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Hydrous Ethanol-gasoline Blends as Alternative Fuels for Spark Ignition Engine: Fuel Properties and Engine Performance

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ARTICLE INFO

Article history:
Received 19 January 2022
Received in revised form 19 May 2022
Accepted 14 June 2022

Keywords:
Engine performance
Engine torque
Fuel properties
Hydrous ethanol-gasoline blends
Spark ignition (SI) engine

ABSTRACT

The fuel characteristics of hydrous ethanol (HE) and gasoline blends (HE10, HE15 and HE20) were investigated as an alternative fuel for spark-ignition (SI) engines and test their performance. The densities of the blends (754.4-769.1 kg m-3) were higher than that of gasoline (739.7 kg m-3); however, their API gravity (55.88-52.3) was lower than that of gasoline (59.53). The kinematic viscosity of the blends (0.588 to 0.670 mm2 s-1) indicated that the blends were more viscous than gasoline (0.4872 mm2 s-1). Flashpoint values of the blends varied from 28.4 to 29.2°C, which were higher than that of gasoline flashpoint value (25.0°C); however, the calorific value of the blends (ranging between 45.21 and 45.08 MJ kg-1) was lower compared to that of gasoline (45.27 MJ kg-1). The Octane number of the blends varied from 92.9 to 95.8, which was higher compared to that of gasoline (90.5). At low engine speed (1500 rpm) and high load (2.5 kg), the engine torque obtained with gasoline was 10.7% higher than that obtained with the blends. However, at high engine speed (2500 rpm) and high load (3.2 kg), the torque with gasoline was only 2.7% higher than with the blends. Overall, HE15 blend showed the best results among the examined blends.

1. INTRODUCTION

The consumption of fossil oil products is rapidly increasing as the global economy develops. The excessive use of fossil fuels has resulted in a number of severe problems to human society's continued development and progress, including global warming, depletion of fossil fuel resources, and environmental fragility. As a result, present research efforts are focusing on renewable energy sources to ensure the global economy and society's long-term viability [1]. In this context, biofuels, such as biodiesel and ethanol, are promising alternatives to fossil fuels.

Ethanol has recently gained popularity as a fuel additive or alternative fuel in both spark-ignition (SI) and compression-ignition engines [2]. However, because of its relatively high-octane number and the fact that it is a clean-burning fuel, ethanol has proven popular in SI engines. The large-scale commercial use of ethanol as a fuel began in the early 2000s. Currently, it is used in SI engines in three forms, namely, as pure ethanol, as a mixture of ethanol and gasoline, and the use of dual fuel injection systems for gasoline and ethanol.

There are two kinds of ethanol consumed for gasoline fuel, namely, hydrous ethanol (HE) and anhydrous ethanol. The hydrous (or wet) ethanol represents the most concentrated grade of ethanol from simple distillation, without the additional dehydration step required to produce anhydrous (or dry) ethanol. Due to the enormous amount of energy required during the distillation and drying processes, anhydrous ethanol (water content less than 1%) is expensive to be produced [3]. As a result, using aqueous ethanol as a fuel will directly enhance the overall energy efficiency, by making it more appealing as a fuel source [4], whereas water distillation and drying account for around 37% of the total cost of producing anhydrous ethanol. In this regard, a research carried out in an ethanol plant based in Minnesota suggested that 10-45% of energy can be saved by just removing the dehydration process from hydrous ethanol Eh95 (95% Ethanol, 5% water) [5]. In 2008 a study done by HE Blends in the Netherlands noted that Eh10-Eh26 ethanol blends are 10-20% less expensive than anhydrous ethanol [6].

Ethanol, as an octane booster and powerful oxygen compound, has been used as a fuel for more than 30 years. The use of ethanol as a fuel reduces greenhouse gas emissions, reduces carbon monoxide, reduces nitrogen oxides and unburned hydrocarbon emissions, increases combustion efficiency, reduces fuel costs, and creates jobs in rural areas. On the other hand, the

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utilization of ethanol and ethanol-gasoline blended fuel helps alleviate rising oil prices by reducing reliance on imported oil.

