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ORIGINAL ARTICLE

Performance of ethanol-gasoline blends of up to E35 as alternative Automotive fuels

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ABSTRACT

A study was conducted to investigate fuel properties, engine performance and exhaust emissions of ethanol-gasoline blends as alternative automotive fuels. Fuel properties of the selected blends such density, API gravity, kinematic viscosity, cloud point, flash and fire point, heat value, and Octane Number, were studied and compared to gasoline. The blends were E0 (pure gasoline), E10, E15, E20, E25, E30 and E35. The performance and exhaust emissions of a variable speed, four stroke, four cylinders, spark ignition engine equipped with a hydraulic dynamometer and exhaust emissions accessories were tested with these blends. Fuel properties results showed that blends densities varied between 0.7396 and 0.7653 kg L^{-1}, while gasoline density was 0.7400 kg L^{-1}. The API gravity of blends varied between 57.10 and 53.50 degrees, which was lower than that of gasoline (59.53 degrees). The kinematic viscosity for blends was 10.48 to 41.9% more viscous than gasoline (0.4872 $mm^2\ s^{-1}$). The flash point for the blends varied from 29.2 to 31.0 °C. The fire point for blends varied from 29 to 32 °C, which was lower than that of gasoline (25 °C). The gross heat content for blends was 4.1 to 11.3% lower than gasoline (47.08 MJ kg^{-1}). While, the Octane number was 4 to 11.6% higher than for gasoline fuel (93.2). Engine performance and exhaust emissions showed that the torque and power output produced with blends increased slightly when the ratio of ethanol in the blend was increased. The specific fuel consumption decreased slightly for all blends compared with gasoline; while, the thermal efficiency increased. The carbon monoxide (CO) concentration was decreased for all blends compared to gasoline. In contrast, nitrogen oxides (NOx) concentration was increased. Although, the tested blends showed diverse results due to differences in fuel properties, E20 showed the best results compared to the other tested blends.

Keywards: Ethanol-gasoline blends; automotive fuel; engine performance; exhaust emissions.

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INTRODUCTION

Bio-fuel initiative has been backed by government policies in the quest for energy security through partially replacing the limited fossil fuels and reducing the threat to the environment from exhaust emissions and global warming. The use of alcohols, which are considered as important forms of bio-fuels produced from biomass (e.g. alcohol, bio-diesel, bio-kerosene, H_2, etc.); blended with gasoline as a fuel for engines, was a subject matter for scientific research since 1980s [1, 2]. Among the different alcohols, ethanol and methanol are recognized as the most suited renewable bio-fuels for spark-ignition (SI) engines [3]. What distinguishes ethanol, as a fuel for SI engines, is the possibility of production from renewable energy sources such as sugar cane, cassava, corn, barley and other types of biomass materials [4, 5]. As reported by Al-Hasan, [6], ethanol is currently a prospective substance for use in automobiles substituting petroleum based fuels. The main reason for advocating ethanol is the possibility of producing it from natural products or waste materials; compared with gasoline, which is produced from non-renewable natural resources. In addition, ethanol shows good anti-knock features. However, the economic aspects still limit its use on a large scale. Hence, instead of pure ethanol, ethanol-gasoline blends are recognized as more attractive fuel types.

Many researchers reported on the ethanol-gasoline blends in terms of engine performance and emission characteristics. For example, Rice et al., [7] reported slight difference in power performance, specific fuel consumption, and thermal efficiency between engines fueled with a pure gasoline and a gasoline blend of 15% ethanol (E15). Another research study at Southern Illinois University showed that the engine power and specific fuel consumption slightly increased with bio-fuel blends [8]. As indicated by the sample data provided in Table 1 [2] bio-fuels were observed to produce less amounts of exhaust carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx) and smoke emissions, compared to the gasoline fuel.

Table 1. Estimated emission sources of air pollution in Sao Paulo – (Guarieiro and Guarieiro, 2013).

Vehicle Type		**Fuel**	**CO**	**HC**	**NOx**
Light vehicles (cars, etc.)		Gasoline	46.65	14.47	5.72
		Ethanol	8.60	4.13	1.37
		Blend (Gasoline/Ethanol)	13.27	6.81	2.46
Commercial vehicles		Gasoline	5.42	1.76	0.72
		Ethanol	0.78	0.38	0.13
		Blend (Gasoline/Ethanol)	0.60	0.30	0.11
		Diesel	0.29	0.34	2.84
Trucks	Light	Diesel	0.16	0.23	1.77
	Medium		0.81	1.15	8.74
	Heavy		2.92	3.36	32.00
Buses	Urban	Diesel	1.87	2.30	19.94
	Road		0.43	0.53	4.72
Motorcycles		Gasoline	15.56	12.92	1.15
		Blend (Gasoline/Ethanol)	0.04	0.04	0.01

