Methanol 15% - gasoline 85%
E5	Ethanol 5% - gasoline 95%
E15	Ethanol 15% - gasoline 85%

Introduction

High fuel demands have caused the depletion of petroleum reserves. According to the international agency, world’s fossil fuels are limited and the depletion of the crude oils is becoming a major concern to the automotive sector. From the previous report by International Energy Agency in 2015, total primary energy has been increasing 221.98% since 1973 until 2013 [1]. Besides that, the extensive usage of crude oil has also increased air pollution as the by-product of exhaust emission [2]. Exhaust emissions from vehicles can cause dangerous effects on human's health [3]. Such problems on the inhalation of vehicles' exhaust are cardiovascular and respiratory [4-6].

Use of alcohols as additives for gasoline fuel has improved thermal efficiency and reduced CO and HC emissions [7]. The alcohol contains high oxygen content compared to pure gasoline; thus, it improves the combustion process in the cylinder [8, 9]. However, it has lower calorific value than gasoline, so it produces less brake power [10, 11]. This experiment was conducted to study the effects of methanol and ethanol blends on gasoline engine performance and exhaust emissions.

Properties of alcohol fuels

According to Simeon Iliev [12], the use of fuel alternatives that contain oxygen (oxygenates) is very important as additive fuel as it can increase the performance and efficiency of the fuel [13]. Several oxygenates fuel additives that have been used were methanol, ethanol, tertiary butyl alcohol and methyl tertiary butyl ether [13-16]. High rate of energy release, excessive temperature and pressure inside the combustion chamber will cause a drop in brake power [17]. Therefore, alcohol will give better fuel characteristics [18] for combustion behaviour and fuel economy. Below is the list on the advantages of using alcohol as a fuel [19] :

1. Alcohol has high oxygen content in which methanol has 49.9% and ethanol has 34.7% compared to gasoline that has none [20].
2. The higher latent heat of vaporization of alcohol will give a cooling effect in the intake and compression stroke [21]. Thus, it will result in less required work input in the compression stroke due to the raises of the volumetric efficiency [22].
3. The engine thermal efficiency will be increased as the propagation speed of laminar flame is higher resulting in reducing time of combustion process [23].

Silva R *et al.* [24], deduced that both ethanol and methanol had higher octane number compared to gasoline. The higher octane number of alcohol allows the fuel blends to have much higher compression ratios and increases the thermal efficiency [25]. However, a significant disadvantage of the alcohol is lower energy content compared to gasoline [26]. Thus, alcohol needs larger volume of fuel to produce the same power as pure gasoline [27]. Table 1 describes the fuel properties of ethanol and methanol compared with pure gasoline.

Table 1: Comparison of fuel properties [26, 28, 29]

Properties	Gasoline	Methanol	Ethanol
Molecular formula	C_5-C_{12}	CH_3OH	C_2H_5OH
Molecular weight	95-120	32	46
Oxygen content (%)	0	49.9	34.7
Density (kg/m^3)	740	792	785
Octane number	>90	111	108
Stoichiometric air/fuel ratio	14.7	6.47	9.0
Auto-ignition temperature (°C)	228-470	465	425
Latent heat of vaporization	305	1103	840
Lower Heating Value (MJ/kg)	43.45	20.10	27.00

Engine performance

Muharrem Eyidogan *et al.* [26] found that the blended fuel (E5, E10, M5 and M10) have higher BSFC compared to pure gasoline. E5, E10, M5 and M10 increased 2.8%, 3.6%, 0.6% and 3.3% of BSFC compared to those of pure gasoline. From Table 1, lower heating values (LHV) for methanol and ethanol are lower than that of gasoline. As a result, higher volume of fuel blends is needed to produce the same brake power as pure gasoline. Although methanol had lower value of LHV than ethanol, the BSFC for methanol was still lower than ethanol. This condition is caused by higher oxygen content of methanol which is 49.9% compared to that of ethanol which is 34.7%. Consequently, the higher oxygen content in the methanol produces a better combustion cycle and reduces the BSFC [30].

