

NO_x Emission Reduction Using Hydrous Ethanol-Gasoline Blend with Syngas in SI Engine

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Abstract

This paper presents a comparatively experimental study of nitrogen oxide (NO_x) emissions from an internal combustion engine fed by gasoline available in the Saudi Arabian market rating octane number (RON 91 and RON 95) with admixtures of syngas with 0% E0, 5% E5 and 10% E10—by volume of pure ethanol—and HE5 and HE10 with water concentrations of 5%, 10%, 30% and 40%—by volume of hydrous ethanol—at stoichiometric mixtures. An on-board plasma system used to produce syngas through the partial oxidation of gasoline with air in a plasma-assisted fuel reformer. The syngas injected in a gasoline engine with a fuel injection system modified for operation with addition of some amount of syngas. The experimental results demonstrated a significant total reduction in NO_x emissions and slightly increased in fuel consumption when mixing gasoline (RON 91 and RON 95), ethanol (E5 and E10) and hydrous ethanol (HE5 and HE10) with syngas. For the use of hydrous ethanol (HE5 and HE10) along with the addition of syngas, for both RON 91 and RON 95, the lowest NO_x emissions are found 72% with a water concentration of 40%.

Keywords

Plasma, Fuel Reforming, Syngas Production, Ethanol, Emissions, Nitrogen Oxides

1. Introduction

Strict regulations on environmental protection have attracted researchers to address reductions in emissions from engines such as hydrocarbons HC, nitrogen oxides NO_x, carbon dioxide CO₂ and carbon monoxide CO. Emissions from en-

gines are considered a major cause of global warming and have direct effects on human health as undesirable emissions generated by the combustion process of ICEs are expelled into the environment. There are current problems with limited fossil fuel resources and worldwide heating phenomena, so researchers are interested in using alternative fuels and preserving the environment. Based on recent research to produce more sustainable fuel for the automotive industry, ethanol is often mixed with gasoline. This process becomes more sustainable if hydrous ethanol is used instead of anhydrous ethanol; therefore, that energy can be saved [1]. Based on experiments using a fuel mix of ethanol and gasoline, fuel consumption and torque production did not change or increase slightly, and carbon monoxide (CO) and hydrocarbon (HC) emissions dropped significantly. It has been observed that changes in nitrogen oxide (NO_x) emissions are influenced by the operation of the engine rather than the ethanol content. Changes can be observed with the exception of reductions in NO_x emissions compared with traditional gasoline fuel [2]. In general, bioethanol and ethanol are more interactive than hydrocarbon gasoline. These compounds include hydroxyl groups such as carbon bonds and polar fracture, and fuel compounds contain nitrogen.

NO_x is formed when the effect of hydrous ethanol in the engine is to reduce pressure, and water absorbs heat. During combustion, water absorbs heat and evaporates to reduce temperature and then reduce NO_x emissions. When comparing, we note the differences between an anhydrous ethanol mix with gasoline and a hydrous ethanol mix with gasoline at an average level (0% - 40% water volume). The NO_x emissions for the hydrous ethanol mix with gasoline are less than those for the anhydrous ethanol mix with gasoline. Water in hydrous ethanol also reduces pressure, temperature and combustion speed compared with that in anhydrous ethanol. In addition, the increased water content of hydrous ethanol improves NO_x emissions. Engine speed affects NO_x emissions so that more fuel is burned, the temperature increases and NO_x emissions increase if the engine speed increases. Oxidation converts nitrogen into NO_x during the combustion process. Moreover, this process is associated with hydrocarbon oxidation and chemical kinetics. In addition, when the nitrogen content of the fuel increases, the amount of NO_x increases. Many studies have also shown that when using ethanol-gasoline blends, increasing ethanol content reduces NO_x emissions. The main reason for the reduction in NO_x emissions is the greater heat evaporation of ethanol in comparison to gasoline. In addition, the temperature of the mixture during combustion is reduced. The effect of gasoline-ethanol mixture emissions with different ethanol ratios has been investigated, and the particle diameter in the assembly is smaller. When the ethanol concentration increases, the aerosol concentration decreases, leading to complete combustion. For this reason, there is a reduction in emissions of nitrogen oxides and carbon monoxide. Anhydrous ethanol fuel tends to have the same properties as ethanol fuel due to the oxygen content in ethanol. The total mixture burns at a stoichiometric mixture when the engine is operating [3] [4].

Nomenclature:			
ICE	Internal combustion engine	HE5	Hydrous ethanol 5
CO	Carbon monoxide	HE10	Hydrous ethanol 10
CO ₂	Carbon dioxide	WC	Water concentration
E5	Ethanol 5	AEAC	Anhydrous ethanol fuel
E10	Ethanol 10	AEHC	Hydrous ethanol fuel
MPB	Mass fraction burned	NO _x	Nitrogen oxide
HC	Hydro carbon	DC	Direct current
λ	Lambda	SO ₂	Sulfur dioxide
ECU	Engine control unit	PPM	Parts per million
RON 91	Rating octane number 91	RON 95	Rating octane number 95
G 91	Gasoline 91	G95	Gasoline 95
EPA	Environment protection agency	FI	Fuel injection
GHG	Greenhouse gases	E0	Gasoline
SI	Spark ignition	MBT	Maximum brake torque
THC	Total hydrocarbon	H ₂	Hydrogen
IC	Internal combustion	CU	Control unit
O ₂	Oxygen	PC	Personal computer
RPM	Revolution per minute	Syngas	Synthesis gas
OHV	Overhead valve	°C	Celsius
BSFC	Brake specific fuel consumption	NO ₂	Nitrogen dioxide