The quantity of the replaced gasoline fuel is regulated by the percentage of ethanol in the blend. However, problems arise, due to the presence of water in the blend, because the commercially available ethanol is rarely found in an anhydrous state [9]. The commonly available ethanol grades contain between 10% and 20% water. Typical local distillation converts the fermented sugar molasses to 190-proof or industrial ethanol, containing 5% water; hence, special measures are required to remove the remaining water at additional costs [10]. Johansen and Schramm, [11] investigated the low-temperature miscibility of ethanol gasoline-water blends in blend fuel applications at -25 and -2°C. They reported that the blend can be successfully used without phase separations within the tested temperature range. The performance and pollutant emissions of a four stroke SI engine operating on ethanol-gasoline blends of 0, 5, 10, 15, and 20% ethanol was investigated by many researchers [12, 13, 5]. They reported a decrease in CO and HC emission when the ethanol was introduced into gasoline.

Currently, the use of E85, a mixture of 85% ethanol and 15% gasoline, for flexible fuel vehicles (FFV) or variable fuel vehicles (VFV), has become common; and there are various manufacturers (such as Ford, General Motors, Chrysler Corporation, etc.) offer vehicles (estimated at over 7 million FFVs on the roads by 2009) that are capable of operating on 100% gasoline, or E85, or any mixture of the two [14]. Ethanol-gasoline blends of various amounts are commonly used in different countries worldwide; e.g. Australia (officially 10%), Brazil (up to 25%), Canada (10%), Sweden (5%) and the USA (up to 10 %), Egebäck et al. [15]. However, in the USA, automotive manufacturers agreed that the use of gasoline with up to 10% ethanol will not affect the warranties of their vehicles [16].

There are several problems affecting the use of a combination of ethanol and gasoline, namely, (i) the ethanol has certain fuel characteristics of less quality compared with gasoline (i.e. moisture, lower heat of combustion and high flash point), (ii) the effect of different ratios of a mixture of ethanol and gasoline on performance and service life has not been identified so far, (iii) there is still lack of knowledge on fuel properties of various ethanol-gasoline blends, and (iv) many experiments and development processes in many countries all over the world have been conducted, but still little data is available, and (v) the ethanol is not supported by most engine manufacturers as alternative automotive fuel, even after the widespread production of ethanol [17].

Sugarcane production is mostly focused in Sudan and backed up by large investments in new sugarcane schemes. Currently, sugarcane production in the Sudan is more than 7.5 Million tons annually across the five major sugar cane schemes (Kenana, Assalaya, Sennar, New Halfa and Gunied). Hence, utilization of ethanol alcohol fermented from surplus sugar molasses in sugar industry, as bio-fuel in the Sudan, is very encouraging and promising. Considering the agricultural potentials of the Sudan, it will be very important and attractive to acquire the knowhow of using ethanol as a substitute to the non-renewable petroleum fuel. In 2009, Kenana Sugar Company (KSC), the Sudan's largest sugar producer; launched an ethanol plant producing 65 ML annually and expected to increase the production to reach about 200 ML per year. The arrangements to introduce ethanol in Sudan, as a bio-fuel for automotive engines, are still very limited. Consequently, the use of the ethanol as bio-fuel should be advocated strongly for research and development as well as a quick and subsidized market introduction. The purpose of this study was to investigate the possibility of utilizing ethanol–gasoline blends as automotive fuel in Sudan based on fuel properties, engine performance and exhaust emissions. The study was undertaken with following objectives:

(i) To determine the properties of ethanol-gasoline blends such as density, API gravity, viscosity, flash and fire point, cloud point, heat value, Octane Number and compare them with those of pure gasoline fuel.

(ii) To evaluate the performance of the engine operated on ethanol-gasoline blends compared with that on gasoline fuel. The tested engine performance characteristics were: torque, power output, fuel consumption, specific fuel consumption and brake thermal efficiency.

(iii) To determine exhaust emissions, such as carbon monoxide (CO) and nitrogen oxides (NO_x), for ethanol-gasoline blends compare to pure gasoline.

MATERIALS AND METHODS

Experiments were carried out to verify the possibility of using ethanol–gasoline blends as automotive fuel based on their properties, engine performance and exhaust emissions. The steps involved in conducting the experimental work include: (i) preparation of ethanol-gasoline blends, (ii) determination of fuel blends properties, and (iii) performance evaluation of an engine operated using fuel blends.

Preparation of ethanol-gasoline blends

Fuel blends were simply produced by pouring gasoline and ethanol constituents into a container and mix them. Up to 50% ratios in 5% increments by volume of the two constituents were prepared as fuel samples. These micro-emulsions were stable and homogeneous, as no distinct phase separation was observed when they centrifuged. Furthermore, blends selection was based on successful completion of the engine test. For simplicity common fuel abbreviation system was adopted. The selected blends are shown in Table 2.

Table 2. Description and abbreviations of the tested fuel blends.

