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Sustainability and Environmental Impact of Hydroxy Addition on a Light-Duty Generator Powered with an Ethanol–Gasoline Blend

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ABSTRACT

Environmental sustainability encompasses various problems including climate change, clean air, renewable energy, non-toxic environments, and capacity to live in a healthy community. Many researchers focus their attention on alternative energy sources, such as ethanol and hydroxy gas, to enhance environmental health and quality of life. The introduction of hydroxy gas as a clean source of energy is gaining significant traction. Also, ethanol has a greater octane number than gasoline. Therefore, the ethanol–gasoline blend has a higher octane number than conventional gasoline. A new combination of hydroxy gas, ethanol, and gasoline is environmentally benign while significantly improving the performance of gasoline engines. This paper tested hydroxy gas in a 197-cc gasoline engine power generator powered with ethanol–gasoline blend. The results demonstrated that thermal efficiency increased up to 23.6 % and fuel consumption decreased up to 36 % on a volume basis, which was a significant improvement over the base engine. Furthermore, the hazardous carbon monoxide reduction reached 11.45 % and the unburned hydrocarbon emissions reached 17.6 %.

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1. INTRODUCTION

An enormous research opportunity has opened up due to the rapid depletion of fossil resources and the global rise in the pace of crude oil production. To meet the increasing demand for fuel, researchers in the automobile industry, in particular, should seek firm and ecologically friendly alternatives. Urban environmental authorities have raised awareness about the effects of using up to 20 % ethanol blends in current vehicles without changing the engine design. Global warming and climate change are still major issues according to climate scientists. Many studies have shown that the main cause of this man-made disaster is excessive atmospheric gas emissions from industry and automobiles. Incomplete combustion releases toxic hydrocarbons into the air.

The researcher has studied ethanol combustion in an internal combustion engine. The use of high compression hydrous ethanol reforming and supercharging lean-burn conditions was explored to enhance thermal efficiency and performance [1]. The amount of ethanol utilized with gasoline blend increased the emission of Nitrogen Oxide (NOx). Total carbon monoxide (CO) and hydrocarbon emissions were reduced. It was determined that various ethanol–gasoline mix ratios produced different levels of energy efficiency and pollution under varied loading circumstances. The results showed that the emission concentration increased with engine load, but decreased with ethanol content [2]. The effect of ethanol-gasoline blend on power, torque, fuel consumption, and emissions was studied analytically to evaluate steady-state engines [3]. There has been a recent interest in the performance of spark-ignition engines operating on ethanol-gasoline blends with a constant fuel-air ratio [4, 5]. Low ethanol blends under 20 % pointed to a significant effect on engine efficiency or torque.

Hydroxy gas (HHO) is one of the potential energy sources that may be used as a viable alternative fuel to fossil fuels. In some instances, the electrolysis of water may be used to create it. HHO increases the power and thermal efficiency of the engine while simultaneously reducing the formation of hazardous carbon deposits, nitrogen oxides, and hydrocarbons. Hydroxy gas is a blend of hydrogen (H_2) and oxygen (O_2) gases. Theoretically, a ratio of 2:1 hydrogen:oxygen is adequate to attain maximum efficiency while burning [6]. In terms of fuel chemistry, HHO is superior to gasoline with an efficient fuel structure. HHO has two atoms of hydrogen and oxygen per combustion unit, while gasoline has thousands of huge molecules of hydrocarbons. HHO gas improves combustion by improving engine thermal

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efficiency and decreasing specific fuel consumption. Because hydrogen and oxygen atoms immediately interact, there are no ignition propagation delays owing to surface transit time. A greater velocity flame front shoots through the cylinder wall upon ignition. By boosting reaction rate and flame speed, HHO's heat energy is able to improve combustion efficiency [7]. It is used as a fuel made of hydrogen and oxygen gases. When heated to the auto-ignition temperature at 570 °C at atmospheric pressure with a ratio of 2:1 hydrogen:oxygen, hydroxy gas burns. When ignited, the gas combination turns to water vapor, releasing energy that drives the reaction at 242 kJ per mole of hydrogen. The quantity of heat produced is independent of combustion mode, although flame temperature changes [6]. Many researchers have been developing HHO as a potential engine enhancer for gasoline and diesel engines and other power source applications [8, 9].

Plexiglas-based water-cooled variable compression gasoline-powered four-stroke engine using a potassium hydroxide electrolyte has been investigated for the experiment. The engine test findings indicate that the overall energy consumption decreases while the brake thermal efficiency improves as the flame velocity increases [10]. A simple novel HHO generator was employed to study the impact of adding HHO as an engine performance enhancement additive. The findings found that the thermal efficiency of the engine was improved by 10 %; fuel consumption was decreased by 35 %; and exhaust emissions were reduced nearly 15 % [10]. A single-cylinder engine confirmed that the novel device generated 25 % fuel savings, decreased exhaust temperature, and cut pollutants. A blend of HHO, air, and gasoline effectively decreased pollutant emissions and increased engine efficiency [11]. The unique blend was tested using a series of engine speeds. The emission of nitrogen oxides was cut by almost half. Additionally, the emission of CO was found to be decreased by 20 % and fuel usage was reduced by 25 % [12]. A HHO system that resulted in the overall improvement of 19 % for engine torque, a 14 % reduction in fuel consumption, and a nominal reduction in exhaust emissions [13]. Upon investigating various hydrogen concentrations, researchers have discovered that the CO emission rate did not change regardless of the concentration of hydrogen and that the hydrogen concentration might regulate the particle emission size [14].

Apart from this, HHO gas is added to the gasoline engine and the quantity of gas fluctuates depending on the current supply. Brake thermal efficiency and specific fuel usage were enhanced under HHO [15]. A comprehensive review of hydrogen blended with enhanced natural gas was provided and an experimental study of hydrogen-natural gas was completed [16]. The process of making HHO using variations in current, voltage, temperature, chemical concentration, and reaction time was performed [17]. The study found a 35 % rise in HHO with little electrical energy and also, production rose upon increasing voltage, temperature, and alkaline electrolyte concentration. Because of its better combustion characteristics, hydrogen has been preferred [18].