In 2008, a study in Brazil conducted by Orlando Volpato Filho reviewed the process of producing Gasoline C (E22) using hydrous ethanol (AEHC, E100) instead of anhydrous ethanol (AEAC) without water separation. According to this paper, there are two types of ethanol used as automotive fuels: anhydrous ethanol fuel (AEAC) and hydrous ethanol fuel (AEHC). Hydrous ethanol can be produced by easy drops, while otherwise dry conditions are needed to produce anhydrous ethanol. Gasoline C can be made by mixing anhydrous ethanol fuel (AEAC) with gasoline (E0). The purpose of mixing is to produce Gasoline C with a very low separation temperature (below -30° Celsius). However, hydrous ethanol fuel (AEHC, E100) can be used in particular climate conditions to make Gasoline C without water phase separation. To prevent water separation, an alcohol is added to the mixture to reduce the separation temperature. For example, a mixture called EHi22 is made by adding isopropanol to EH22, and then the mixture separation temperature will drop from -30° to -100° Celsius. The study showed that greenhouse gas (GHG) emissions from the production of anhydrous ethanol are approximately $436 \text{ kg CO}_2/\text{m}^3$ of ethanol, while those from hydrous ethanol are $417 \text{ kg CO}_2/\text{m}^3$. Therefore, by switching to AEHC, approximately 85 billion kg CO₂ per year of GHG emissions can be avoided. On average, ethanol productivity from one ton of sugar cane is 85 litres of AEAC and 90

litres of AEHC. To produce AEHC, the process requires approximately 2.7 MJ/l of ethanol, while more complex processes that consume approximately 2.9 MJ/l are needed to produce AEAC. The study suggested using the energy saved from the dehydration of AEHC to produce electricity. In summary, the use of AEHC instead of AEAC will reduce GHG emissions, improve energy efficiency, and allow extra electricity to be sold, and for new plants, lower capital cost can be achieved, leading to more inexpensive Gasoline C [5].

Munsin *et al.* investigated the effects of using hydrous ethanol with increasing water content (above 40% by volume) on the spark ignition engine emissions and rendering for different loads and water contents in ethanol. The results were presented for an engine speed of 3600 rpm and the stoichiometric condition, and ethanol with 5% water content had lower HC and NO_x emissions than the Environmental Protection Agency boundary pattern in 2011 after the catalytic transformer. In contrast, prior to the catalytic transformer, HC + NO_x emissions were higher than the Environmental Protection Agency boundary; however, CO was lower than the Environmental Protection Agency boundary in both cases. In addition, increasing the load increased the overall efficiency and NO_x emissions, but the brake-specific fuel consumption (BSFC) and the HC, acetaldehyde and formaldehyde emissions decreased. The study revealed that at a constant load, increasing water content decreases the emissions of nitrogen oxides and total efficiency and increases CO, HC, BSFC, acetaldehyde and formaldehyde emissions. A catalytic converter is recommended when using hydrous ethanol because it reduces all emissions. It is worth pointing out that using hydrous ethanol had negative effects on the engine materials, lubricant and fuel system, such as oxidation of engine parts and lubricity failure [6].

El-Faroug *et al.* discussed the stability of ethanol-gasoline-water blends; the properties of hydrous ethanol along with those of its mix with gasoline; and their effect on the combustion properties, emissions and engine rendering in spark ignition (SI) engines. Almost all results showed refinement in combustion properties and improved engine rendering by using hydrous ethanol. Hydrous ethanol has a higher octane count than that of gasoline, resulting in a higher compression ratio. In addition, using hydrous ethanol (with low water content) improves combustion efficiency, cylinder pressure, heat release rate, flame speed and cylinder temperature. However, it reduces the duration of combustion, directional engine knocking and temperature of combustion. In terms of engine rendering and brake power, the results showed refinement in the torque, thermal brake efficiency and mean effective pressure brakes when using hydrous ethanol. According to the study, increasing the water content in the mixture allows the ignition points to advance to the maximum brake torque (MBT) condition and results in an increase in the engine torque and power output. However, water content above 30% had an adverse impact on engine rendering. Therefore, it was revealed that E70W30 fuel is a good substitute fuel for engine performance and cost. It was presented that hydrous ethanol blends have lower NO_x emissions than gasoline and anhydrous ethanol blends. Furthermore, a small reduction in

CO, CO₂ and unburned HC emissions was observed. Moreover, high water content lowered the combustion temperature, leading to higher amounts of unburned HCs. However, acetaldehyde and formaldehyde emissions were relatively higher than those from gasoline, while emissions of nitrogen oxides decreased with increasing water content [7].

De Melo *et al.* examined the effect of adding hydrous ethanol to E25 on the characteristics of the combustion of flexible fuel engines and emissions under different operating conditions. The study identified gasoline E25 as H0 and hydrous ethanol as H100. These fuels were mixed by volume to produce H30, H50 and H80. According to this paper, increasing ethanol content caused an increase in the maximum pressure in the cylinder for fuel-rich conditions (torque of 105 Nm) because the high octane number of ethanol allows the spark timing to progress. However, for the case of the stoichiometric condition (torque of 60 Nm), most of the spark timing and pressure were maintained at the same scale except at the speed of 3875 rpm. For such torque and speed, engine knocking restricted the spark timing from reaching the MBT for the H0 and H30 fuels. One of the combustion characteristics covered by the study was combustion duration, which did not present any significant changes with ethanol addition except for H0, which presented a higher value for 60 Nm torque. It was observed that ethanol addition increases the specific consumption, shifts the mass fraction burned (MFB) and changes the crank angle of the maximum pressure due to the increase in the spark timing angle. Ethanol addition increases energy efficiency except from H30 to H50, where it drops. For the addition of ethanol above 50%, H30 presented high energy efficiency. However, the highest energy efficiency observed among all fuels was for H100 for the whole operating conditions. The results showed a reduction in the total hydrocarbon (THC) and CO emissions with ethanol addition but increased emissions of CO₂, unburned ethanol and aldehydes. NO_x emissions presented a different behaviour. These emissions decreased with ethanol addition at low speeds of 1500 rpm to 2250 rpm and increased at high speeds of 4500 rpm. However, for both operating conditions, ethanol content above 50% did not show important changes in NO_x emissions. In addition to the effects of fuel and speed, a high load (105 m) produces less NO_x emissions [8].

Huang *et al.* investigated the integration of oxygen in mixtures with the addition of ethanol is studied for reducing hydrocarbon (HC) and carbon monoxide (CO) emissions and increasing combustion efficiency. Moreover, mixing anhydrous ethanol at higher temperatures makes the mixture better and combustion more complete. Mixing hydrous ethanol will reduce the stability of the blended fuel. Hydrogenated ethanol can be used because it is a promising substance for gasoline and is more popular because of reduced harmful emissions and energy conservation [9].

The role of ethanol in the engine is to burn the rich air-fuel mixture, and through combustion, ethanol generates higher production capacity than gasoline. Additionally, a smaller amount of non-burning hydrocarbons and NO_x is

emitted due to the lower heating value, leading to increased fuel consumption of ethanol. It was observed that with increasing concentration of water, the ignition timing should be developed to ensure sufficient water evaporation. It was also observed that emissions are low in NO_x and contain a high proportion of water because high temperature leads to evaporation of water and low temperature of the cylinder [10].