In some countries, ethanol is produced from sugar-cane molasses, and it is very encouraging and promising renewable energy source as biofuel. Given the enormous agricultural potential in many countries, it will be very important and attractive to gain technical knowledge of using ethanol as an alternative to non-renewable petroleum fuels. In 2009, Kenana Sugar Company, as an example of a large producer of ethanol in Africa and the Arab world, has launched an ethanol plant producing 65 million liters per year, and is expected to increase to about 200 million liters per year. However, arrangements for the introduction of ethanol in some countries, as a biofuel for car engines, are still very limited. Hence, substantial actions should be taken to encourage the use of ethanol as biofuel through research and development as well as an immediate and subsidized introduction to the market.

Through the literature, there was no independent review article that addressed the stability, combustion, engine performance and emissions of hydrous ethanol-gasoline blends on SI engines. Therefore, relying on fuel properties and engine performance, the main target of this study was to explore the usage efficiency of hydrous ethanol-gasoline blends as fuel for SI engines by following the below objectives.

- To determine and track the miscibility of hydrous ethanol in gasoline, as well as the watery separation phase of hydrous ethanol-gasoline blends.
- To estimate the characteristics of hydrous ethanol-gasoline blends such as density, API gravity, kinematic viscosity, cloud point, flash point, heat value and octane number.
- To assess the key factors of engine performance such as torque, brake power, brake specific fuel consumption, brake mean effective pressure and brake thermal efficiency, when using hydrous ethanol-gasoline blends as substitutional fuel compared to pure gasoline.

2. MATERIALS AND METHODS

Experiments were performed to validate the usage efficiency of hydrous ethanol-gasoline blends as fuels for spark ignition (SI) engines based on some properties and the results of engine performance. Hydrous ethanol (HE) used in this experiment was colorless alcohol, having a concentration of 93% and extracted from sugar molasses. The tested blends were prepared by adding HE up to 20% to pure gasoline to operate a small engine. The engine used was a four-stroke gasoline engine (2.6 kw) and it’s a part of a test rig designed by S.P (SPEAIPL) Engineers Company, India. The steps involved in conducting the experimental work include:

(i) Preparation of hydrous ethanol-gasoline blends,
(ii) Determination of the properties of the fuel blends, and
(iii) Evaluation of the performance of an engine running with the fuel blends.

2.1 Preparation of Hydrous Ethanol-Gasoline Blends

Preparation of fuel blends was simply achieved by pouring gasoline and HE constituents into a container and mixing them thoroughly. The samples were collected in a 40 ml graduated tube and kept in the refrigerator to monitor the watery phase separation at low temperature (10°C). The experimental work was performed for different fuel blends, as shown in Table 1. The characteristics of both gasoline and hydrous ethanol as illustrated by El-Faroug *et al.* [7] are also shown in Table 2.

Table 1. Descriptions and abbreviations of the tested fuel blends.

No.	Fuel / Blend	Abbreviation
1	100% Hydrous Ethanol	HE
2	100% gasoline (reference fuel)	HE0
3	90% gasoline +10% hydrous ethanol	HE10
4	85% gasoline +15% hydrous ethanol	HE15
5	80% gasoline +20% hydrous ethanol	HE20

Table 2. Characteristics of gasoline and hydrous ethanol.

Property	Unit	Gasoline	Hydrous Ethanol
Water content	w/w%	0	6.8 [8]
Boiling point	℃	25–225	77 – 78.3
Vapor pressure	kPa at 38 ℃	48–103	15.4
Latent heat of vaporization	kJ/kg	380–500	948
Lower heating value	MJ/kg	42.9–43.4	24.76 – 25.235
Flammability limit	vol %	1.4–7.6	3.3 – 19.0
Research octane number	-	88–100	111.1
Motor octane number	-	80–90	91.8 – 103.3
Solubility in water in 20°C	mL/100 mL of H_2O	<0.1	fully miscible

2.2 Properties of Reference Fuels and Fuel Blends

Fuel properties experiments were performed in the laboratory; The American Standard for Testing Materials (ASTM) protocols for petroleum products were used to assess the tested blends. The density, API gravity, kinematic viscosity, calorific value gross, flash points, and cloud point of each fuel sample were all determined.