Furthermore, it was found that biodiesel generated combustion, reduced efficiency, raised carbon dioxide (CO_2) emissions, and caused low combustion. In case of hydrogen-biodiesel, we can see a significant reduction in CO and HC emissions. In a study, 5-25 % HHO in air intake on a single-cylinder SI gasoline engine was evaluated. The findings revealed that when hydroxy levels increased, thermal efficiency and HC emissions also increased. Additionally, the findings revealed that NOx emissions increased as the percentage of HHO increased. The authors calculated the performance of a four-cylinder gasoline engine using an electronically controlled hydrogen injection system. The addition of hydrogen reduced cyclic engine fluctuation, according to the testing findings [19]. Accordingly, the engine performance was evaluated by mixing oxygen-hydrogen (H_2/O_2) with gasoline and liquefied petroleum gas. These experiments were conducted by varying the engine load and emission and performance parameters were evaluated [20]. By using H_2/O_2 mixture in compression, ignition engines reduced fuel consumption and pollutants. The performance test was applied to a constant/test mix using diesel engine. Thermal efficiency was enhanced by 3 %, while CO_2 and H_2O emissions were reduced [21]. The addition of hydrogen to a gasoline methanol engine increased the braking mean effective pressure. The addition of 3 % hydrogen to the fuel source improved both the thermal and volumetric efficiency [22].

The findings indicated that the addition of HHO gas improved brake thermal efficiency by 13 % and reduced brake-specific fuel consumption by 11 %. The HHO gas enrichment reduced CO by 9 % and HC by 21 % while increasing NOx by 6.5 %. The findings demonstrated that the addition of HHO gas raised the lean operating limit of Liquefied Petroleum Gas (LPG) from 1.35 to 1.56 [8]. It was found that the SI engines had lower NOx concentrations, whereas the diesel engines had higher NOx concentrations. While HC concentrations fell by 24 %, CO concentrations rose by 34 %, and NOx remained stable [23]. *Moringa oleifera* biodiesel exhibited a minor increase in brake thermal efficiency owing to the HHO gas. However, adding HHO gas to the mixes reduced the brake specific fuel usage. In terms of emissions, adding biodiesel blends decreased CO, HC, and CO_2 concentrations. No decrease in NOx was seen. However, adding HHO to biodiesel decreased the average NOx by 6 %, which is a significant impact. Overall, HHO enhancing biodiesel blends may replace current fossil fuels due to their better fuel characteristics [24]. The Compressed Natural Gas (CNG) with HHO blend demonstrated superior performance, with a 15 % improvement in average brake power when compared with CNG and yet, with a 15 % reduction when compared with gasoline. CNG-HHO beat gasoline and CNG in terms of emission of HC, CO_2, CO, and brake specific fuel consumption were all reduced by 31 % when compared to gasoline. In comparison to CNG, CNG–HHO generated an average of 13 % more NOx [25].

When the current experimental research on hydrogen supplementation in SI engines is compared with the earlier literatures, many researchers have tried experimental studies for hydrogen supplementation in spark-ignition engines (as shown in Table 1). In general, researchers concentrate on gasoline with hydrogen supplemental experiments in Spark Ignition (SI) and Compression Ignition (CI) engines using LPG, biofuel and alcohol addition for performance improvement.

In India, light-duty power generator engines are still widely used that have high emission. Since renewable energy is not accessible in all locations and seasons in India, certain modifications are required to enhance the combustion rate and thermal efficiency. It is produced from agricultural resources such as sugarcane and maize, making it a viable alternative to gasoline to reduce dependence on fossil fuels and net carbon emissions. It may enhance the performance of a light-duty gasoline generator engine. Completing the burning of HHO with gasoline minimizes harmful pollutants [33, 34].

The key motivation for concentrating on the SI engine study was to improve the thermal efficiency and minimize the global emission. Accordingly, the present work was carried out on a light-duty power generator engine. Hydroxy gas was regulated at two flow variations of 0.15 kg/hr and 0.25 kg/hr on 10 % ethanol-blended gasoline (E10) fuel. Installation of an electrolyser that continuously supplies hydroxy gas to the engine is simple, effective, and ecologically beneficial.

Table 1. Studies on the effect of HHO addition on SI and CI engines

Authors	Engine	Fuel used	BTE	SFC	CO	HC	NOx
Cakmak et al., 2021 [8]	SI engine	HHO + LPG	12.9 %⇧	11.2 %⇩	8.7 %⇩	21 %⇩	6.42 %⇧
Gatot Setyono et al., 2020 [26]	SI engine	Ethanol + HHO	5 %⇧	6 %⇩	–	–	–
Bahman Najafi et al., 2021 [27]	Diesel engine dual fuel	B20 + HHO	3.2 %⇧	13.5 %⇩	21.2 %⇩	–	13.7 %⇧
Usman et al., 2020 [28]	SI engine @219 cc	HHO + LPG	7 %⇧	15 %⇩	21 %⇩	21.8 %⇩	16.1 %⇧
Shajahan et al., 2020 [29]	SI engine	HHO	22.8 %⇧	36.4 %⇩	10.5 %⇩	24 %⇩	–
Hariharan et al., 2019 [18]	SI engine @ 553 cc	HHO	4.5 %⇧	12 %⇩	48.5 %⇩	47.5 %⇩	20.5 %⇧
Baltacioglu et al., 2019 [30]	Diesel engine @ 219 cc	B10 + E5 + HHO	2.82 %⇧	8.39 %⇩	–	–	8.57 %⇧
Karagoz et al., 2018 [31]	SI engine @1124 cc	H_2/O_2	10.4 %⇧	3.3 %⇩	12.5 %⇩	25 %⇩	23 %⇧
Brayek et al., 2016 [32]	SI engine @ 98 cc	H_2/O_2	–	10.4 %⇩	42 %⇩	20.5 %⇩	20 %⇧
Kassaby et al., 2016 [7]	SI engine @ 1289 cc	HHO	10 %⇧	34 %⇩	18 %⇩	14 %⇩	15 %⇩

The necessary test runs with and without hydroxy gas were conducted under four different load conditions from zero to full load to ensure the optimum performance and lowest pollutant emissions. The objective of the present work is to: (1) study the impact of hydroxy gas on the improvement of performance parameters in small generator SI engine powered with ethanol gasoline blend; (2) investigate the engine performance and emission characteristics adoption with hydroxy gas and choose an optimized injection rate of hydroxy gas to enhance the thermal efficiency and minimize the HC and CO emission.