No.	Fuel / Blend	Abbreviation
1	100%gasoline (reference fuel)	E0 (Gasoline)
2	90%gasoline +10% ethanol	E10
3	85%gasoline +15% ethanol	E15
4	80%gasoline +20% ethanol	E20
5	75%gasoline +25% ethanol	E25
6	70%gasoline + 30%ethanol	E30
7	65%gasoline +35%ethanol	E35

Table 3. Detailed descriptions of the utilized ethanol alcohol.

Property	Value
Boiling point	78.5 °C
Heat of combustion	23.625 MJ L^{-1}
Heat of vaporization	33.74 kJ $mole^{-1}$
Octane rating	106 - 108
Stoichiometric air/fuel ratio	9/1
Concentration	99.6 – 99.8%
Acidity	≤ 30 mg L^{-1}
Water content	≤ 0.3
Density	0.789 kg L^{-1} @ 20°C
Point of humidity	< 6.5

Determination of fuel blends properties:

The fuel blends evaluated in this study were various ethanol-gasoline blends. The ethanol (ethyl alcohol, C_2H_6O) was processed in Kenana Ethanol Alcohol Co. Ltd. Kenana's ethanol alcohol, which is extracted from sugar molasses, can be characterized as colorless and have a concentration of 99.7%. Detailed specifications of ethanol alcohol are presented in Table 3. Gasoline fuel, obtained from local fuel stations, was used as a reference fuel in this study.

Fuel properties experiments were carried out at the Laboratories of Central Petroleum (CPL), Ministry of Petroleum, and the Department of Petroleum and Gas Engineering of the Faculty of Engineering, University of Khartoum.

Fuel properties of the tested blends were determined in accordance with American Standard for Testing Materials (ASTM) procedures for petroleum products. Each fuel sample was evaluated to determine the density, API gravity, viscosity, flash and fire points, cloud point, and heat of combustion. The standard methods used for the determination of fuel properties of the tested blend are presented in Table 4.

Performance evaluation of an engine operated using fuel blends.

Engine tests were carried out at the College of Engineering of Sudan University of Science and Technology. The engine used in this study is a commercial four-cylinder four-stroke gasoline engine with 1587 cc multi-port injection. It has a cylinder bore of 80.5 mm, a stroke of 78 mm, a compression ratio of 8.5:1, and a maximum power output of 61 kW@ 5400 rpm. No modifications were made to the engine.

Table 4. Standard methods used for the determination of fuel properties.

Fuel Property	Procedure
Density	Hydrometer method (ASTM D287 Standard).
API gravity	Calculated from density results.
Kinematic Viscosity	Cannon-Fenske Opaque viscometer as per ASTM D445
Flash and Fire Points	Penskey-Marton apparatus (ASTM D93A)
Cloud and Pour Points	Petrotest (ASTM D97 Standard)
Heat of Combustion	Record Bomb Calorimeter according to PARR 1266 standards, France (ASTM D240)
Calorific Value	Calorimeter Method
Octane Rating	Cooperative Fuels Research (CFR) Engine (D2699), Figure 1

Figure 1. Cooperative Fuels Research (CFR) engine.

The experimental engine was coupled to a dynamometer instrument to determine the load and torque. Portable industrial combustion and emission Eurotron Eco line 6000 model analyzer was used for measuring CO and NOx. Exhaust emissions were determined from samples taken at three replications and at 30 seconds intervals. Figure 2 illustrates the schematic diagram of the experimental engine setup. The Experimental engine setup included four major systems: (i) engine system, (ii) power measurement system, (iii) engine speed system, and (iv) fuel consumption and emission system.

The performance tests of the engine operated on ethanol/gasoline fuel were conducted at various loading conditions. Settings of the engine running condition were performed through the rotational speeds. The engine was started at 2100 rpm with increment of 300 rpm each time up to 3300 rpm. For each rotational speed, the time was set at 1 minute for measuring load and torque and 30 seconds for measuring emission gas. The engine was then gradually loaded to determine the power developed at different loads and the corresponding fuel consumption was measured on weight basis using electric balance and stop watch. Stabilization period for loading was adjusted to get other sets of reading.