Reforming is a scientifically proven process for cracking complex chemical compounds. Research confirms that fuel reuse and the decomposition of complex hydrocarbons into syngas can be used to control the combustion process. Tar conversion also has a beneficial effect on fuel repair as a process of tar removal. The use of ethanol allowed easier conversion of isooctane. The conclusion was that ethanol content had a significant impact on the conversion and transitional reforming of fuel with different ethanol ratios and the impact of reforming performance. Reforming can be split into two main groups: non-catalytic and catalytic reforming. One type of non-catalytic reforming involves the high-temperature cracking of chemical compounds. A second type of non-catalytic reforming is interesting in that plasma repair is performed to produce hydrogen. Reforming is widely carried out in the energy industry [10]. Different types of advanced devices are used in reforming for hydrogen production. For example, Heywood *et al.* developed a plasmatron device to generate hydrogen with the help of plasma, and the device was demonstrated in an SI engine with gasoline to significantly decrease NO_x emissions by 80% and increase the efficiency of the engine. Hydrogen is effective in engine fuel for obtaining a low flame temperature to reduce NO_x emissions [11].

The researchers combined the engine and internal combustion to operate the engine using gasoline as a main fuel blended with hydrogen gas created by the reformer. In this way, emissions of exhaust gases, fuel consumption and engine efficiency can be reduced. However, it is necessary to examine the following parameters: operating temperature, cold start time, fuel type and hydrogen content in the syngas [9]. It is necessary to increase engine efficiency and reduce vehicle emissions for better gas reduction and air quality. The SI engine emissions can be reduced by adding hydrogen by a plasmatron, which is an electric gas heater that uses gases to react at a high temperature to produce a syngas containing hydrogen. In addition, among the concepts to reduce emissions is the generation of hydrogen by microplasmatron, which is used onboard. The plasmatron works by controlling high temperature to heat the gases and partially ionize them at a high temperature to form cold plasma. The plasmatron is then mixed, and the hydrocarbon fuel reforming process produces a syngas that contains hydrogen. Using this method, many types of fuels can be repaired and converted to syngas using plasma at high temperature and production of syngas (H₂ + CO) [12] [13] [14] [15].

Hoang *et al.* [16] studied the gasoline with ethanol at different percentages. The fuel was mixing with E5 and E10 to analyze engine emission characteristics. The emission of nitrogen oxides was formed at a high temperature of 1500°C in

the combustion process. In addition, Results indicated that NO_x emission decreased when using E5 and E10 compared to the original gasoline and E5 had less emission in NO_x compared to E10. The study stated that the main factor in the change in NO_x emission concentration was the effect of ethanol on the temperature in the combustion chamber.

Xiaokang *et al.* [17] investigated experimentally performance, exhaust noise, and emission products of a gasoline engine operated with hydrous ethanol gasoline with 10%, 20% hydrous ethanol by volume (E10W and E20W) and pure gasoline (E0). The tests—that were performed at different engine speeds—showed that as the engine speed is increased, pure gasoline showed an advantage in low exhaust noise. Better thermal efficiency, significantly lower CO and HC emissions were attained by hydrous ethanol gasoline at all operating conditions. However, significant NO_x emission and slight brake specific fuel consumption (BSFC) were noticed for E10W and E20W. Comparing E10W with E20W, E10W showed that BSFC, HC and NO_x emissions are decreased with the increase of engine speed, while CO emission was only slightly increased. Hence, hydrous ethanol gasoline can be considered as a promising alternative fuel for SI engine.

This study is an ongoing work that investigates exhaust emissions and provides gasoline engines with gasoline fuel. Early empirical results clearly demonstrated that NO_x engine emissions are reduced after syngas rich in hydrogen from the plasma-assisted fuel adapter has been added to the staff fork of the tested engine. An extremely significant decrease in harmful pollution was observed for lean conditions. Continuing this work, investigations of ultra-lean systems have been implemented. This study investigates the effect a stoichiometric mixture regime in the presence of 5 and 10 vol.% anhydrous ethanol-gasoline blended fuel (E5 and E10) and hydrous ethanol-gasoline (HE5 and HE10 with water concentration = 5%, 10%, 30% and 40%) on two types of fuel available in the Saudi Arabian gasoline market: RON91 and RON95.

2. Materials and Methods

The test bench used in this study consisted of four supported systems: modified gasoline engine, feeding, plasma, and load systems. A Subaru EH72 FI gasoline engine with a fuel injection system was used in the experiments. **Table 1** explains the technical specifications of the engine. **Table 2** lists properties and constituents of Saudi Arabia's RON 91 and RON 95 sample [18]. **Figure 1** illustrates a schematic diagram of the experiments, while **Figure 2** shows the test bench. A specifically developed engine control unit (ECU) was modified, and a Bosch HFM5 flow metre from Bush was installed in the suction channel of the engine for precise measurement of airflow. Two original built-in fuel injectors were operated electronically by the ECU metre fuel. A Hitec HS635HB servo was installed and connected to the throttle arm to control the computer from the throttle position. The exhaust emissions (CO₂, CO, NO_x, and HC) and O₂ concentrations were monitored using an automotive INFRACAR 5M3T.01 exhaust gas analyser. While loading the engine, an Enders ESE 1506 DSG-GT ES

DUPLEX SSG 132 Medium power electric generator was used, and along the engine shaft, the load was adjusted by choosing the number of heaters connected to the generator. The fuel adapter for generating syngas consisted of a plasma discharge unit and a reactor. **Figure 3** shows a diagram of the plasma discharge chamber. The plasmatron cathode is a copper electrode that is cooled with water by a tungsten rod inserted into the copper tip. A high-voltage DC power source from Technix, an SR10-(P/N/R), was used to operate the plasmatron in arc flux to position the transition from discharge at approximately atmospheric pressure. The power supply ensures a maximum output voltage of 10 kV, and the current is operated at any required level in a range of 0 to 500 mA. Adding steam to the fuel mixture helps to avoid soot formation during the gasoline repair process. **Figure 4** shows a schematic of the plasmatron fuel mixing and evaporation unit.

Table 1. Technical specifications of the engine.