2. EXPERIMENTAL DETAILS

2.1. Hydroxy gas production

Hydrogen is the most reliable alternative due to the current worldwide lack of energy. The practicality of electrolysis lies in the production of hydrogen. HHO is still widely recognized in vehicles that use water as fuel. Despite the tremendous amount of energy required to decompose water molecules, several controversial ideas persist about HHO fuel or fuel additives. In this research, HHO was generated by electrolysis of water utilizing titanium electrodes as both cathode and anode. Sodium sulfate was employed as an electrolyte in an electrolytic cell, and it decomposed water with the liberation of heat. Heat control techniques were sufficient. The electrolysis process also liberated energy. The pulse width modulation technique for HHO production was invented and produced by Baltacıoglu (2019) [30]. In this procedure, the hydroxy output is regulated under the operating requirements of internal combustion engines. A 12-volt, 14-amp battery was employed to provide current to the anode, which was subsequently transferred to the cathode through the electrolyte. The electrolytic glass chamber contained everything required to handle the ingredients and HHO delivery and production. The properties of base fuel gasoline, ethanol, and HHO are tabulated in Table 2.

Table 2. Properties of gasoline, ethanol, and hydroxy gas

Properties	Ethanol	Gasoline	Hydroxy gas
Chemical formula	C_2H_5OH	C_8H_{18}	HHO
Density at 20 °C (kg/m^3)	789	765	600
Molecular weight (g/mole)	46.07	114.18	17.01
Stoichiometric air-to-fuel ratio	8.94	14.49	34
Autoignition temperature (°C)	363	257	585
Net heating value (MJ/kg)	26.8	44	55
Octane number (research)	111	92	130
Oxygen content wt. %	35	0	33

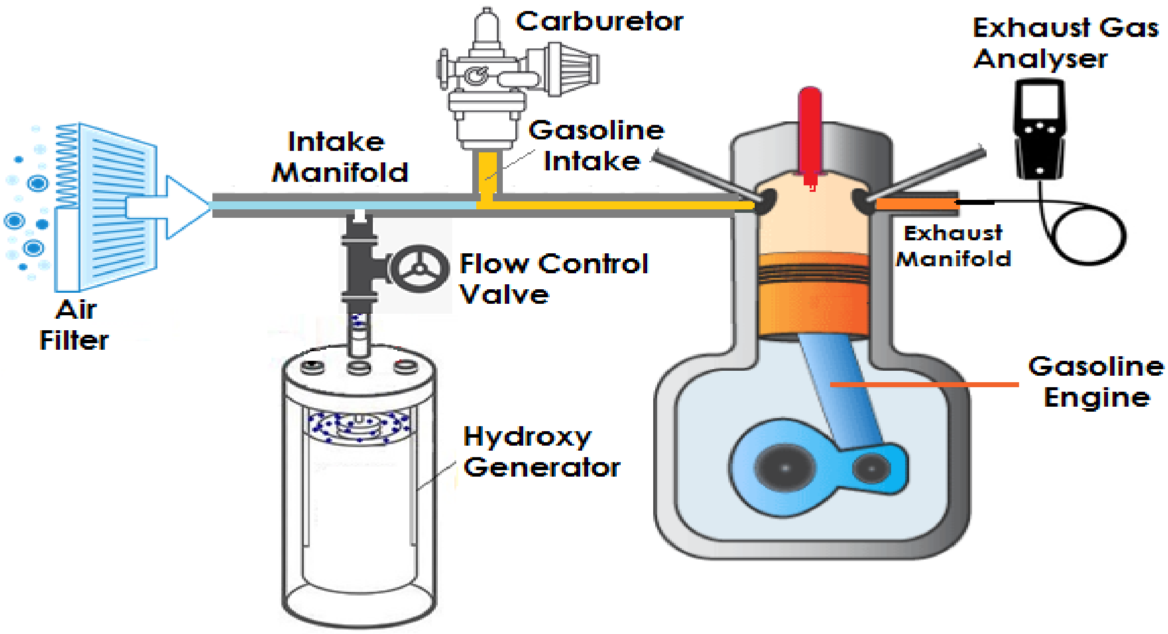
A hydroxy generator generated HHO when installed in the engine without any modifications to the engine assembly. Electrolysis of different molar concentrations of aqueous catalyst was employed to generate much of the gas generated. Sodium hydroxide (NaOH) aqueous solutions were utilized as electrolytes in this research. Further separating the anode and cathode electrodes is done by a semipermeable membrane which is immersed in the electrolyte. The primary chemical component is a catalyst composed of sodium hydroxide, often referred to as caustic soda. It is a salt composed of sodium and hydroxide ions. In the creation of hydrogen, the use of sodium hydroxide leads to high hydrogen generation rates and reduced operating temperatures. The positively charged anodes were successful in decomposing the water molecules contained in the electrolyte, allowing for the release of oxygen and hydrogen gases over the top surface of the reactor's upper surface. Although the simple mixing of HHO and hydrogen had little effect on lowering fuel consumption, the mixture had a significant impact on improving the competency of the fuel. Although the HHO composition of 1/3 volume percent and 2/3 volume percent hydrogen with an octane rating of 130 has reduced in recent years, it still provides adequate performance in engines that run on gaseous fuels or gasoline. Greater fuel combustion translates into less waste being released into the environment. It is then necessary to supply the combustion chamber with the hydroxy gas produced [35].