Research made by Shayan S.B [31] using four-cylinder, four stroke, multi-point injection system presented the results of performance tests (BSFC and BTE) and exhaust emissions (CO, CO_2, HC and NO_x). The experiment was conducted with different concentrations of methanol blends (M5, M7.5, M10, M12.5 and M15) under wide open throttle and variable speed ranging from 1500 - 5000 rpm. The results presented that BTE increased as the concentrations of methanol increased. The highest BTE was obtained using M15 at approximately 32.5%. At overall test conditions, brake thermal efficiency reached its maximum value at the engine speed of 2250 rpm [31]. There are several factors that contribute to the BTE. Such factors are:

1. The oxygen content in the fuel blends [32] in which the presence of oxygen molecules promotes better combustion process.
2. Lower heating value of the fuel [20] resulted in lower energy supplied to the engine. In addition, the increase of octane rating of the fuel was due to alcohol addition, causing the BTE to increase [33]. Therefore, a lower knock resistance caused gasoline to have lower BTE.

Exhaust emissions

B. M. Masum *et al.* [32] investigated the effects of using multiple alcohols (methanol, ethanol, propanol, butanol, pentanol and hexanol) at different percentage ratios with the results compared to those of conventional ethanol-gasoline blends. The engine used during the experiment was a four-cylinder, four strokes and multipoint injection system SI engine. Results obtained from the experiment depicted the variations of carbon monoxide emission in relation to engine speed. During high engine speed condition, alcohol-gasoline blends emit lower CO emission than that of pure gasoline. High engine speed has caused limited time to complete the combustion process, thus resulting higher CO emissions of pure gasoline fuel. With higher flame speed of alcohol, it promotes complete combustion and lowers the CO emission [34]. Formation of carbon monoxide indicates loss of power, result of oxygen deficiency in combustion chamber [35]. Emission of CO is unavoidable with available technology, since it is not possible to achieve a supply of required air with proper mixing in combustion chamber which can sufficiently burn all fuel or even with higher air, the emission of carbon monoxide increases the result of higher oxygen molecule [36]. This condition can be explained by the enrichment of oxygen owing to the ethanol and methanol, in which an increase in the proportion of oxygen will promote further oxidation of CO during the combustion cycle [37]. Another significant reason for this reduction is that ethanol (C_2H_5OH) and methanol (CH_3OH) have less carbon than gasoline (C_8H_{18}).

Ahmad O. Hasan *et al.* [38] studied on exhaust emissions (HC, CO and NO_x) reduction efficiency in gasoline bi-mode on SI/HCCI engine. Nitrogen and oxygen actively react at high temperature. Therefore, high temperatures and viability of oxygen are the main factors for the increase formation of NO_x [39]. When methanol percentage increases, the NO_x concentration also increases. When combustion process is closer to stoichiometric, flame temperature increases; therefore, the NO_x emission is increased [31]. According to H S Farkade *et al.* [36], NO_x formation occurred at low equivalence ratio and high adiabatic flame temperature. NO_x can be controlled by lowering down the flame temperature. As the oxygen percentage increases, it will provide complete combustion with higher temperature resulting in higher NO_x formation.

Proposed solutions

Hence, in this research, different percentages of methanol and ethanol-gasoline blends (5% and 15%) were mixed with gasoline fuel to investigate the influence of selected alcohol blends on engine performance (brake power, BSFC and BTE) and exhaust emissions (CO, HC and NO_x). The critical tasks were to solve the problem of fossil fuel depletion and reduce hazardous emissions caused by vehicle fuels with the idea of applying alcohol (methanol and ethanol) as alternative fuel. At the end of this research, the results obtained were compared with previous researches from M. Eyidogan, A. Pikunas and S. B Shayan as they have proven good similarities, except minor differences on the percentage of alcohol blends and operating conditions.

Methodology

Fuel preparations

In this study, ethanol and methanol were chosen as fuel blends. The blending percentage of fuel blends were described in Table 2. Blending processes were done using magnetic stirrer by continuously stirring the fuel blends at temperature of 22-24^{o}C to maintain the homogeneity [40]. It is suggested to prepare the fuel blends just before the engine testing as it is needed to prevent separation process due to higher rate of evaporation of alcohol fuel.

Table 2: Test matrices

Pattern	**Description**			**Notation**
	Methanol	**Ethanol**	**Gasoline**	
Test 1	5% volume percentage	-	95% volume percentage	M5
Test 2	15% volume percentage	-	85% volume percentage	M15
Test 3	-	5% volume percentage	95% volume percentage	E5
Test 4	-	15% volume percentage	85% volume percentage	E15

Engine specifications

A four stroke, four cylinder spark ignition engine was used during the experiment. Table 3 lists the details and specifications of the engine in this research.