2.3 Engine Performance Tests

The engine test rig used in this study comprised a single-cylinder, four strokes engine of 2.6 kW and up to 3600 rpm. Figure 1 shows the test rig, which was used to conduct the experiments with various concentrations of HE (10, 15, and 20% vol.) in gasoline.

Fig 1. Setup of the test rig: (A) engine coupled with a motor, (B) load and speed measuring board, and (C) loading heaters and voltage and current measuring board.

The experimental platform was utilized to measure the selected engine performance parameters for various fuel blends. The measured engine parameters include the torque, brake power, brake specific fuel consumption, engine brake thermal efficiency and the brake mean effective pressure. The selected engine performance parameters were calculated as follows:

(i) Brake power (P_b) is obtained by multiplying the engine brake torque (T) and rotational speed (ω).

$$P_b = T/\omega \tag{1}$$

(ii) Brake specific fuel consumption (BSFC) is the value of fuel consumed ($\dot{m}_f$) per unit of power produced (P_b).

$$BSFC = \dot{m}_f / P_b \tag{2}$$

(iii) Brake mean effective pressure (BMEP) is the measure of the torque produced per cycle as a function of the engine size.

$$BMEP = T/V_d \tag{3}$$

Where, V_d is the piston displacement volume per cycle.

(iv) The engine brake thermal efficiency (η_t) is the measure of the fuel conversion efficiency, given by the relationship between the energy available at the engine output and the fuel energy content

$$\eta_t = P_b / (\dot{m}_f * C.V) \tag{4}$$

Where, C.V is the fuel calorific value.

3. RESULTS AND DISCUSSION

3.1 Fuel Properties

Table 3 displays the results of the properties of the tested fuel blends. However, the following is a discussion of the obtained results, their variation and significance.

(i) Density: The measured values of density (g cm-3) for the tested fuel blends at a temperature of 15°C are presented in Table 3. It appears that the blend densities were found to vary between the highest value of 0.814 g cm-3 recorded for the hydrous ethanol (HE) and the lowest value of 0.740 g cm-3 for the gasoline and 0.7691 g cm-3 for HE20. It was also revealed that as the HE proportions in the fuel blend grew, the density of the blend increased; where the recorded density increased from 0.754 g cm-3 to 0.758 g cm-3 and to 0.769 g cm-3 for the fuel blends HE10, HE15, and HE20, respectively.

(ii) API Gravity: It appears that the API gravity of the blends varies from the lowest value of 42.27 for the HE

and to the highest value of 59.53 for gasoline (Table 3). The value of the API gravity was found to decrease as the percentage of HE in the mix increased. However, it was still within the range that an internal combustion engine could be managed (80 Degree).

(iii) Kinematic Viscosity: The kinematic viscosity of the tested blends was measured at 40°C, and the values are presented in Table 3. It was observed that the hydrous ethanol was more viscous (1.445 cSt) than gasoline (0.487cSt). Hence, more proportion of the HE resulted in a more viscous fuel blend. In general, the viscosities of the tested blends were within an acceptable range for spark-ignition engines (at 37.78°C, the kinematic viscosity is 0.71 cSt).

(iv) Flash Point: Table 3 presents the measured values of the flash point for the assessed fuel. From the findings, the flash point for HE10, HE15, and HE20 was found to be 28.4, 30.0, and 29.2°C, respectively. According to these values, the flash points of the tested fuel blends were above the standard values (80°F ≈ 26.67°C) for handling and storage of gasoline, which has a flash point below the freezing point of water.

(v) Cloud Point: Table 3 illustrates the cloud observations for the gasoline blends that were examined. The cloud point for the tested gasoline mixtures was found to be 13, 13, and 5°C for the HE10, HE15, and HE20 blends, respectively.