Description	Specification
Type	Air-Cooled, 4-Stroke, V-Twin Cylinder, Horizontal P.T.O. shaft, OHV Gasoline Engine
Bore × Stroke, mm	84 × 65
Displacement, cm ³	720
Compression ratio	8.1
Continuous output, kW (HP)/r.p.m.	14.9 (20.0)/3600
Maximum torque, Nm/r.p.m.	52.2/2800
Charging capacity, V - A	12 - 15 or 12 - 30 (Option)

Table 2. Properties and constituents of Saudi Arabia's RON 91 and RON 95 sample.

Description	RON 91	RON 95
Calculate octane number	90.44	94.66
Initial boiling point (C)	39	35.7
Final boiling point (C)	204	197.2
Relative density	0.679	0.688
Vapor pressure (kPa @ 37.8 C)	36.75	39.58
Lower heating value (kJ/kg)	43.932	43.304
Constituents (% mass) Paraffins	10.544	9.033
I-paraffins	36.853	37.500
olefin	13.911	13.373
Naphthenes	5.665	10.427
Aromatic	28.870	24.961
Total C14+	0	0.096
Total unknown	1.752	2.269
Total	100	100
% Carbon	86.045	86.413
% Hydrogen	13.156	13.163
H/C	0.153	0.152
Average molecular weight	85.571	88.288

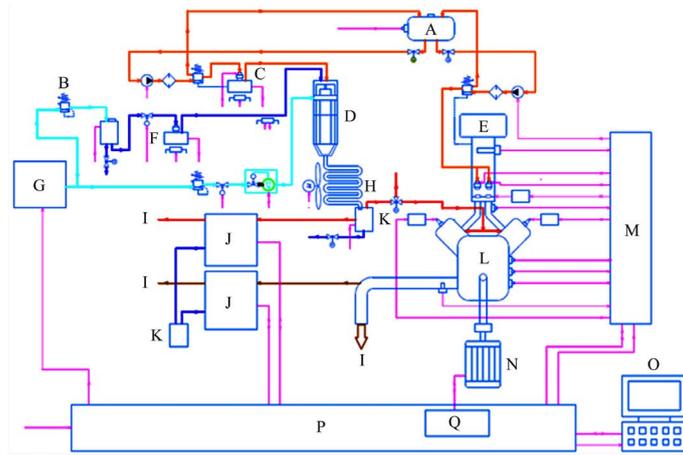


Figure 1. Schematic of the experimental setup showing: (A) Fuel Tank, (B) Pressure Regulator, (C) Fuel Evaporator, (D) Plasma Converter, (E) Air Filter, (F) Water Evaporator, (G) Air Compressor, (H) Chiller, (I) Exhaust, (J) Gas Analyser, (K) Condensate Tank, (L) Engine, (M) ECU, (N) Electric Generator, (O) PC, (P) Stand CU, (Q) Inverter.



Figure 2. Left: Rear view of the test bench showing: (A) Power Supply, (B) Boiler, (C) Air Heater, (D) Reactor, (E) Filters, (F) Cooler. Right: Front view of the test bench showing: (A) Engine, (B) Power Supply, (C) Engine Gas Analyser, (D) Chiller, (E) Main Control Box.

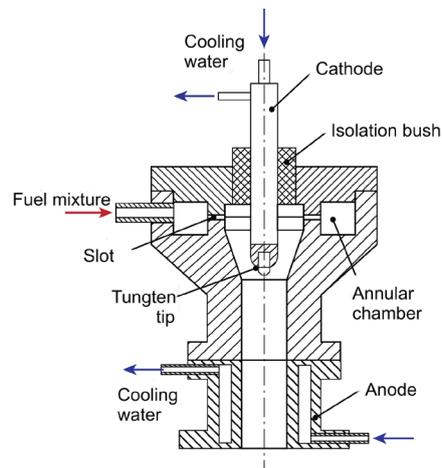


Figure 3. Discharge unit of the plasma converter.

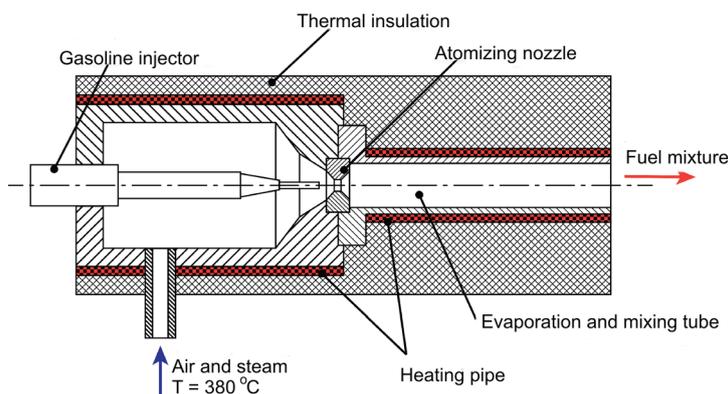


Figure 4. Schematic of the plasmatron fuel mixing and evaporation unit.

The evaporation of gasoline droplets was performed in the mixing tube located downstream of the pitchforking nozzle. This tube is an electrically heated section of a stainless steel tube with an internal diameter of 8 mm and a length of 260 mm. The steam generator consists of a hot electric boiler and a high-pressure superheater with a pressure range from 3.5 bar to 6 bar. An Omega 5400 mass flow controller and an ISMATEC REGLO-CPF flow pump control the mass flow rate of air and the gasoline used to produce the rich syngas in the plasma reformer, respectively. The experimental studies were carried out at a speed of 2700 rpm at stoichiometric air/fuel ration mixture ($\lambda = 1.0$). Plasma system operation parameter optimization was performed to obtain the maximum hydrogen content for both gasoline types (RON 91 and RON95), such as hydrogen yield, total gas flow rate, steam flow rate, and initial mixture composition dependences. The pressure in the boiler was fixed at 0.3 MPa, and the fuel flow rate was 4 g/min. The ignition advance (ignition timing) was at 15° . More than 500 runs with various electrical power loads were conducted. Engine rendering was in comparison to two types of fuel: a usual air-gasoline mixture and an air-gasoline mixture with syngas. During the experiments, the cooler for the plasma conversion products was given a new design due to the formation of a solid carbonic plug that made the cooler coils impermeable. Several unsuccessful attempts were made to dissolve the carbonic plug using various solvents such as acetone, dioxin, and gasoline. Therefore, a new design was made to increase and overhaul the life of the new cooler for the conversion products.