Table 3: Engine specification

Engine Specifications	**Description**
Engine type	SI engine
Number of cylinder	4
Displacement volume	1596 cc
Bore	78mm
Stroke	84 mm

Compression ratio	10:1
Fuel system	Multi-point electric port fuel system
Max output	78kW at 6000 rpm
Max torque	135 N.m at 4000 rpm

Experimental setup

The engine was started and allowed to warm up for a period of 10 min until the oil temperature was in the range of 70-80 °C and the stability of engine operation was achieved. Fuel blend test started with methanol-gasoline blends, followed by ethanol-gasoline blends. Gasoline was used after each test engine to drain fuel blends in the fuel line. The engine was tested about 15 min for each blend test with the engine speed in range of 1000-4000 rpm at wide open throttle.

Figure 1 shows the schematic diagram of the experimental setup. The engine was coupled to an Eddy Current Dynamometer (Froude Hoffman model AG150) with a maximum power of 150kW to measure torque and engine power. KOBOLD ZOD (KOBOLD) positive-displacement type flow meter was used in order to obtain the fuel flow rate. Finally, gas analyser AVL DiCom 4000 (AVL DiTEST) was used to measure exhaust emissions of CO, HC and NO_x.

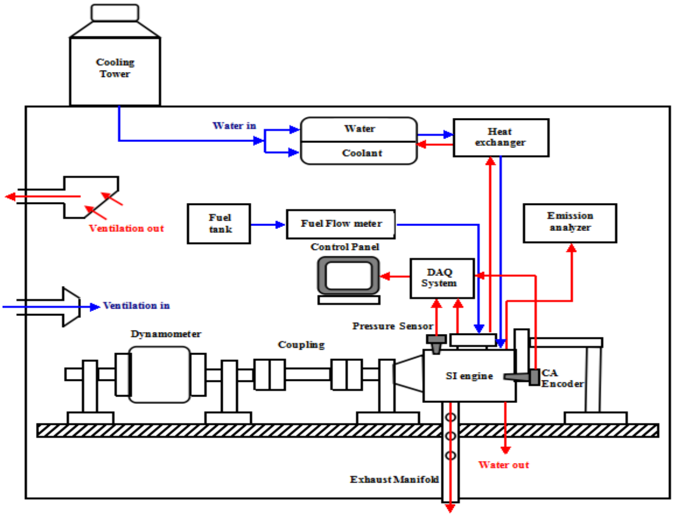

Figure 1: Schematic diagram of engine experimental setup

Calculation methods

Brake power used to indicate the power actually delivered by the engine. The brake power is defined as follows [39]:

$$Brake\ power = \frac{2\pi NT}{60000}\ [\text{kW}] \quad (1)$$

With, N = Engine speed (rpm)
T = Engine torque (N.m)

The BSFC is the fuel consumption characteristic of an engine. It is expressed as fuel consumption in kilograms of fuel per kilowatt-hour [41].

$$BSFC = \frac{\dot{m}}{Bp}\left[\frac{g}{kW.hr}\right] \quad (2)$$

With, $\dot{m}$ = Fuel mass flow rate ($\frac{g}{hr}$)
B_p = Brake power (kW)

The BTE is the ratio of energy in the brake power to the input fuel energy in appropriate units [9].

$$BTE = \frac{Bp}{CV \times 360}\ [\%] \quad (3)$$

With, B_p = Brake power (kW)
CV = Calorific value ($\frac{kJ}{kg}$)

Result and Discussion

The overall results were described in this sector with brief discussions on fuel properties which have the effects on engine performance and exhaust emissions. Such properties are:

1. Lower heating value (LHV) :
   Provide energy for the fuel during combustion process in which fuel with higher carbon content released higher energy, such as gasoline.
2. Latent heat of vaporization:
   Discharge higher air-fuel charge cooling and increase the density of the fuel.
3. Oxygen content:
   Fuel with higher oxygen content promotes more complete combustion such as alcohol. The presence of oxygen content also increases thermal efficiency and reduces exhaust emissions of CO and HC.
4. Research octane number (RON):
   A higher RON corresponds to higher anti-knocking index. It provides lower ignition tendency and reduces knocking tendency.