(vi) Calorific Value: The gross heat content of the tested fuel blends decreased by 0.13%, 0.20%, and 0.42% for HE10, HE15, and HE20, respectively (Table 3), compared to gasoline (45.27 MJ kg-1). The low heat value of hydrous ethanol contributed to the decrease in the heat values of the tested blends. These findings are consistent with those of a previous study [4].

(vii) Octane Number: The octane numbers for the fuel blends tested were greater than those for gasoline fuel (90.5) by 2.43% (HE10), 3.87% (HE15), and 5.3% (HE20), as presented in Table 3.

Table 3. Properties of the tested Fuels (HE ≡ Hydrous Ethanol).

Fuel	Density g cm^{-3} @ 15°C	API Gravity	Kinematic Viscosity, cSt @ 40°C	Flash point °C	Cloud Point °C	Calorific value MJ kg^{-1}	Octane Number (MON)
Gasoline	0.740	59.53 [9]	0.487	25.0	-	45.27	90.5
HE	0.814	42.27	1.445	-	-	44.69	91.8-103.3 [10]
HE10	0.754	55.88	0.588	28.4	13	45.21	92.7
HE15	0.758	54.93	0.636	30.0	13	45.18	94.0
HE20	0.769	52.30	0.670	29.2	5	45.08	95.3

Table 4. Summary results of the engine performance parameters.

	Fuel	1500 rpm			2500 rpm			
		Load 1	Load 2	Load 3	Load 1	Load 2	Load 3	Mean
Torque, Nm	Gasoline	4.905	5.886	6.867	5.886	7.603	9.074	6.704
	HE10	3.679	4.415	5.641	4.905	6.377	7.848	5.478
	HE15	3.679	4.905	6.131	5.15	6.867	8.829	5.927
	HE20	3.434	4.415	5.396	4.905	6.377	8.093	5.437
Brake Power, kW	Gasoline	0.77	0.925	1.079	1.541	1.990	2.376	1.447
	HE10	0.578	0.693	0.886	1.284	1.669	2.055	1.194
	HE15	0.578	0.771	0.963	1.348	1.798	2.344	1.300
	HE20	0.539	0.693	0.848	1.284	1.669	2.119	1.192
BSFC, kg/kWh	Gasoline	0.766	0.646	0.566	0.453	0.382	0.392	0.534
	HE10	1.061	0.764	0.678	0.536	0.497	0.425	0.660
	HE15	0.872	0.717	0.634	0.473	0.442	0.376	0.586
	HE20	0.949	0.750	0.647	0.498	0.443	0.415	0.617
BMEP, bar	Gasoline	4.17	5.004	5.838	5.004	6.464	7.715	5.699
	HE10	3.128	3.753	4.796	4.17	5.421	6.672	4.657
	HE15	3.128	4.17	5.213	4.379	5.838	7.506	5.039
	HE20	2.919	3.753	4.587	4.170	5.421	6.881	4.622
Brake Th. Eff., %	Gasoline	10.38	12.32	14.06	17.56	20.81	20.29	15.903
	HE10	7.51	10.42	11.75	14.87	16.03	18.73	13.218
	HE15	9.14	11.11	12.57	16.86	18.02	21.18	14.813
	HE20	8.42	10.64	12.34	16.04	18.04	19.24	14.120

3.2 Engine Performance

Table 4 presents the engine performance parameters findings gained for the tested fuels. The tests were performed at two engine speeds (1500 and 2500 rpm) and three different loads (electrical resistances, of 0.5 kg load increments). The three different loads were 1.5 kg, 2 kg and 2.5 kg for 1500 rpm and 2.2 kg, 2.7 kg and 3.2 kg for 2500 rpm. The investigated engine performance parameters include the engine torque, brake power (Pb), brake-specific fuel consumption (BSFC), brake mean effective pressure (BMEP), and brake thermal efficiency.