3. Results and Discussion

NO_x emission content and fuel consumption are influenced by blending gasoline fuel (RON91 or RON95) with ethanol (E5 and E10) and hydrous ethanol (HE5 and HE10) at different water concentrations (W.C. = 5%, 10%, 30% and 40%). Discussion in detailed is following for both cases of injecting and without injecting of the syngas to the engine. The reduction of NO_x emissions content due to using of hydrous ethanol (HE) and syngas can be attributed to decreased combustion and engine temperature by the effect of presence of water vapour in

the mixture, where lower combustion temperature yields lower generation of NO_x emissions. Slight increasing of fuel consumption due to using hydrous ethanol and syngas can be justified as part of combustion energy, which is consumed to vaporize the non-completely vaporized water in the fuel mixture. **Table 3** displays maximum NO_x emissions reduction (ppm) during the experiment at water concentration of 40% volume of hydrous ethanol.

3.1. NO_x Emissions: Gasoline, Anhydrous Ethanol and Hydrous Ethanol without Syngas

Figure 5 and **Figure 6** show NO_x emissions for gasoline RON91 and gasoline RON95, respectively, with blend conditions: E5 and HE5 (at water concentrations 5%, 10%, 30% and 40%) without injecting of syngas to the engine. NO_x emissions reduced significantly when using E5. Moreover, when adding HE5 with different water concentrations, NO_x emissions increased at the case of water concentration 5%, while, NO_x emissions decreased gradually with the increase of water concentration from 10% to 40% at the low-range and mid-range of load for both RON91 and RON95, where lowest NO_x emissions were found to be a water concentration of 40%. At the high-range load, lowest emissions content was at HE5 with a water concentration of 10%.

Figure 7 and **Figure 8** show NO_x emissions for emissions for gasoline RON91 and gasoline RON95, respectively, with blend conditions: E10 and HE10 (at water concentrations 5%, 10%, 30% and 40%) without injecting of syngas to the engine. NO_x emissions reduced significantly when using E10. Furthermore, when adding HE510 with different water concentrations, NO_x emissions increased at the case of water concentration 5%, while, NO_x emissions decreased gradually with the increase of water concentration from 10% to 40% at the low-range and mid-range of load for both RON91 and RON95, where lowest NO_x emissions were found to be a water concentration of 40%. At the high-range load, lowest emissions content was at HE10 with a water concentration of 30%.

Table 3. Maximum NO_x emissions reduction (ppm) for engine speed of 2700 RPM at maximum load of 10 kW for each fuel types of gasoline Ron 91 and 95 at water concentration of 40% volume of hydrous ethanol.

Blends	Fuel Types					
	Gasoline RON 91			Gasoline RON 95		
	Without syngas (ppm)	With syngas (ppm)	NO _x Reduction (%)	Without syngas (ppm)	With syngas (ppm)	NO _x Reduction (%)
E0	1460	1006	31	1330	1060	20
E0 + E	660	500	24	700	550	21
NO _x Reduction in (%)	54	50	-	47	48	-
E0	1460	1006	31	1330	1060	20
E0 + HE (WC = 40 %)	650	400	38	490	300	39
NO _x Reduction in (%)	55	60	-	63	72	-

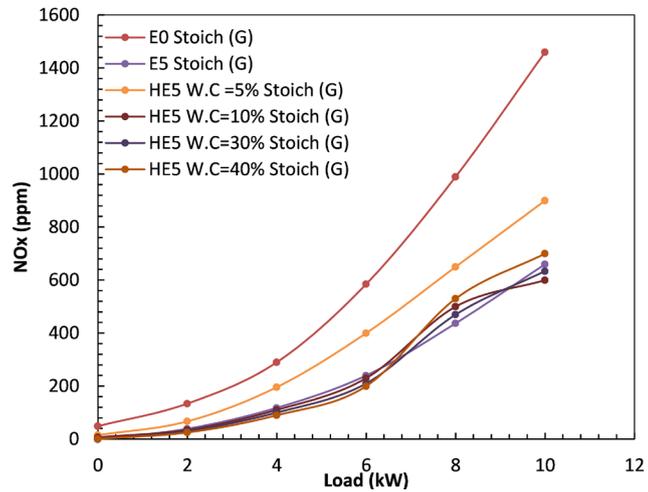


Figure 5. NOx emissions for E0-E5-HE5-Gasoline 91 octane number with different water concentrations at a stoichiometric mixture without syngas.

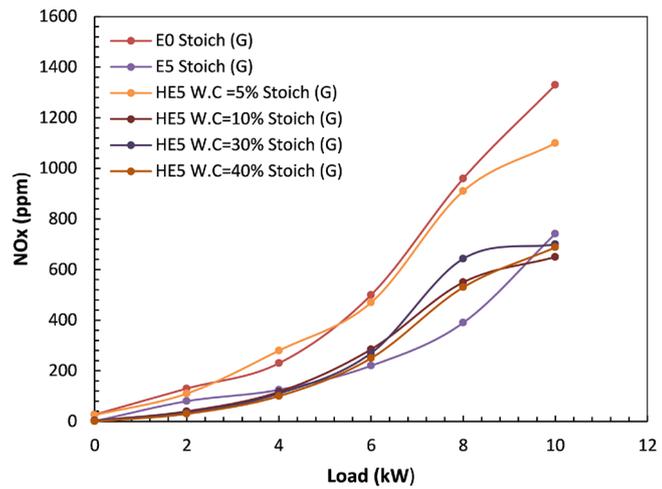


Figure 6. NOx emissions for E0-E5-HE5-Gasoline 95 octane number with different water concentrations at a stoichiometric mixture without syngas.

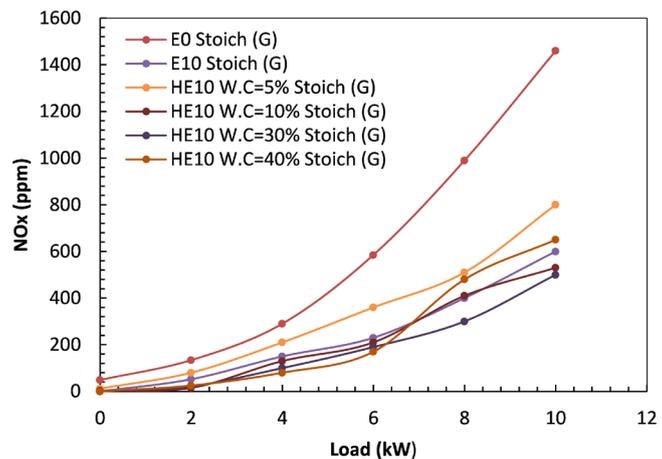


Figure 7. NOx emissions for E0-E10-HE10-Gasoline 91 octane number with different water concentrations at a stoichiometric mixture without syngas.