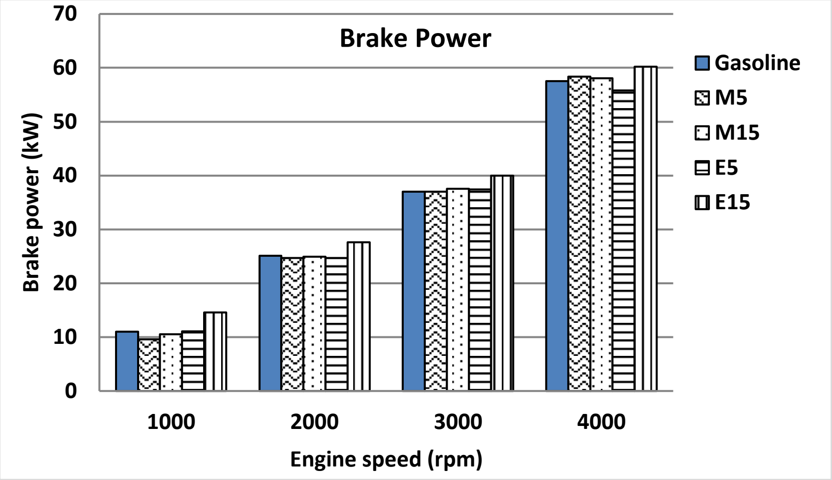

Figure 2: Variations of brake power with engine speed (rpm)

Figure 2 depicts the trend of brake power from a spark ignition engine operating at various engine speeds (1000 – 4000 rpm). From the above figure, the brake power shows an increasing pattern as the engine speed is increased. At the speed of 3000 rpm, E15 produces the highest brake power compared to those of other fuels which are 40kW, 37.4kW, 37.6kW, 37.0kW and 37.02kW for E15, E5, M15, M5 and pure gasoline, respectively.

The increase in brake power of the fuel blends is mainly due to the higher latent heat of vaporization of alcohol compared to gasoline. It is also providing air-fuel charge cooling to increase the density of the charge and increase the power output [31]. According to Alvydas Pikunas *et al.* [42], the addition of ethanol to the blended fuel provides more combustion in the engine as ethanol is known as partially oxidized. Therefore, the presence of the oxygen in the blends leads to leaning effect due to a more complete combustion of ethanol-gasoline blends. As a result, by using the alcohol, it will provide a better combustion; thus, increases the brake power.

Figure 3 compares the values of BSFC with engine speed ranging from 1000 to 4000 rpm. In overall test condition, M5, M15, E5 and E15 have increased 1.09%, 3.27%, 0.54% and 2.72% compared to those of pure gasoline. With the increasing concentrations of alcohol, the BSFC values are increased. This is mainly contributed to lower LHV of methanol and ethanol than that of pure gasoline which are 20.1 and 27.0 MJ/kg for methanol and ethanol, respectively. Alcohol fuel consumes higher BSFC to produce the same engine power as pure gasoline fuel. The high value of BSFC of methanol and methanol may be caused by higher alcohol density [29]. Figure 2 also shows that in overall engine speed conditions, BSFC for methanol-gasoline blends is higher compared to ethanol-gasoline blends. This result is typically ascribed to the lower heating value of the methanol [20], in which E5 shows the lowest BSFC compared to other alcohol blends.

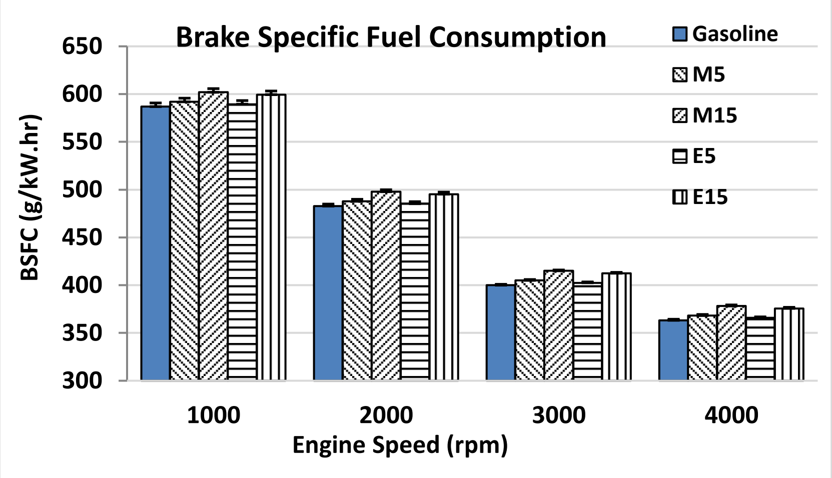

Figure 3: Variations of BSFC with engine speed (rpm)