3.2.1 Engine torque

Engine torque results under different fuel blends are shown in Figure 2. For all the evaluated fuel blends, an increase in engine speed is accompanied by an increase in engine torque. The results also revealed that pure gasoline had the highest engine torque under all the examined engine loads and speeds. This is attributed to the higher heat value of gasoline; compared to other tested fuel blends, which is responsible for the higher engine torque; and this is in agreement with El-Faroug *et al.* [7]. However, the HE15 fuel (15% hydrous ethanol and 85% gasoline) showed the highest engine torque compared to other fuel blends (HE10 and HE20). Where, the mean value of the recorded engine torque for the HE15 was 5.927 N.m, which is about 11.59% less than for pure gasoline (6.704 N.m).

3.2.2 Engine brake power

Figure 3 shows that the brake power produced by blends is proportional to the change in torque for the same factors, that lead to increased, or decreased torque, at low speed and high load for all fuels used in the experiment with increased power; when using gasoline fuel (1.078634 kW). It was higher than blends (17.86%, 10.71%, and 21.43%) for (HE10, HE15, and HE20), respectively.

With higher speed and load the use of hydrous ethanol-gasoline blends produced higher power led to decrease the ratio of increase in gasoline (1.078634 kW) up to (13.51%, 2.7%, and 10.81%) higher power than (HE10, HE15, and HE20), and that less than all results at the lower speed (1500 rpm) and low load, and a peak brake power of engine test 2.6 kW at 3600 rpm. As explained before, the higher flame velocity of HE is probably the main responsible for the differences observed at high engine speed. which is agreement with the findings by Liu *et al.* [11].

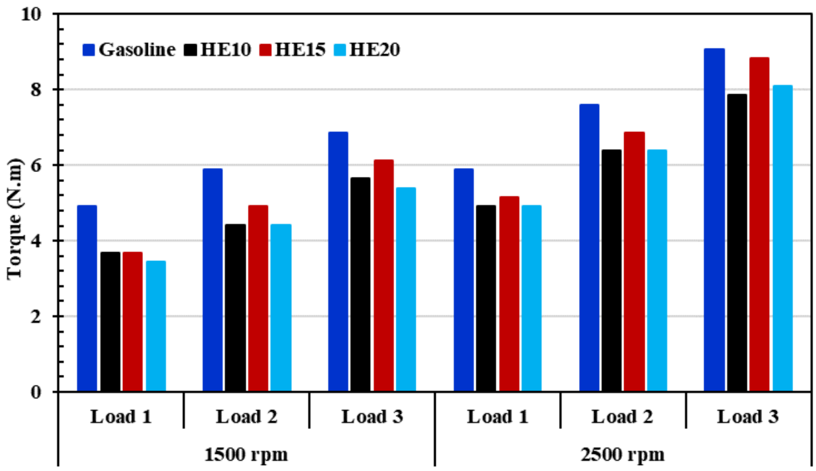

Fig 2. Engine torque for the tested fuel blends.

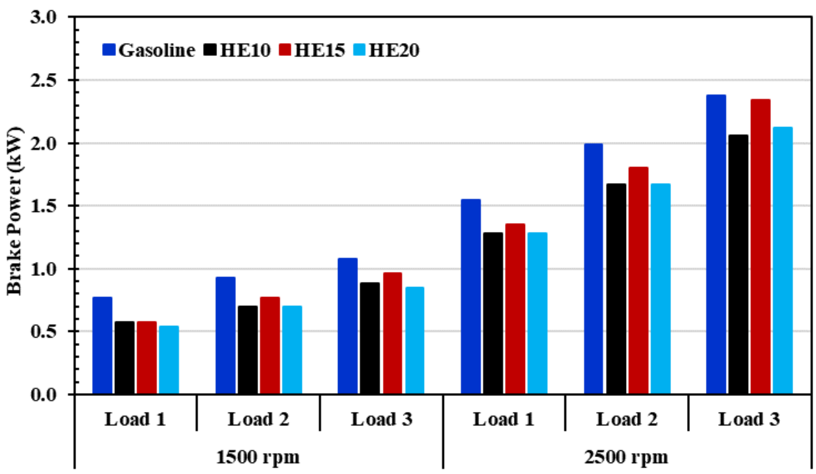

Fig 3. Brake power versus hydrous ethanol-gasoline blends.