2.2. Engine setup

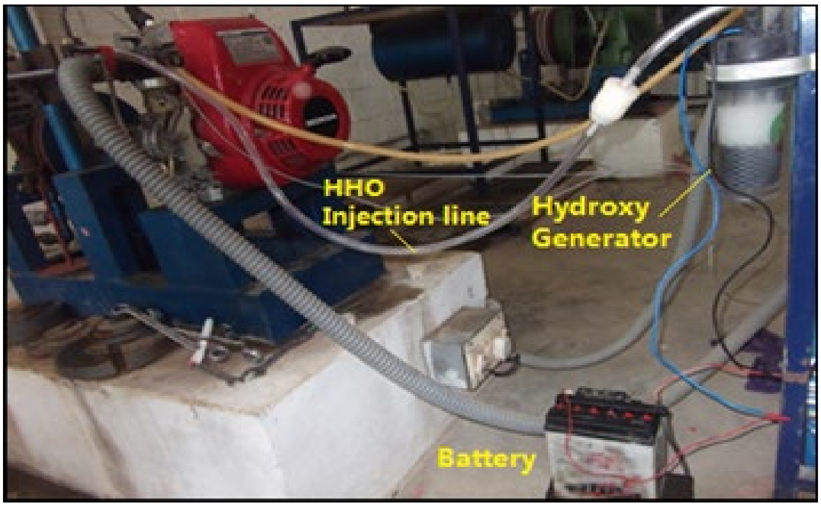
The engine utilized in the test was built according to the specifications (Table 3). It was decided to conduct this investigation using a spark-ignition engine at a compression ratio of 4.5:1 and a peak output of 3 kW at an engine speed of 3600 rpm, as a single-cylinder, four-stroke air-cooled engine. After injecting the controlled volume of hydroxy gas into the air intake manifold and mixing it with gasoline and air, the engine was ready to go. It is the primary job of hydrogen to enrich the reaction and that of oxygen to support the process of oxygen to enrich the reaction.

Table 3. Experimental engine specification

Parameter	Description
Engine type	Four-stroke, single-cylinder
Power	3 kW @ 3600 rpm
Fuel	Gasoline and kerosene
Displacement	197 cc
Bore and stroke	67 × 56 mm
Compression ratio	4.5:1
Cooling system	Air-cooled engine
Load type	Mechanical type



(a) Schematic diagram of the experimental setup



(b) Experimental engine setup with Hydroxy gas

(c) Experimental engine setup with loading setup

Figure 1. Experimental setup

A single-cylinder four-stroke air-cooled, spark-ignition engine with an incremental load was used in this study to examine the ethanol blend and HHO performance and emission characteristics. The incremental load was changed by mechanical loading. A schematic diagram of the use of hydroxy gas in a light-duty power generator engine is shown in Figure 1 (a) and gasoline engine experimental setup is shown in Figure 1 (b) and (c). The engine was first started using gasoline and was, then, subjected to a series of tests until steady-state operating conditions were achieved. Thermal efficiency, specific fuel consumption, HC, CO, and oxygen emissions were measured. The test runs were carried out according to the weight of the load. Similar procedures were used when using ethanol-blended gasoline with HHO enrichment. The HHO was tested for two different contributions of 0.15 kg/hr and 0.25 kg/hr. At the time of the experiment, the atmospheric pressure was 1.013 bar and the temperature was approximately 30 °C. To achieve greater precision, all possible measurable parameters were gathered in each trial and the mean values were calculated.

2.3. Experimental analysis

The experiment was performed in the single cylinder gasoline engine specified in Table 3. The thermal efficiency and specific fuel consumption were analyzed using the following equations:

Thermal efficiency = (Indicated power / Head supplied) × 100

Indicated power = Friction power + Brake power

Brake power = $(2\pi NT) / 60$

Torque = Weight × Radius

Head supplied = Fuel consumption × Calorific value

Fuel consumption = $(Q*10\text{-}6 / t)$ × Density

Specific fuel consumption = Total fuel consumption / Brake power

where N is the speed of the engine in rpm, T is torque (Nm), Weight is used for loading on the engine (kg), Radius is radius of drum used for loading (m), Q is sample fuel consumption measured as 10 ml, and t is the time taken for fuel consumption (sec).

On the analysis of emission measurement, Crypton 680 series Analyser was used for this research. It is a fully microprocessor-controlled exhaust gas analyzer employing Non-Dispersive Infra-Red (NDIR) Techniques. The unit measures carbon monoxide, carbon dioxide, and hydrocarbons. A further channel is provided employing electrochemical measurement of oxygen and chemical sensor used for nitrogen oxides. It has a response time of 11 seconds to 95 % of final reading under the Operating Pressure of 750-1100 bar. It operates at a minimum flow rate of 5 litres/min. The technical details of Crypton 680 emission analyzer are tabulated in Table 4.

Table 4. Details of emission analyser

Measurement	Range	Accuracy	Resolution	Instrument
CO	0 to 10 %	± 0.03 %	0.01 % vol.	Crypton 680 series analyzer, NDIR technique
HC	0 to 10000 ppm	± 10 ppm	1 ppm vol.	Crypton 680 series analyzer, NDIR technique
Oxygen	0 to 25 %	± 0.10 %	0.01 % vol.	Crypton 680 series analyzer, Electrochemical measurement
NOx	0 to 5000 ppm	± 25 ppm	1 ppm	Crypton 680 series analyzer, chemical sensor

On the experimentation, the Crypton 680 series Analyzer was connected at the exhaust system and the emission values were observed for different fuel blends in different loading conditions. The percentage of variation for each parameter can be observed in comparison with base gasoline readings.

3. RESULTS AND DISCUSSION

3.1. Impact on thermal efficiency

The maximum thermal efficiency of gasoline engines is about 30 %. This implies that the remaining 70 % of the heat energy was lost, but it was used to maintain engine temperature and extend the engine span life. Accordingly, half of heat energy was injected into the exhaust gases. The other half of the heat energy was carried out with the cooling unit of the engine through the radiator. Figure 2 depicts the change in thermal efficiency as a function of load, while the blending of HHO results in increased combustion, as previously stated. The thermal efficiency achieved using HHO at full load was raised from 13 % to 23.6 % at two flow variations along with ethanol blend because the flame speed of hydrogen was three times greater than the gasoline and the extensive flammability of hydrogen that scattered throughout the chamber achieved complete combustion. Moreover, hydrogen enables combustion to finish in a shorter amount of time [19].