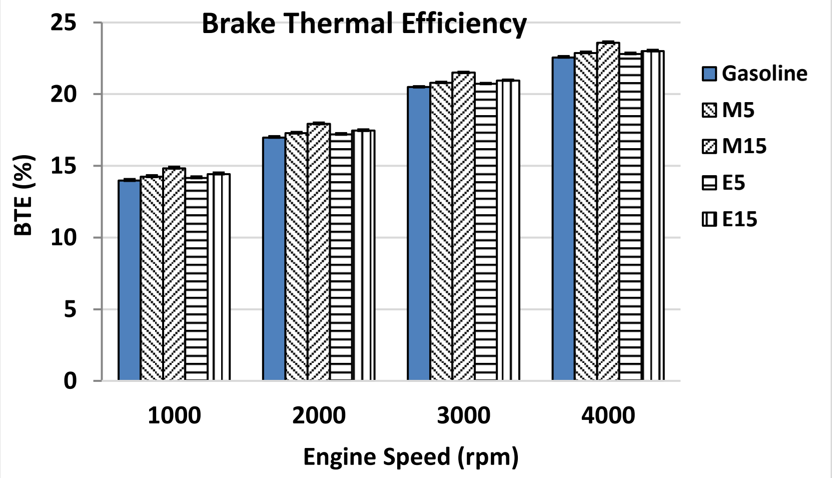

Figure 4: Variations of BTE with engine speed (rpm)

Figure 4 portrays the patterns of brake thermal efficiency for different fuel blends at varying engine speed (1000 rpm to 4000 rpm) under wide open throttle conditions. In overall test conditions, the brake thermal efficiency is increased as the engine speed increases. M15 has the highest value of BTE obtained at engine speed of 4000 rpm which is 23.59%. Brake thermal efficiency is increased with the increase of alcohol concentration. This is due to the better combustion as alcohol is partially oxygenated [26, 33].

In addition to this, Figure 4 presents that M15 has the highest BTE in all engine test conditions. It can be contributed by the value of lower heating value [19] and higher oxygen content of methanol [32] which can be referred in Table 1. Methanol also has higher latent heat of vaporization compared to gasoline and ethanol [43]. Hence, it will cause the effect of cooling to increase [6]. The increase of the latent heat of vaporization will increase the vaporization rate of the fuel in the compression stroke [44].

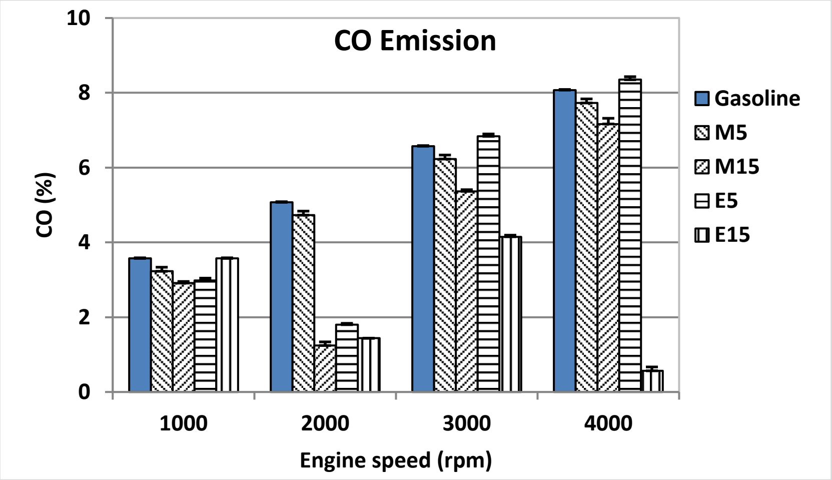

Figure 5: Variations of CO (%) with engine speed (rpm)

Figure 5 presents the CO emission varies with the engine speed ranging from 1000 - 4000 rpm at wide open throttle. The exhaust emission increased simultaneously as the engine speed is increased. However, the overall exhaust emission for the alcohol blends shows a decreasing pattern compared to that of gasoline. At the engine speed of 3000 rpm, E15 shows the lowest emission of 4.152% while E5 emitted a slightly higher emission of CO than gasoline, with 6.836% and 6.572% for E5 and gasoline, respectively.