3.2.3 Brake specific fuel consumption

The higher hydrous ethanol-gasoline blend fuel consumption for obtaining an equivalent engine power, shown in Figure 4, was expected. Because of the lower heating value of HE in comparison to gasoline, BSFC for HE10 is up to (38.47%) which was greater at lower speed and load than for gasoline. This result agrees with Costa and Sodré [8]. This value decreases to (19.82%), at the same speed and high load as the following: (19.82%, 12.04%, and 14.38%) for (HE10, HE15, and HE20) respectively, were higher than gasoline (0.565717 kg kwh-1). All these results change at higher speed and load with a decrease in brake-specific fuel consumption (BSFC) at high speed of engine especially at high load, (8.44%, and 5.88%) for (HE10, and HE20) respectively, higher than gasoline (0.391945 kg kwh-1). Except when HE15 was used the consumption decreases up to (4%) lower than gasoline fuel. HE15 blend had the best specific fuel consumption rate, and all specific fuel consumption rates while using any hydrous ethanol-gasoline blend exhibited greater values than when using pure gasoline in the test rig.

In Figure 4 and Table 4 the results for brake-specific fuel consumption (BSFC) for all fuels and operating conditions were presented. From Figure 4 and Table 4, it can be noted an increase in BSFC with HE increase, due to reduce LHV of hydrous ethanol when comparing with gasoline.

3.2.4 Brake mean effective pressure

Equation 3 shows that BMEP is directly proportional to the torque developed by the engine. Figure 5 shows slightly higher BMEP at speed of 2500 rpm and loads 2, 3 (2.7 kg and 3.2 kg., respectively) when gasoline and hydrous ethanol-gasoline blend (HE15) were used as fuel. For speed of 1500 rpm, the use of HE blends produced a lower BMEP. At low engine speed (1500 rpm) the higher heating value of gasoline is responsible for the higher BMEP obtained to compare with hydrous ethanol-gasoline blends. At high engine speed (2500 rpm), there is less time available to complete combustion in an engine cycle, and a faster flame velocity is required.

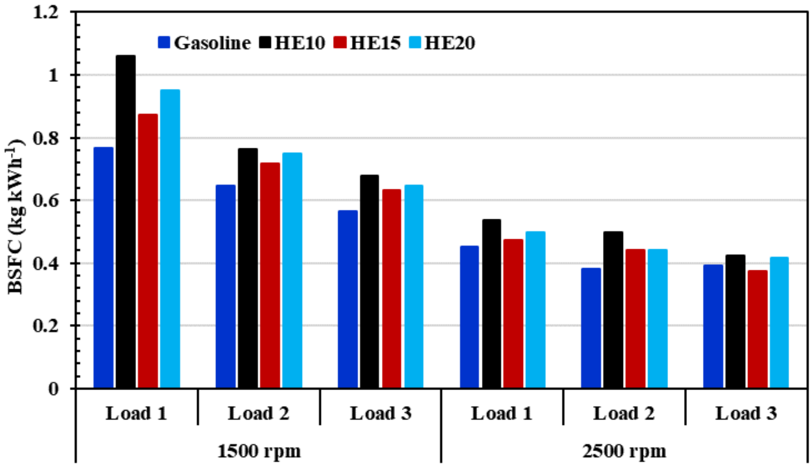

Fig 4. BSFC versus hydrous ethanol-gasoline blends.