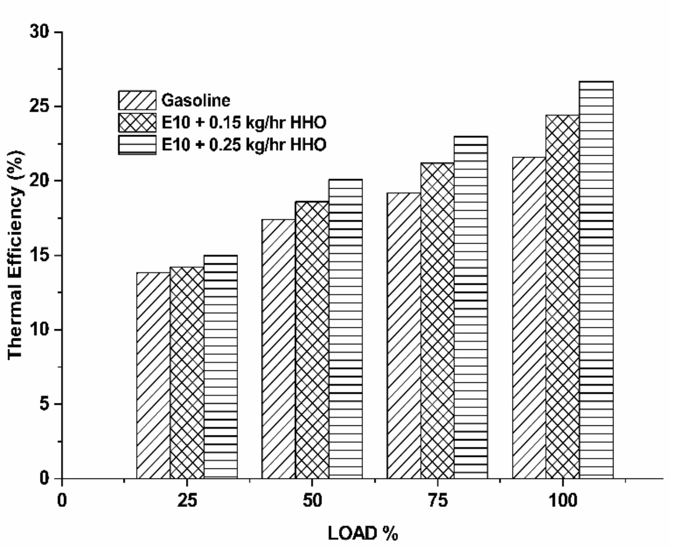


Figure 2. Impact of HHO of thermal efficiency on ethanol-gasoline engine

The cycle exhibits characteristics that are closer to perfect constant volume combustion and an improvement in efficiency. The improved thermal efficiency was recorded by 15 %, 20 %, 23.6 %, and 26.7 % for 0.25 kg/hr HHO injection with ethanol blend in load conditions of 25 %, 50 %, 75 %, and 100 %, respectively. This is due to stratified charges surrounding the spark plug. The remainder of the region is occupied by the lean mixture, resulting in a higher combustion rate than when running an engine test with gasoline alone [21]. Consequently, the characteristics of hydroxy gas lead to complete combustion and high thermal efficiency in large quantities. The enrichment of 0.25 kg/hr HHO was noted to be 19.1 % and 8.6 % higher than conventional fuel and lower than hydroxy gas induction rate. Upon the adoption of HHO, this improvement was noticed by enhanced flame velocity and greater air utilization, which resulted in better power output of the engine. In contrast, the combustion efficiency of the engine operating without HHO under various load conditions declined [30]. Moreover, the thermal efficiency of ethanol blend gasoline was lower than that of gasoline and HHO enrichment because ethanol had a lower stoichiometric ratio than gasoline, which enabled greater fuel mass to be burned with the same quantity of air [26].

3.2. Impact on brake specific fuel consumption

Figure 3 shows the impacts of the induction of HHO into ethanol mixed gasoline on brake specific fuel consumption under four different loads conditions. From the result, it was found that specific fuel consumption in the initial load condition was higher for all test fuel. This result was responsible for high friction power and inferior combustion in the initial load condition. Similar to a previous related work, the higher fuel consumption than other load results from the HHO generator's partial power absorption being more significant than that of the other loads [31]. The result was noted that specific fuel consumption (BSFC) of ethanol blend was observed to be higher than other fuel. It could be attributed to lower heating value of ethanol which required a greater amount of fuel to produce the same power output of the engine. The effect of HHO injection on an ethanol blend demonstrated that BSFC increased from 27 % to 36 % as compared to gasoline operated engine.

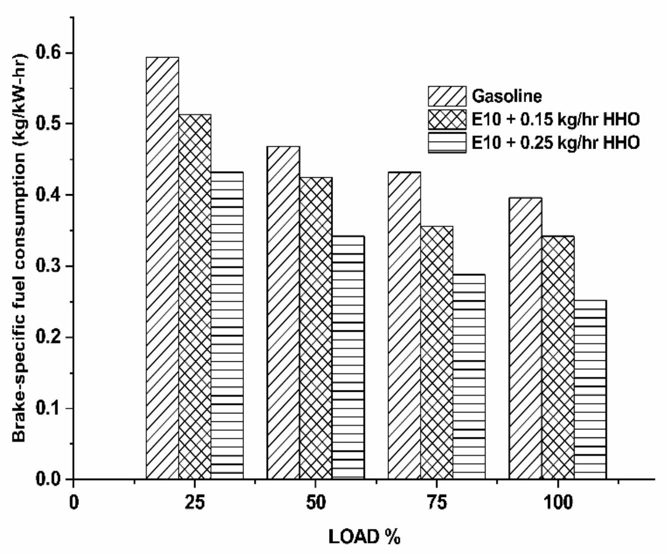


Figure 3. Impact of HHO of brake specific fuel consumption on the ethanol-gasoline engine

The result of BSFC was 0.396, 0.342, and 0.252 kg/kW.hr for gasoline, 0.15 kg/hr and 0.25 kg/hr of HHO injection with ethanol blend, respectively. It was clearly identified that the association of HHO with gasoline minimized the fuel consumption owing to enhanced flame propagation and less flame-quenching zones, which exhibited a better combustion rate [33]. From the results, 0.15 kg/hr HHO addition resulted in decreased fuel consumption between 9.2 % and 17.5 % relative to gasoline in initial and peak load conditions. The least BSFC was noticed for 0.25 kg/hr of HHO addition at peak load owing to better flame speed and enriched energy value of A/F mixture which led to consumption of less fuel quantity to produce the same brake power [22].