Carbon monoxide is a product of incomplete combustion of fuel. As the concentration of alcohol is increased, the emission of CO will be decreased. Three major factors that contribute to the CO emission are; 1) presence of oxygen content of the fuel blends; 2) carbon content of alcohol; and 3) the effect of air-fuel ratio (AFR). The enrichment of oxygen is owed to ethanol and methanol, where it contains oxygen molecule and promotes further oxidation of CO during the engine exhaust [12]. The reduction of the CO emissions by methanol and ethanol-gasoline blends was also due to lower carbon in the ethanol (C_2H_5OH) and the methanol (CH_3OH) compared to gasoline (C_8H_{18}).

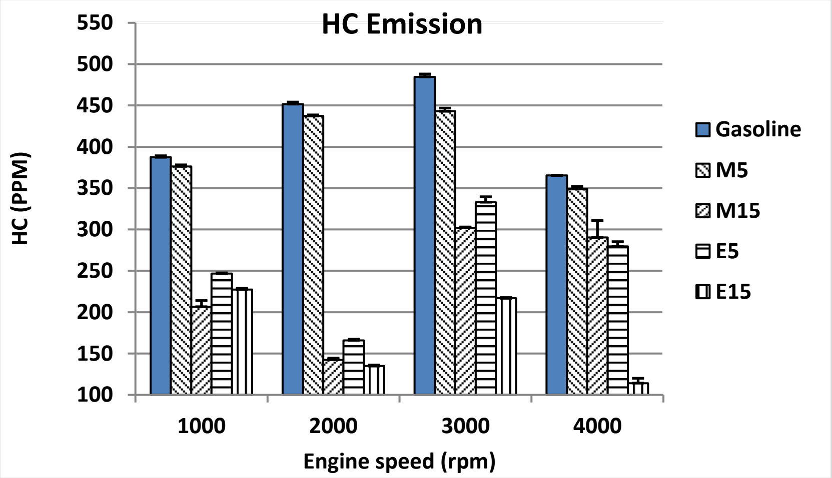

Figure 6: Variations of HC (%) with engine speed (rpm)

Figure 6 shows the pattern of the HC emission at various engine speeds (1000 – 4000 rpm) and at full throttle condition by using 4 cylinder spark ignition engine. HC emission increases from 1000 rpm until 3000 rpm and decreases at 4000 rpm. It also shows that at the engine speed of 3000 rpm, gasoline emitted the highest emission of HC compared to E15 which is 484.67 ppm and 216.8 ppm respectively.

The emission of HC is also due to incomplete combustion caused by the lack of air supply. According to B.M Masum *et al.* [32], reduce of HC emission is due to the rich of oxygen content in the alcohol blends; thus, it enhances combustion efficiency. At the same time, laminar flame speed of alcohol is higher than gasoline; thus, it increases the combustion efficiency [19]. Therefore, Figure 6 shows that E15 has the lowest HC emission compared to the other blends. The increase of alcohol will increase the AEC and decrease the equivalence air-fuel ratio that leads to leaner condition. Leaner condition will promote more effective combustion; thus, lowering the HC emission. The increase of the HC formation indicated the power loss resulting into less brake thermal efficiency [36].