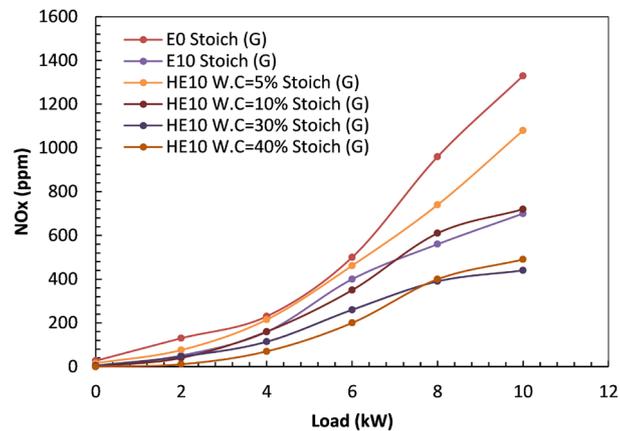


Figure 8. NOx emissions for E0-E10-HE10-Gasoline 95 octane number with different water concentrations at a stoichiometric mixture without syngas.

3.2. NOX Emissions: Gasoline, Anhydrous Ethanol and Hydrous Ethanol with Syngas

Effect of injecting the syngas with pure gasoline (E0) on emissions was demonstrated in a previous study, Al-Harbi *et al.* [14], where the NOx emissions were dramatically reduced. **Figure 9** and **Figure 10** show NOx emissions for gasoline RON91 and gasoline RON95, respectively, with blend conditions: E5 and HE5 (at water concentrations 5%, 10%, 30% and 40%) while the engine is injected with syngas at the same time. NOx emissions reduced significantly when using E5 along with adding syngas. Moreover, when adding HE5 with different water concentrations, NOx emissions increased at the case of water concentration 5%, while, NOx emissions decreased gradually with the increase of water concentration from 10% to 40% at the low-range and mid-range of load for both RON91 and RON95, where lowest NOx emissions were found to be a water concentration of 40%.

Figure 11 and **Figure 12** show NOx emissions for gasoline RON91 and gasoline RON95, respectively, with blend conditions: E10 and HE10 (at water concentrations 5%, 10%, 30% and 40%) while the engine is injected with syngas at the same time. NOx emissions reduced significantly when using E10 along with adding syngas. Moreover, when adding HE5 with different water concentrations, NOx emissions increased at the case of water concentration 5%, while, NOx emissions decreased gradually with the increase of water concentration from 10% to 40% at the low-range and mid-range of load for both RON91 and RON95, where lowest NOx emissions were found to be a water concentration of 40%.

3.3. Fuel Consumption: Gasoline, Anhydrous Ethanol and Hydrous Ethanol without Syngas

Figure 13 and **Figure 14** show the fuel consumption for gasoline RON91 and gasoline RON95, respectively, with blend conditions: E5 and HE5 (at water concentrations 5%, 10%, 30% and 40%) without syngas. For RON91, fuel consump-

tion decreases slightly when E5 is used low-range of load then increases in the mid-range and high-range of load. In addition, when using HE5 with different water concentrations, fuel consumption increases in general. For RON95 fuel consumption of E5 is, almost, the same as that of E0, where there is no significant change. Moreover, when using HE5 with different water concentrations, fuel consumption increases in general.

Figure 15 and **Figure 16** show the fuel consumption for gasoline RON91 and gasoline RON95, respectively, with blend conditions: E5 and HE5 (at water concentrations 5%, 10%, 30% and 40%) without syngas. When using E10, for both RON91 and RON95, the increase in fuel consumption grows as the load increases. Furthermore, when using HE10 with different water concentrations, fuel consumption increases in general for both RON91 and RON95 at all load ranges.

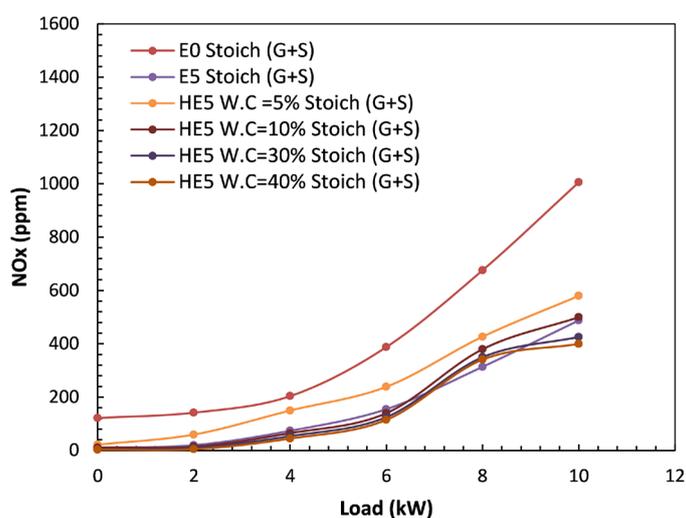


Figure 9. NO_x emissions for E0-E5-HE5-Gasoline 91 octane number with different water concentrations at a stoichiometric mixture with syngas.

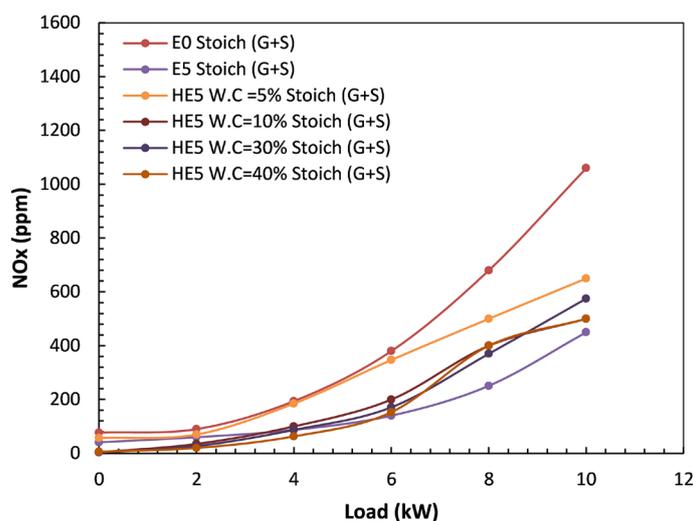


Figure 10. NO_x emissions for E0-E5-HE5-Gasoline 95 octane number with different water concentrations at a stoichiometric mixture with syngas.