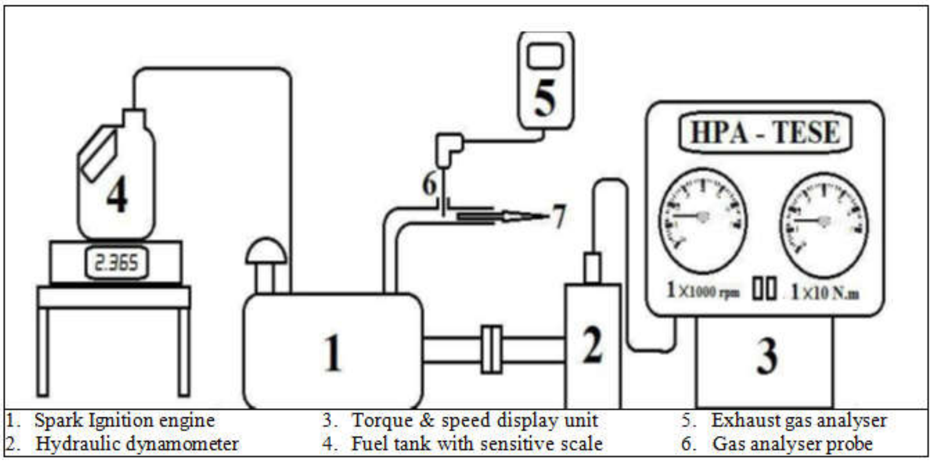

Figure 2. Schematic diagram of the test engine setup.

RESULTS AND DISCUSSION

3.1 FUEL PROPERTIES

The results of the tested fuel blends properties are summarized in Table 5. While their regression equations in terms of ethanol percentage are presented in Table 6. Discussion of the tested blends fuel properties, their variation and their significance are as follows:

(i) Density: The average values of density (kg L^{-1}) for the tested fuel blends at a temperature of 15 ^{o}C are presented in Table 5. From the results, it appears that the blend densities were found to vary from 0.7400 kg L^{-1} for gasoline to 0.7653 kg L^{-1} for E35. It was 0.0.05% lighter for E10 than gasoline; but 1.28 %, 1.91%, 2.31%, 2.88%, and 3.42%, heavier than gasoline fuel for E15, E20, E25, E30, and E35, respectively. The densities of blends were found to increase continuously and linearly by approximately 0.0008 kg L^{-1} for every increment of 1% ethanol (Table 6). The general density trend in this study is in agreement with previous studies [18-20] that the increase in ethanol content in the fuel blend was associated with an increase in the density of the mixture.

(ii) API Gravity: The average values of API gravity for blends at a temperature of 15 ^{o}C are presented in Table 4. From the result it appears that the blend API gravities were found to vary from 59.53 for gasoline to 55.21 for E35. It was 4.1%, 4%, 6.8%, and 7.3% for E10, E15, E20, E25, E30 and E35, respectively. The API gravities of blends were found to decrease continuously and linearly, approximately 0.1664 for every increment of 1% ethanol (Table 6). In general, API gravity decreases as the percentage of ethanol in the mixture increases [20, 17] but it still within the range that can be handled by an internal combustion engine.

Table 5. Fuel properties of the tested fuel blends.

Fuel blend	Density, kg L^{-1} @ 15.6 °C	API gravity, deg	Kinematic viscosity $mm^2 s^{-1}$ @ 30 °C	Flash point, °C	Fire point, °C	Cloud Point, °C	Heat of combustion, MJ L^{-1}	Octane number
Gasoline	0.7400	59.53	0.4872	_	25.0	-22	34.84	93.2
E10	0.7396	57.10	0.5383	_	29.0	> 8	33.19	97.1
E15	0.7495	57.09	0.5619	_	29.1	> 8	32.91	98.6
E20	0.7541	55.95	0.6007	29.2	30.0	> 8	32.43	100.4
E25	0.7571	55.21	0.6380	30.0	32.0	> 8	31.70	99.5
E30	0.7613	54.30	0.6614	29.2	30.2	> 8	31.53	102.5
E35	0.7653	53.50	0.6914	31.0	32.0	> 8	30.92	104.1

Table 6. Regression equations of the tested fuel blends properties in terms of ethanol %.

Attribute	Regression Equation	R^2
Density, kg L^{-1}	Y = 0.0008X+0.737	0.9333
API, Deg	Y = -0.1664X+59.306	0.9826
Viscosity, $mm^2 s^{-1}$	Y = 0.006X+0.4814	0.9944
Heat Value, MJ L^{-1}	Y = -0.1069X+34.564	0.9775
Octane Number	Y = 0.29X+93.75	0.9551

Y = measured property, X = ethanol percentage in the blend.

(iii) Kinematic Viscosity: The average values for kinematic viscosity of the tested blends, at 30 °C, are presented in Table 5. They were found to be 10.4%, 15.3%, 23.3% , 30.9%, 35.7% and 41% more viscous than the pure gasoline fuel (0.4872 $mm^2 s^{-1}$) for the E10, E15, E20, E25 , E30, and E35 blends, respectively. Blends kinematic viscosities were found to increase continuously and linearly by approximately 0.006 $mm^2 s^{-1}$ for every increment of 1% ethanol (Table 6). The results are in agreement with Dhaundiyal, [20]. In general the blends viscosities were within acceptable range for spark ignition engine.