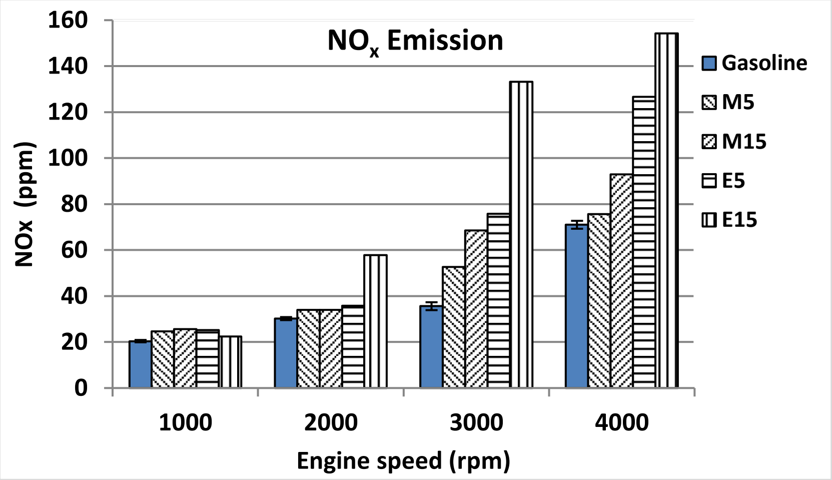

Figure 7: Variations of NO$_x$ (%) with engine speed (rpm)

Figure 7 indicates the pattern of NO$_x$ emission by varying the engine speed from 1000 rpm to 4000 rpm at full throttle condition. The graph shows an increase in NO$_x$ emission as the engine speed is increased. At the engine speed of 4000 rpm, the highest NO$_x$ emission is emitted by using E15 which recorded 154.2 ppm compared to gasoline which is 71 ppm.

The formation of NO$_x$ is contributed by many factors like the temperature inside the cylinder and viability of oxygen. The NO$_x$ formation is increased with the increase of the alcohol blends. This is due to the increase of the flame temperature. Because the addition of alcohol will lower the equivalence air-fuel ratio [36], it will give leaner effect. Thus, effective combustion is achieved and the flame temperature will be increased. Figure 7 also shows E15 resulted the highest of NO$_x$ compared to other blends. This is due to the lowest latent heat of vaporization of E15. The latent heat of vaporization of the blend decreases as the ethanol concentration in the blend is increasing. Therefore, lower latent heat of vaporization will reduce the cooling effect inside the cylinder, thus resulted to higher NO$_x$ emission.

Conclusion

This research investigates the effects of different alcohol (ethanol and methanol) fuel blends on the engine performance and exhaust emissions. The test was conducted by using 1.6L 4-strokes, 4-cylinders spark ignition (SI) engine. The engine test was conducted at variations of engine speed under wide open full throttle with different blend ratio of alcohol blends (E5, E15. M5 and M15) to obtain the engine brake power, brake specific fuel consumption (BSFC), brake thermal efficiency (BTE) and exhaust gas emissions (HC, CO and NOx). On the basis of obtained experimental results, the main findings can be concluded as follows:

1. Higher latent heat of vaporization of methanol and ethanol improves the engine brake power produced by the methanol and ethanol-gasoline blends as E15 provided approximately 4.6% and 8.0% higher than that of gasoline at engine speed of 3000 and 4000 rpm, approximately.
2. Alcohol-gasoline blends have a higher value of BSFC than gasoline fuel as it increases 1.39%, 3.39%, 0.57% and 2.82% for M5, M15, E5 and E15 respectively. These results are due to the lower LHV of methanol and ethanol which are 20.00MJ/kg and 26.9MJ/kg compared to gasoline fuel of 43.45MJ/kg.
3. Optimized blends for alcohol-gasoline blend which produced the highest value of BTE is M15 as it recorded 5.23% increment compared to pure gasoline fuel. This obtained finding is ascribed by higher oxygen content of methanol compared to ethanol and gasoline.
4. All alcohol gasoline blends emitted lower CO emission than that of pure gasoline. Emission of CO has been decreased by 5.92%, 28.33%, 14.25% and 58.23% for M5, M15, E5 and E15, respectively.
5. As well as CO emission, fuel blends of M5, M15, E5 and E15 has reduced 4.92%, 44.26%, 39.3% and 58.96% of HC emissions, respectively.
6. NOx emissions produced by the fuel blends were higher than that of gasoline fuel with E15 emitting the largest amount of NOx emissions at 2000, 3000 and 4000 rpm with 57.8, 133.2 and 154.2 ppm, respectively.

The overall results show that the engine operating with E15 improved the exhaust gases emission without scarifying engine performance. Therefore, it can be concluded that the additional of alcohol (ethanol and methanol) to gasoline can be considered as the alternative fuel formulation strategy to improve engine performance and control the exhaust gases emission. Alcohol has a higher potential as alternative fuel as it improves engine performance and reduces exhaust emissions. However, certain properties of alcohol need to be refined and improved by adding another source of biofuel for future development, such as the value of lower heating value (LHV).

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