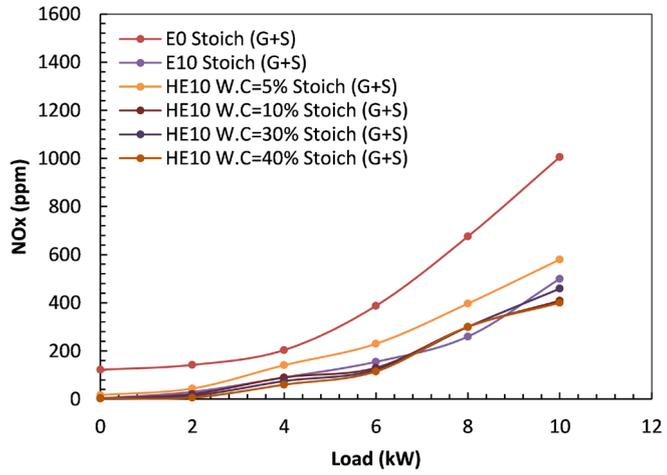


Figure 11. NOx emissions for E0-E10-HE10-Gasoline 91 octane number with different water concentrations at a stoichiometric mixture with syngas.

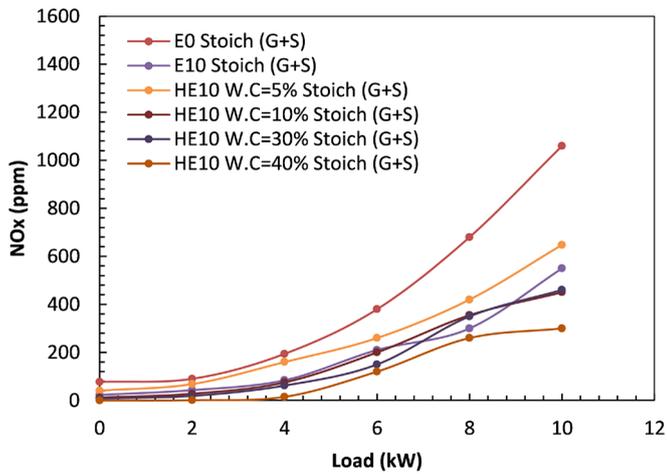


Figure 12. NOx emissions for E0-E10-HE10-Gasoline 95 octane number with different water concentrations at a stoichiometric mixture with syngas.

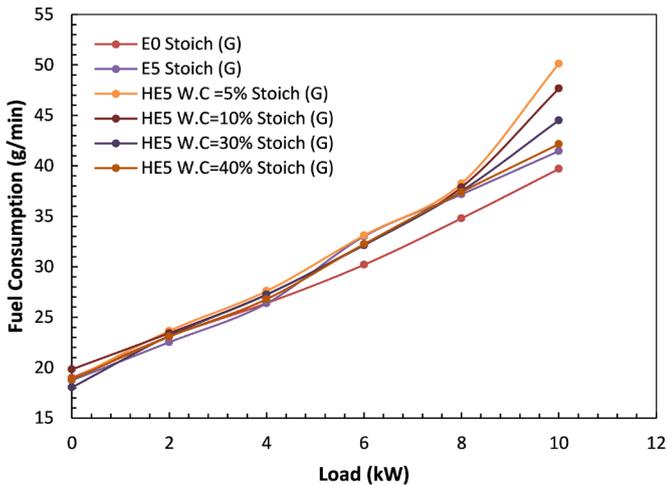


Figure 13. Fuel consumption of E0-E5-HE5-Gasoline 91 octane number with different water concentrations at a stoichiometric mixture without syngas.

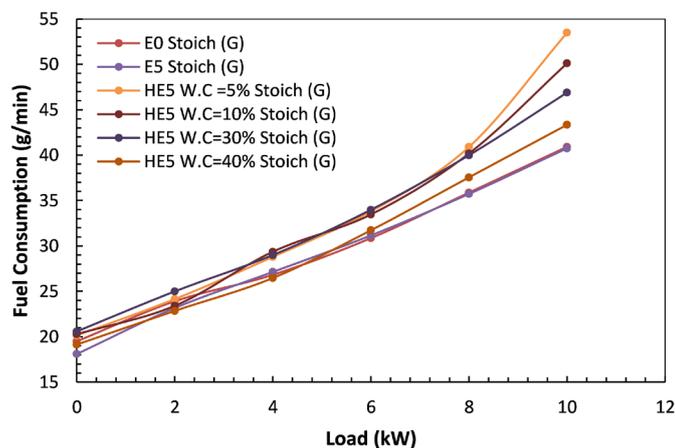


Figure 14. Fuel consumption of E0-E5-HE5-Gasoline 95 octane number with different water concentrations at a stoichiometric mixture without syngas.

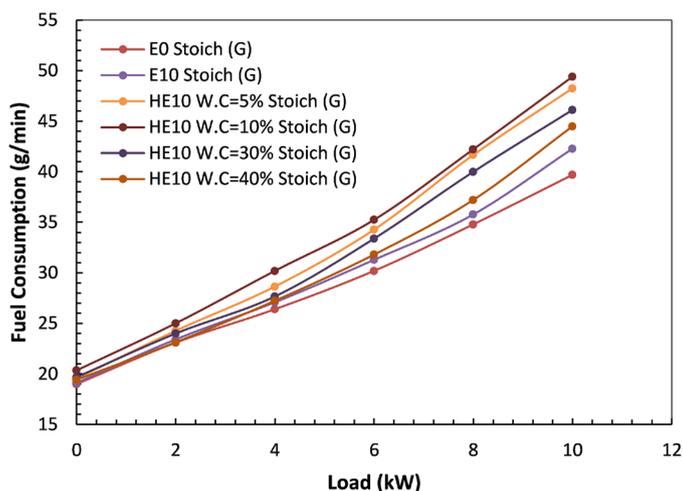


Figure 15. Fuel consumption of E0-E10-HE10-Gasoline 91 octane number with different water concentrations at a stoichiometric mixture without syngas.