3.3. Impact of carbon monoxide emissions

With regard to CO concentrations in the air, they are deficient and restricted, but are primarily used in the formation of a low-level ozone. Figure 4 presents the CO emission rate as a function of different load conditions for gasoline and its ethanol blend with HHO induction. The Air-Fuel (A/F) ratio and combustion efficiency are the prime reason for the formation of CO emission in internal combustion engines. In the engine, a mid-range load condition led to a drop in CO emission. It was mainly due to chemically correct A/F mixture condition that enhanced the combustion rate [2]. CO emissions might have been reduced by adding oxygenated compounds, which promoted CO combustion in the cylinder or post-combustion processes. It was evident that the inherent O_2 content in the ethanol would lead to a reduction in CO emissions. However, dilution of the fuel may not be the only way to decrease CO emissions. When rising the hydrogen concentration with the ethanol blend, a drastic reduction in CO emission was observed for all load ranges, mainly because the lower C/H ratio in the hydrogen fuel restricts the CO formation [12].

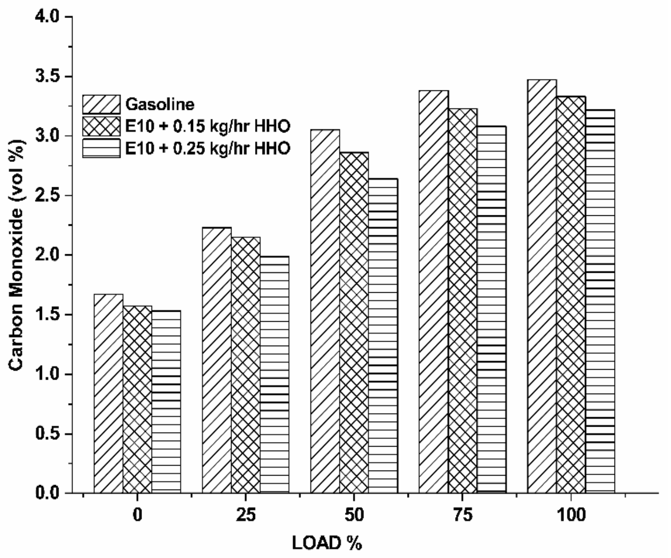


Figure 4. Impact of HHO of carbon monoxide on ethanol-gasoline engine

Improved combustion and lean engine operation caused by the blending of HHO resulted in CO volume percentage reduction rates of 7.2 % to 11.5 % and 3.85 % to 9.2 % for 0.25 kg/hr and 0.15 kg/hr, respectively, as related to gasoline fuel. Moreover, the absence of carbon in HHO substantially reduced CO generation. HHO allows the engine to operate even at a low level of load condition. This result might result from the superior properties of HHO such as wide range of flammability and high flame velocity [15]. High diffusivity of HHO could be easily prepared by the homogenous ethanol blend that leads to a shorter combustion period and promotes the conversion rate of CO_2, thereby reducing CO emission drastically [26].

3.4. Impact on oxygen

Figure 5 exhibits the presence of oxygen content in exhaust gas as a function of engine load for gasoline and its blends with HHO. The leaning action of ethanol also has the additional effect of raising the A/F fuel ratio to a higher value, resulting in the combustion process being closer to stoichiometric conditions and decreasing the oxygen concentration in the exhaust [21]. The test results showed that increase in the engine load causes a reduction in oxygen emissions for all test fuels because of their enhanced combustion rate. The combustion process is expedited under greater engine load circumstances, as seen in the graph. It is possible to infer that the addition of HHO to gasoline resulted in a reduction in the quantity of oxygen produced during the post combustion process [23].

This is mainly due to the high stoichiometric A/F ratio of HHO that utilizes much air during combustion and leads to the insignificant presence of O_2 in exhaust gas. The addition of HHO resulted in complete combustion and lean engine performance and led to a reduction in oxygen concentration from 13.1 vol. % to 7.4 vol. % for 0.15 kg/hr HHO enrichment. Moreover, the rate of adding 0.25 kg/hr HHO enhanced the combustion rate, which led to a substantial increase in heat conversion. It is evident that the amount of oxygen availability in the exhaust for 0.25 kg/hr of HHO addition was 7 %, 22 %, 28 %, and 44 % lower when compared with gasoline in the four load conditions, respectively.

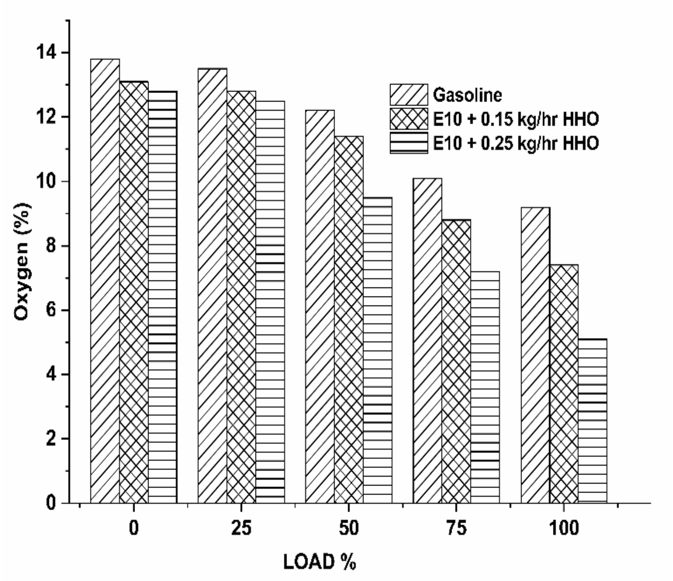


Figure 5. Impact of HHO of oxygen on ethanol-gasoline engine

3.5. Impact on unburned hydrocarbon emissions

The results demonstrated the quantity of unburned hydrocarbons (UBHCs) released into the atmosphere. Figure 6 displays the difference in HC emission with various engine load conditions for gasoline and its blend with enriched hydrogen. It was found that HC emission gradually dropped up to a mid-range load condition and then, it drastically increased due to fuel rich zone which was higher in peak load conditions [31]. Incomplete combustion of fuel is a significant reason for the presence of UBHC in exhaust. UBHC emissions in the exhaust were reduced by 17.6 % at a maximum load and 22 % at a minimum load in the presence of 0.25 kg/hr of HHO when compared with gasoline. HHO with ethanol blend was adopted and it was found that the significant reduction of HC emission was observed for all load conditions. A greater degree of complete combustion and improved engine performance with the addition of HHO influenced lower HC emission formation [34]. Consequently, percentage reduction in UBHC volume ranged between 5 % and 10 % when measured at a volumetric flow rate of 0.15 kg/hr as related to gasoline. It might be due to the enhanced chemical reaction and lack of carbon in the reaction mixture, which led to promotion of the complete oxidation of HC. The result of HC emission from gasoline and 0.15 kg/hr and 0.25 kg/hr of HHO with ethanol bend was 272, 245, and 224 ppm, respectively. The high rate of HHO results in scattered throughput from the cylinder, thereby promoting uniform combustion. Hydrogen reacts within a shorter quenching time than gasoline and results in a reduction in HC emissions. The strong flammability limits of ethanol and the relatively high in-cylinder pressure as well as the temperature generated by the fast flame velocity and the ethanol blends resulted in a decrease in the volume of HC emissions. Increase in oxygen by blending with ethanol led to complete combustion and, as a consequence, reduced levels of UBHC emissions [36].