(iv) Flash and Fire Points: The average values of flash and fire points for the tested fuel blends are presented in Table 5. From the results, it appears that the blends flash point for E20, E25, E30 and E35 were 29.2, 30.0, 29.2 and 31.0 °C, respectively. However, E10, E15 and gasoline started to fire before determining their flash point. While, the fire points were found to be 29.0, 29.1, 30.0, 32.0, 30.2 and 32.0 °C for E10, E15, E20, E25, E30 and E35, respectively, and the fire point of gasoline was 25 °C. Blends flash and fire points according to their values are above the standards values for handling and storage of gasoline fuels which has a flash point below the freezing point of water.

(v) Cloud Point: The average values of the cloud point for the tested fuel blends are presented in Table 5. From the results, it appears that the cloud point for gasoline is -22 °C and up to above 8 °C for all the other tested blends. The cloud point typically occurs between 5 °C and 8°C above the pour point.

(vi) Heat of Combustion: The average values of gross heat content for the tested fuel blends are presented in Table 5. The gross heat content of blends decreased by 4.7%, 5.5%, 6.9%, 9.1%, 9.5% and 11.3% for E10, E15, E20 and E25, respectively, compared to gasoline fuel (34 MJ L^{-1}). Blends heat values were found to decrease continuously and linearly, by approximately 0.1069 MJ L^{-1} for every increment of 1% ethanol (Table 6). The results are in agreement with previous studies [20, 17]. The decrease of heating values present in the blends was due to ethanol that has a low heat value (23.625 MJ L^{-1} Compared to gasoline.

(vii) Octane Number: The average values of Octane number for the tested blends are presented in Table 5. They were found to be 4.0%, 5.4%, 8.08%, 6.33%, 9.7% and 11.6% higher than that of the gasoline fuel (93.2) for blends E10 , E15 , E20 , E25, E30 and E35, respectively. Blends Octane ratings were found to increase continuously and linearly, approximately 0.29 for every increment of 1% ethanol (Table 6). Yamin et al., [21] investigated the effect of ethanol addition to low Octane Number gasoline, in terms of calorific value, Octane Number, compression ratio at knocking and engine performance. They blended locally produced gasoline (Octane Number 87) with six different percentages of ethanol, namely 10%, 15%, 20%, 25%, 30%, and 35% on volume basis. They found that the Octane Number of gasoline increased continuously with the ethanol percentages in gasoline. They reported that the ethanol was an effective compound for increasing the value of the Octane Number of gasoline. They also found that the engine performance improved as the percentage of ethanol increased in the blend within the range studied. As mentioned before, ethanol has a lower heating value than gasoline, which will reduce the energy content of the fuel. However this can be partly offset by the higher Octane Number of ethanol. Many additives have been developed to improve the performance of petroleum fuels to increase the knock resistance and raise the Octane number. Fuel refiners were able to use a wide variety of lower Octane hydrocarbons in gasoline. The increase in Octane number with the increase in ethanol content in the ethanol-gasoline mixture was also reported by many researchers [20, 17].

3.2 ENGINE PERFORMANCE

Engine performance test results on ethanol-gasoline blends were presented in Figures 3 to 6. The engine torque output increased slightly by 0.81%, 0.95%, 1.73%, 2.15%, 2.99% and 3.50% with increasing ethanol percentage for E5, E10, E15, E20, E25, E30 and E35, respectively, comparing with gasoline. Similarly, the engine power output increased slightly by 0.21%, 0.25%, 0.47%, 0.58%, 1.28% and 1.14% with increasing ethanol percentage for E5, E10, E15, E20, E25, E30 and E35, respectively, comparing with gasoline. The results show slight increase in torque and brake power when test engine has experienced different ethanol gasoline blends percentage compared to pure gasoline, because the added ethanol produces lean mixtures that increases the brake power to a higher value and makes the burning more efficient [13]. The brake power followed same attitude because it is the product of torque and engine speed.

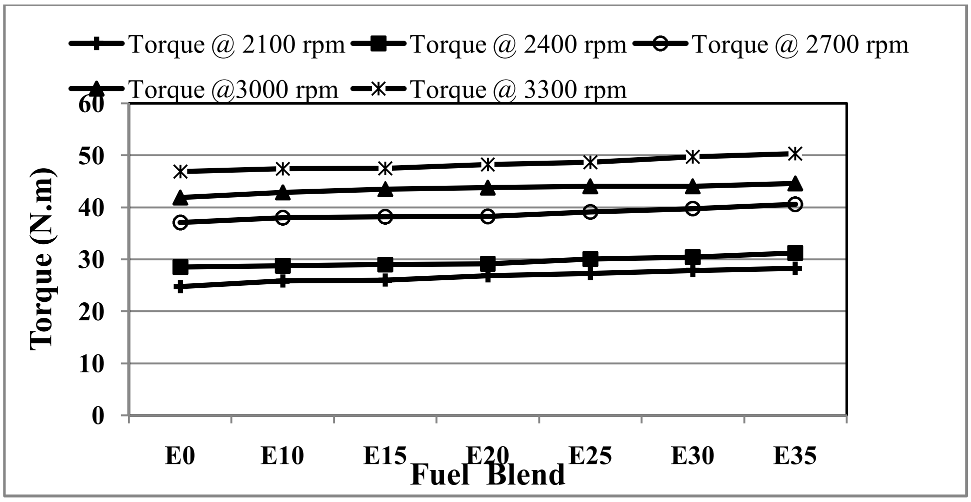

Figure 3. Torque versus ethanol-gasoline blends.