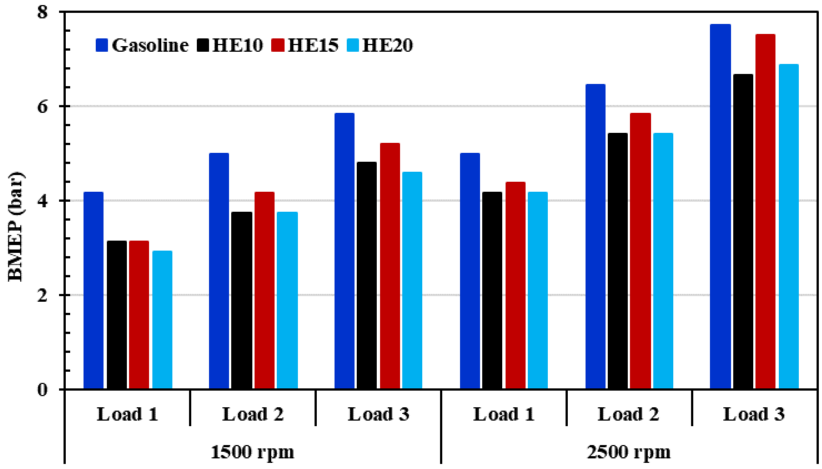

Fig 5. BMEP versus hydrous ethanol-gasoline blends.

3.2.5 Brake thermal efficiency (%)

Figure 6 shows. In the use of gasoline, at low speed and high load of the engine in the experiment, the engine produced brake thermal efficiency higher than that produced when using hydrous ethanol-gasoline blends (16.43%, 10.57%, and 12.2%) for (HE10, HE15, and HE20) respectively. This explains the decrease in energy lost through the cylinder walls as the combustion period, which is related to the ignition time, increases. For the examined blends, the HE15 blend had the highest engine brake thermal efficiency value, while the HE10 blend had the lowest value. The brake thermal efficiency obtained with HE15 blend was 4.38% higher than that obtained with the gasoline fuel, which is in agreement with the findings by Munsin *et al.* [1] and de Melo *et al.* [12]. The peak brake thermal efficiency observed was 21.18%, at 2500 rpm and high load. while HE10 and HE20 blends were presented decrease in brake thermal efficiency up to 7.66% and 5.15%, respectively, Lower than that of gasoline fuel. This could be explained by the decrease in the heat energy lost through the cylinder walls due to a shorter combustion period.

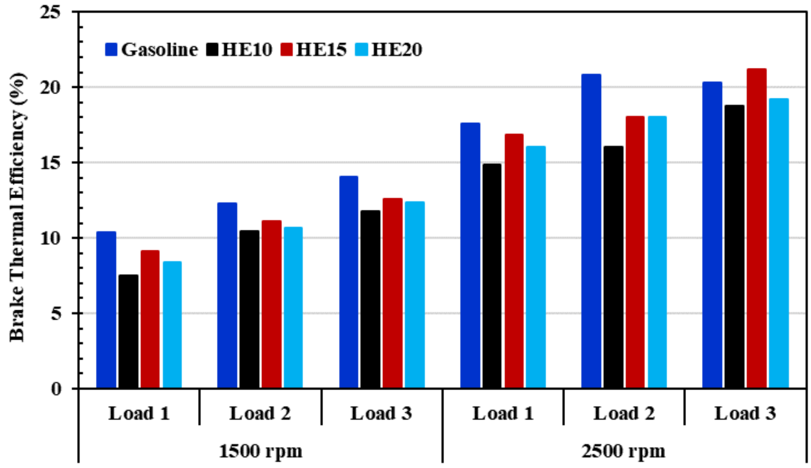

Fig 6. Brake thermal efficiency versus hydrous ethanol-gasoline blends.