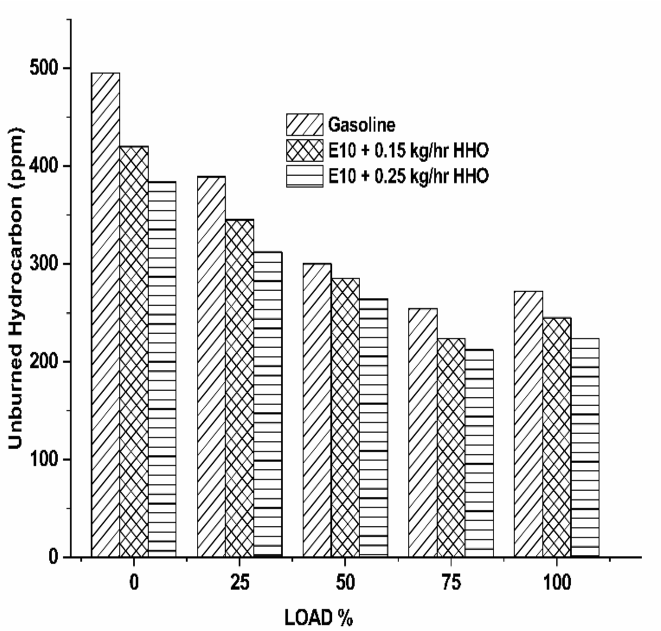


Figure 6. Impact of HHO of UBHC on ethanol-gasoline engine

3.6. Impact on nitrogen oxides emissions

The influence of hydrogen enrichment with ethanol blend on the formation of NOx emission in SI engine is presented in Figure 7. Production of high cylinder temperature during combustion results in NOx formation in the engine; similarly, with a gradual increase in the concentration of HHO, the NOx gradually increased in SI engine. It could be attributed to the higher heat value of hydrogen that dissipates a greater amount of heat during combustion and also aids in the promotion of nitrogen oxidation. In addition, the presence of HHO in the combustion chamber enhanced both the intensity of combustion and the temperature of the combustion chamber and this resulted in increase in the NOx emission [31]. NOx emissions in the exhaust were recorded to be 25 % higher than base gasoline as compared with the presence of 0.25 kg/hr of HHO in the mid-range load condition. However, the rate of increase was 33 % in the maximum load condition at a HHO injection of 0.15 kg/hr on the ethanol-gasoline blend. The primary cause for this was a greater concentration of HHO in the combustion chamber, which increased the temperature of the combustion chamber and resulted in the production of NOx in the process [24]. In the cylinder, the probe's temperature and the excess quantity of oxygen concentration have the most significant effect on the production of NOx emissions. When exposed to high temperatures, the nitrogen chains were eventually decomposed and dissolved. Next, these nitrogen bonds combined with the oxygen molecules in the monotonic form was contained inside the cylinder. The formation of NOx emissions was also influenced by the rate at which nitrogen molecules reacted throughout combustion when the temperature increased beyond a threshold [16].

3.7. Comparison of present investigation with literatures

The current experimental study of ethanol and HHO fuel in the SI engine is compared to the literature, which indicates that many researchers have experimentally investigated HHO supplementary fuel in the engine. Table 5 compares the present study's performance and emissions to those of Hariharan et al., 2019 [18], Usman et al., 2020 [28], and Çakmak et al., 2021 [8].

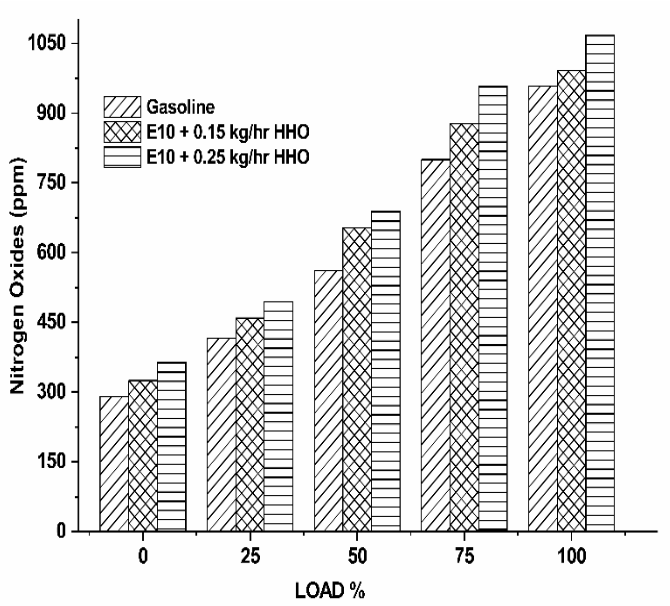


Figure 7. Impact of HHO of nitrogen oxides on the ethanol-gasoline engine

Table 5. Comparison of experimental results of SI engine

Parameters	Hariharan et al., 2019 [18]	Usman et al., 2020 [28]	Çakmak et al., 2021 [8]	Present study
Engine Specification	CI engine, 3.7 kW @ 6000 rpm	SI engine, 219 cc Single cylinder	SI engine Single cylinder	SI engine, 3 kW @ 3600 rpm
Supplementary fuel	HHO	HHO + LPG	HHO + LPG	HHO + E10
Thermal efficiency (%)	4.5 %⇧	7 %⇧	12.9 %⇧	23.6 %⇧
Specific fuel consumption (kg/kW-hr)	12 %⇩	15 %⇩	11.2 %⇩	36 %⇩
CO (%)	48.5 %⇩	21 %⇩	8.7 %⇩	11.5 %⇩
HC (ppm)	47.6 %⇩	-	21 %⇩	22 %⇩
NOx (ppm)	20.5 %⇧	16.1 %⇧	6.42 %⇧	25 %⇧