The specific fuel consumption decreased by 0.46%, 0.45%, 1.19%, 0.96%, 0.98%, and 1.01% with increased with increasing ethanol for E5, E10, E15, E20, E25, E30 and E35, respectively, comparing with gasoline. The best specific fuel consumption was achieved for E20 blend and all specific fuel consumption when using any ethanol and gasoline blends are registered lower values compared to those values when utilized pure gasoline in test engine. Also it's clear that, from Fig. 5 the fuel mass flow has the dominant effect on BSFC compared to brake power, that the BSFC decreases when engine speed increase. In other words the increasing percentage in fuel mass flow throughout engine speed range is higher than the increasing percentage of brake power. The brake thermal efficiency increased slightly by 1.13%, 0.10%, 4.39% 1.45%, 1.97%, and 1.77% with increasing ethanol for E5, E10, E15, E20, E25, E30 and E35, respectively, comparing with gasoline. The brake thermal efficiencies of all blends were greater than pure gasoline although the heat value of gasoline is greater than ethanol blends. In general for blends, thermal efficiency increased when ethanol percentage increased. The maximum engine brake thermal efficiency occurred for E20 blend while for minimum occurred for E10 blend.

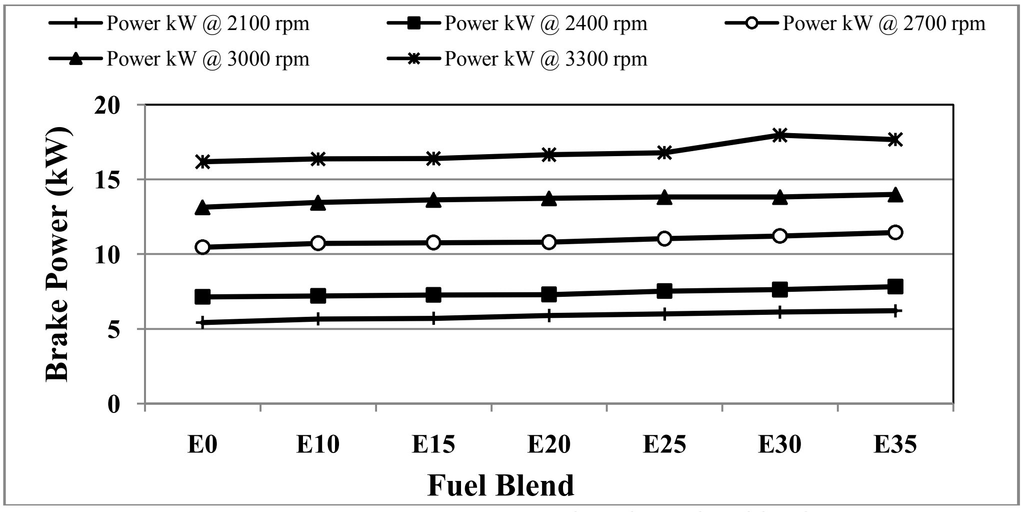

Figure 4. Power output versus ethanol-gasoline blends.

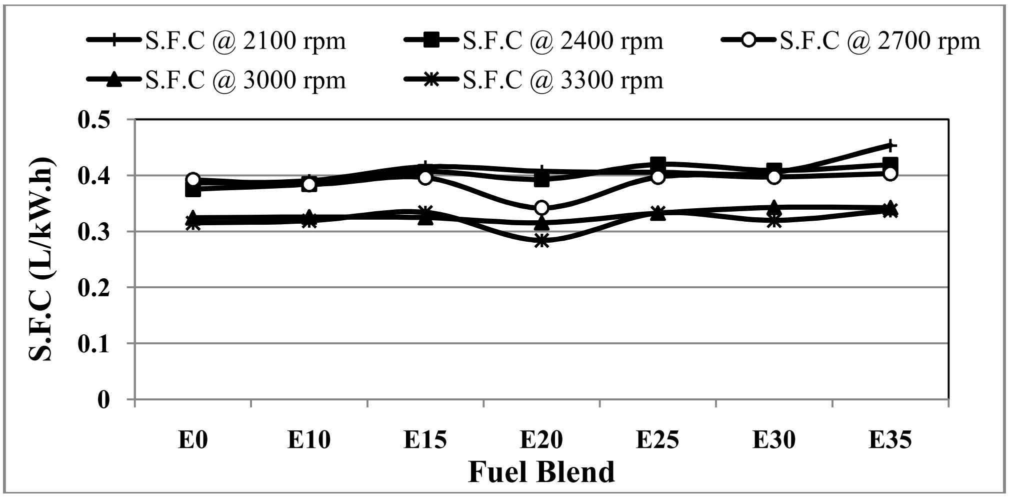

Figure 5. Specific Fuel Consumption (S.F.C.) versus ethanol-gasoline blends.