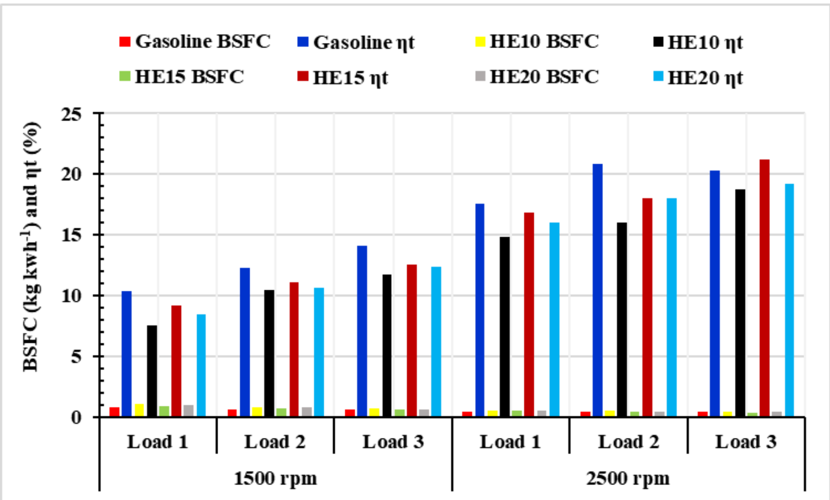

Fig 7. Effect of water content on BSFC and B.Th. efficiency.

3.3 Effect of Water content on BSFC and Brake Thermal Efficiency

Figure 7 shows the effect of water content on BSFC and brake thermal efficiency (ηt) at low speed (1500 rpm) and high load, with increased water content in blends (HE10, HE15, and HE20) increased BSFC by (19.82%, 12.04%, and 14.38%) respectively, and this means the heat value per mass of HE is reduced with higher water content. Brake thermal efficiency gradually decreased by (16.43%, 10.57%, and 12.2%) due to the water content in blends was increased (HE10, HE15, and HE20) respectively, that led to longing combustion duration and heat energy lost through cylinder walls, when compared with gasoline.

At high engine speed and high load, increasing water content in blends (HE10, and HE20 by volume) increased BSFC by 8.44%, and 5.88%, respectively, and decreased BSFC by (4%) for (HE15) lower than that of gasoline. Brake thermal efficiency decreased by (7.66%, and 5.15%) for (HE10, and HE20) respectively, as water content increased in blends and this led to longing combustion duration as mentioned and increased by (4.38%) for (HE15), when compared with gasoline. This agrees with the findings reported by Munsin *et al.* [1].

4. CONCLUSIONS

This research could lead to the following conclusions:

- The density and viscosity of the examined hydrous ethanol-gasoline blends increased as the proportion of hydrous ethanol (HE) in the blend gasoline increased, whereas API gravity and heat value decreased as the proportion of HE in the blend gasoline increased. furthermore, the flash point was discovered to be higher than that of gasoline.
- Blends of hydrous ethanol-gasoline without co-solvents at lower temperatures (10 ℃), might partially avoid the problem of water content of blends (10-15% by vol). At lower temperatures, it might require a solution to higher content of water in the blend such as distillation. The observations for the samples studied showed no watery phase separation at temperature 10 ℃.
- Without modifying the engine, HE fuels have been successfully tested and evaluated as an alternate fuel for SI engines with up to 20% mixtures.
- The use of gasoline fuel at low engine speed 1500 rpm obtained torque and BMEP up to (17.86%, 10.71%, and 21.43%) higher than blends (HE10, HE15, and HE20) respectively, when used in the engine tests. For a high-speed of 2500 rpm, the use of hydrous ethanol-gasoline blends obtained high torque and BMEP which reduced the ratio of increase to (13.51%, 2.7%, and 10.81%) for (HE10, HE15, and HE20) respectively, Lower than gasoline.
- Brake specific fuel consumptions for hydrous ethanol-gasoline blends produced up to (8.44%, and 5.88%) for (HE10, and HE20) respectively, higher than that when pure gasoline fuel was used, BSFC was (4%) for HE15 lower than that when pure gasoline fuel was used, at higher speed and load.
- The usage of hydrous ethanol-gasoline blends resulted in higher brake thermal efficiency of the engine. throughout the higher engine speed (2500 rpm) investigated, reaching a maximum improvement of 4.38% when HE15 was used as fuel, higher than that of gasoline.
- Overall, hydrous ethanol-gasoline blends can be used as a fuel with a good performance at part load conditions, also from the results, there are some important features in engine performance when HE15 was used as fuel.

ACKNOWLEDGMENT

King Saud University provided financial support for this study through the Vice Deanship of Research Chairs. The authors wish to express their appreciation to the Engineering Faculty of Khartoum and El Imam El Mahdi Universities, Sudan.

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