These experimental studies demonstrated that Brake specific fuel consumption figures might be improved. The current research looked into a greater decrease in specific fuel consumption than previous studies; this is because the engine capacity is smaller and the combustion conduit is smaller, which enables a wider variety of flames and a quicker combustion rate. The greater thermal efficiency obtained compared to previous studies is due to the hydrogen sharing affecting the pace of combustion. Emissions in all previous investigations, including this experimental study, revealed that harmful compounds such as unburned hydrocarbons and carbon monoxide were significantly reduced. This is because of the increased flame velocity and calorific value induced by hydrogen enrichment. On the other hand, the higher temperature generated by HHO supplemented combustion led to the generation of more nitrogen oxides.

3.8. Environmental impact of HHO on gasoline engine

This study mainly focuses on reducing harmful emissions of CO and HC from a small gasoline power generator. CO harms human health by decreasing the ability of blood to transport oxygen to and from tissues. Furthermore, CO enters the circulation rapidly, converting hemoglobin to carboxyhemoglobin (COHb). Similarly, when CO is found in the lungs, hemoglobin does not reach 100 % oxygen saturation. The American Heart Association reports that COHb values of 10 % cause headaches, 25 % cause nausea and weakness, and 35 % cause coma or death in otherwise healthy people. CO affects human health by impairing the capacity of the blood to carry oxygen to and from the body's tissues. CO is breathed and quickly crosses the lung alveolar epithelium into the bloodstream, where it converts hemoglobin to COHb.

Changes in cognitive functioning, psychological issues, and respiratory system damage are all related to HC exposure. Apart from this, cancer and other general health problems are also linked to HC exposure. There has also been an effort to measure toxicity. One example is benzene, which causes leukemia in humans and is present in gasoline and crude oil. This HC is also known to decrease white blood cell synthesis, suppress the immune system, and increase white blood cell susceptibility to infection. There is evidence that reactive and hydrophobic aromatic compounds such as benzenes, naphthalene, styrene, or xylene isomers that harm seed germination in many plants. Additionally, the phototoxicity of contaminants changes with plant growth stage [33].

The present investigation revealed that HHO on an ethanol mix improved fuel economy and efficiency. The smaller engine capacity and combustion conduit enable a broader spectrum of flames and a faster combustion rate. Because hydrogen sharing influenced the fastness of fuel burning, this research generated higher thermal efficiency. Other studies, such as the current research, showed that pollution emissions such as UBHCs and CO were greatly decreased. This is because hydrogen enrichment increases the flame velocity and calorific value. The greater temperature in hydrogen-added combustion produces more nitrogen. To run this engine with a hydrogen electrolyzer, the values of increased thermal efficiency and reduced pollution emissions have been highlighted.

4. CONCLUSIONS

The fossil fuel industry now supplies a significant portion of the world's energy requirements, particularly in transportation. As a result of the scarcity of fossil fuels and the increasing release of hazardous pollutants into the environment, experts have turned their attention to alternative energy sources such as ethanol and HHO. An experimental investigation was conducted on a light-duty power generator powered by an ethanol-gasoline blend with HHO to improve the engine's performance and reduce harmful emissions. HHO was generated by an electrolysis process and added to the intake manifold at two different flow rates and in 10 % ethanol-blended gasoline. The further advantages include the following:

- With the addition of HHO, the thermal efficiency at the maximum load increased to 13 % and 23.6 % at 0.15 kg/hr and 0.25 kg/hr, respectively, owing to the boost produced by increased hydrogen flame velocity and a more comprehensive range of flames when using HHO.
- The combustion rate of ethanol-gasoline with a mixture of HHO was significantly enhanced. Fuel consumption was remarkably enhanced from 9 % to 36 % on a volume basis in different loading conditions.
- Enhanced and lean engine operation caused by the injection of HHO resulted in the CO volume reduction of 7.2 % to 11.5 % and 3.85 % to 9.2 % at volumes of 0.25 kg/hr and 0.15 kg/hr, respectively. In addition, the oxygen present in the exhaust was considerably reduced by 44 % due to the greater volume of complete combustion.
- The concentration of UBHCs was reduced by 17.6 % at maximum load and by 22 % at minimum load in the presence of 0.25 kg/hr of HHO, owing to the increased chain reaction caused by hydrogen and the absence of carbon in the system.
- NOx emissions were recorded to be 25 % more than base gasoline at minimum load in the presence of 0.25 kg/hr HHO and 33 % high at the maximum load with 0.15 kg/hr of HHO due to an increase in combustion chamber temperature.

In the future, the present study can be protracted in the case of high-speed SI engine to enhance the performance and combustion characteristics using doping of nanoparticle with gasoline. The numerical study may target SI engine fuelled with another alternative energy to increase performance parameters. Furthermore, this research may be enhanced by including exhaust gas recirculation assistance to decrease NO_X emissions and be modified to run in the dual fuel mode.

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NOMENCLATURE

BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
CO_2	Carbon dioxide
CO	Carbon monoxide
COHb	Carboxyhemoglobin
CNG	Compressed Natural Gas
CI	Compression Ignition
E10	10 % Ethanol-blended gasoline
HC	Hydrocarbon

H_2	Hydrogen
HHO	Hydroxy gas
LPG	Liquefied Petroleum Gas
NOx	Nitrogen Oxide
NDIR	Non-Dispersive Infra-Red
O_2	Oxygen
NaOH	Sodium hydroxide
SI	Spark Ignition
UBHC	Unburned Hydrocarbons

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