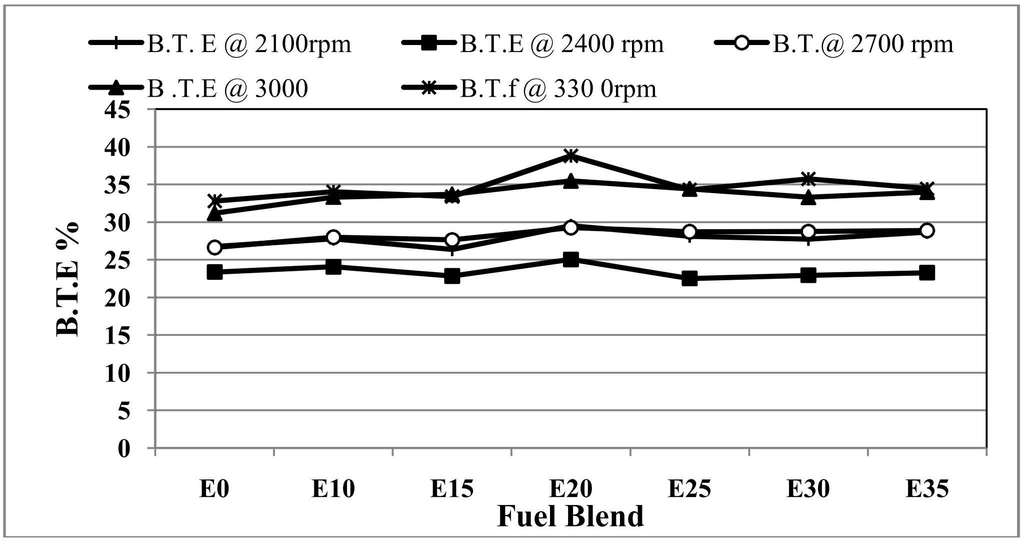

Figure 6. Brake Thermal Efficiency (B.T.E.) versus ethanol-gasoline blend.

3.3 EXHAUST EMISSIONS

Figures 7 and 8 represent the exhaust emissions concentration versus loads for various blends. The Carbon Monoxide (CO) concentration was apparently decreased for E10, E15 and E20, and increased dramatically for E25, E30 and E35 with the increasing ethanol content in the fuel blend. In general, the hydrocarbon in exhaust is mainly caused by the misfiring or incomplete combustion, which occurs in highly rich or lean situation. Carbon monoxide is a toxic product of incomplete combustion of carbon-containing fuels; hence, a decrease in CO exhaust concentration is significant because it indicates a more complete burn of the fuel which results in a decrease in emission of this toxic compound. As the engine is running in rich oxygen percentage because of the presence of ethanol, CO emission was decreased in the exhaust because there is sufficient oxygen to convert all carbon atoms of fuel into CO_2. CO_2 concentration is dominant by relative air-fuel ratio and CO emission. That is, the concentration of CO_2 emission is offset by CO emission. CO and CO_2 have a complementary correlation; which mean, when CO emission decreases, the amount of CO_2 increases [22]. The Nitrogen Oxides (NO_X) concentration was increased dramatically for E10, E15 and E20 and decreased for E25, E30 and E35 with increasing ethanol content in the fuel blends. Nitrogen Oxides is a general term for oxides of nitrogen, or any mixture of nitric oxide, nitrogen dioxide, nitrous oxide, etc. The most common of this group is nitric oxide. Some of the NO_X compounds are toxic and can readily combine with oxygen or water to form other compounds which are harmful to the environment. Nitrous oxide formation mainly depends on temperature, and a reduction in temperature can cause a reduction in NOx. With ethanol addition to gasoline, the maximum temperatures of combustion may be reduced and the reasons can be attributed to a low burning rate or flame temperature of ethanol causing a delay in ignition, and consequently causing a rise in the temperature of exhaust. Furthermore, with more ethanol concentrations, the peak temperatures of combustion may come down due to bulk quenching of the combustion products resulting in lower fuel-air ratios and an increase in NOx emissions. Finally, by taking the initiative in compromising between lower specific fuel consumption and lower CO emissions on one hand, and higher torque and power outputs, break thermal efficiency, and the global commitment to mitigate the NO_X emissions on the other hand; it is reasonable to clarify that, the best alternative fuel for spark ignition engine that has been investigated by this study work is E20 fuel blend among the tested blends.

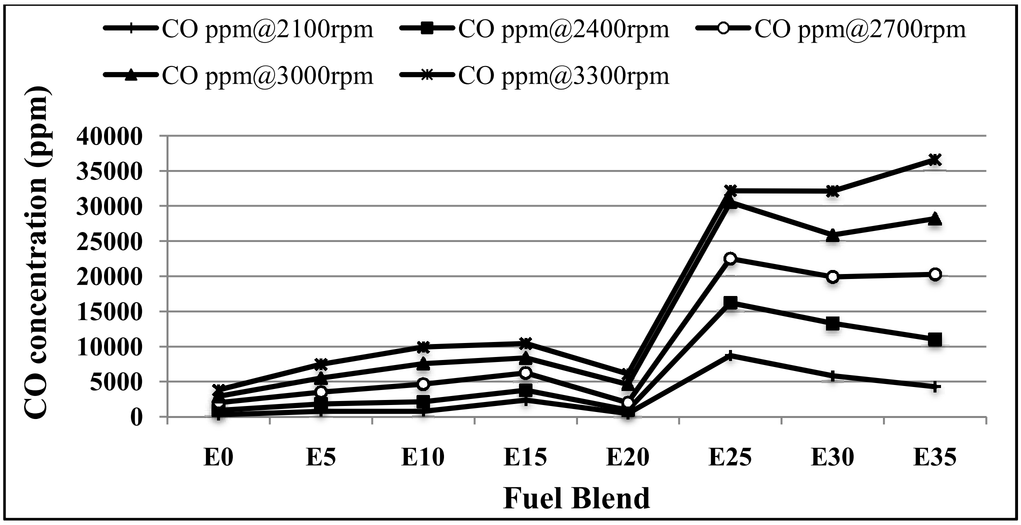

Figure 7. CO concentration versus ethanol-gasoline blends.

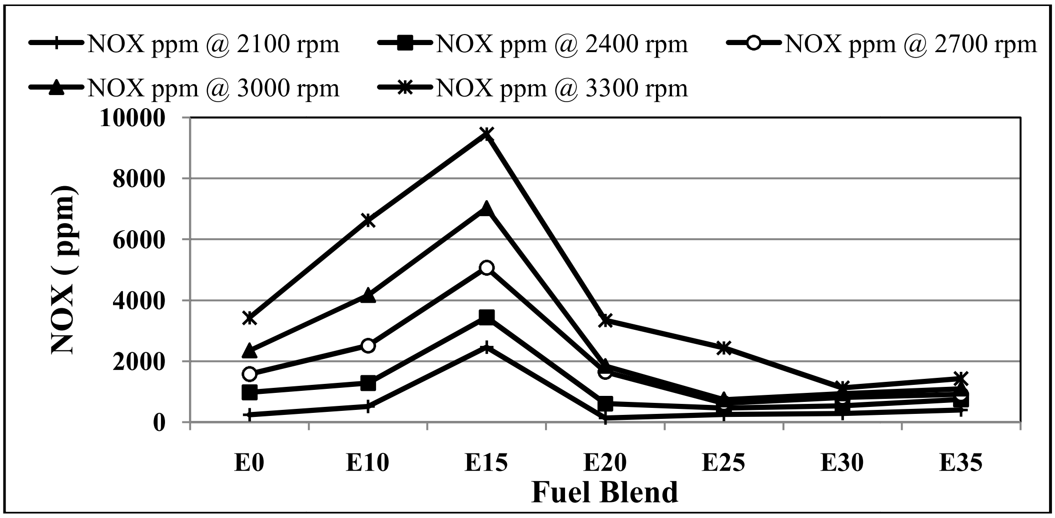

Figure 8. NOx concentration versus ethanol-gasoline blends.

CONCLUSIONS

The following conclusions could be drawn from this study:

- Ethanol-gasoline fuel blends of up to 35% ethanol content have been tested and evaluated successfully as alternative fuel for spark ignition engine without engine modifications.
- Density and viscosity of the tested blends increased with the increase in the percentage of ethanol, while API gravity and heat value decreased with the increased ethanol content. Furthermore, cloud point, flash and fire points were found to be higher for blends than for pure gasoline fuel.
- Octane rating of the tested blends based on Research Octane Number (RON) was increased with the increase in ethanol content compared to pure gasoline fuel.
- The tested blends exhibited slightly higher power, torque, and fuel consumption with the increase in the percentage of ethanol compared to pure gasoline fuel.

- The tested blends developed slightly lower specific fuel consumption and higher brake thermal efficiency with the increase in ethanol content compared to pure gasoline.
- The tested blends showed low carbon monoxide concentration; in contrast, they recorded higher nitrogen oxides.
- Among the tested blends, E20 showed the best results. Hence, assessment of the performance of SI engines operating on ethanol-gasoline blends for long time is highly recommended.

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