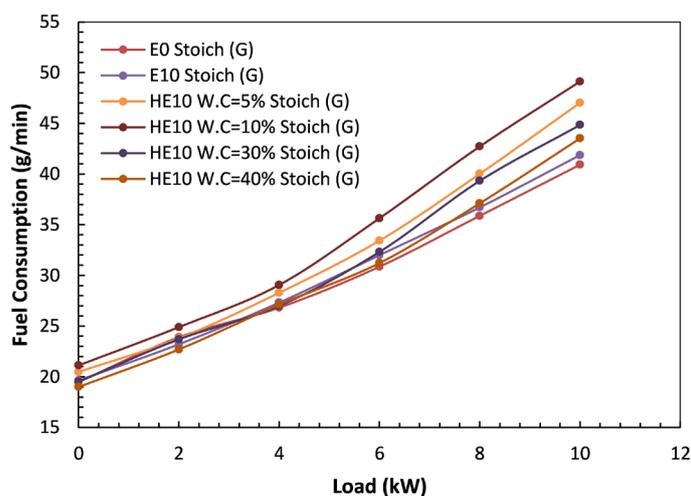


Figure 16. Fuel consumption of E0-E10-HE10-Gasoline 95 octane number with different water concentrations at a stoichiometric mixture without syngas.

3.4. Fuel Consumption: Gasoline, Anhydrous Ethanol and Hydrous Ethanol with Syngas

Figure 17 and **Figure 18** show the fuel consumption for gasoline RON91 and gasoline RON95, respectively, with blend conditions: E5 and HE5 (at water concentrations 5%, 10%, 30% and 40%) while the engine is injected with syngas. For RON91, when using E5 with syngas, fuel consumption increases. Moreover, HE5 with different water concentrations with syngas decreased the fuel consumption at low-range load, while it is increased, in general, at the mid and high-range of load. For RON95, using E5 with syngas decreases fuel consumption in general. As well as, fuel consumption is decreased, generally, for HE5 at different water concentrations with syngas.

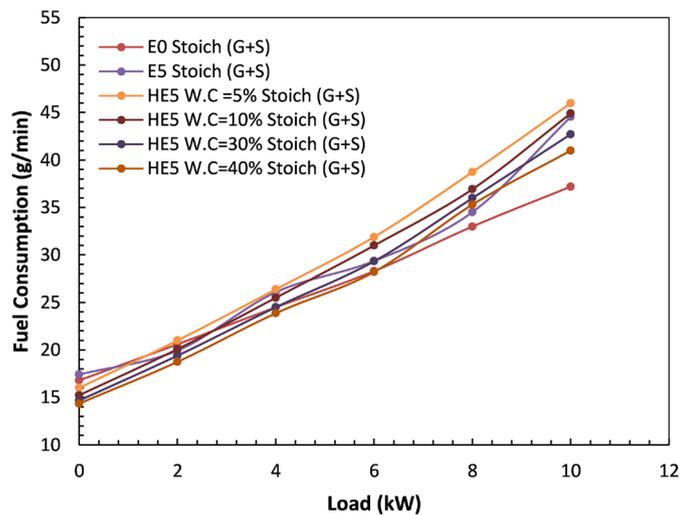


Figure 17. Fuel consumption of E0-E5-HE5-Gasoline 91 octane number with different water concentrations at a stoichiometric mixture with syngas.

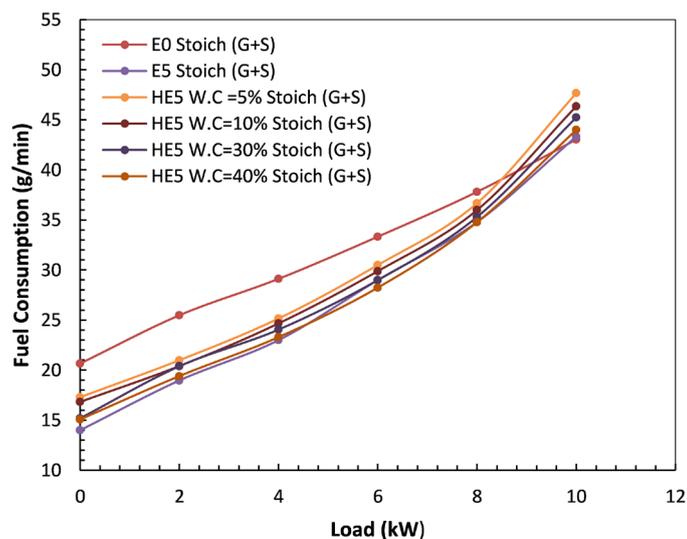


Figure 18. Fuel consumption of E0-E5-HE5-Gasoline 95 octane number with different water concentrations at a stoichiometric mixture with syngas.

Figure 19 and **Figure 20** show the fuel consumption for gasoline RON91 and gasoline RON95, respectively, with blend conditions: E5 and HE5 (at water concentrations 5%, 10%, 30% and 40%) while the engine is injected with syngas. For RON91, when using E10 with syngas, the fuel consumption decreases at low and mid-range of load, then increases for a higher load. Additionally, HE10 with different water concentrations with syngas decreased the fuel consumption at low-range load, while it is increased, in general, at the mid and high-range of load. For RON95, using E10 with syngas decreases fuel consumption in general. As well as, fuel consumption is decreased, generally, for HE10 at different water concentrations along with syngas.

4. Conclusions

This study investigates the effect of 5 and 10 vol.% anhydrous ethanol-gasoline

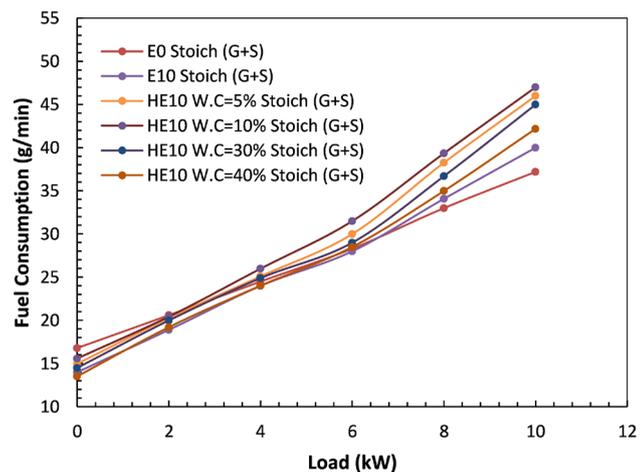


Figure 19. Fuel consumption of E0-E5-HE5-Gasoline 91 octane number with different water concentrations at a stoichiometric mixture with syngas.

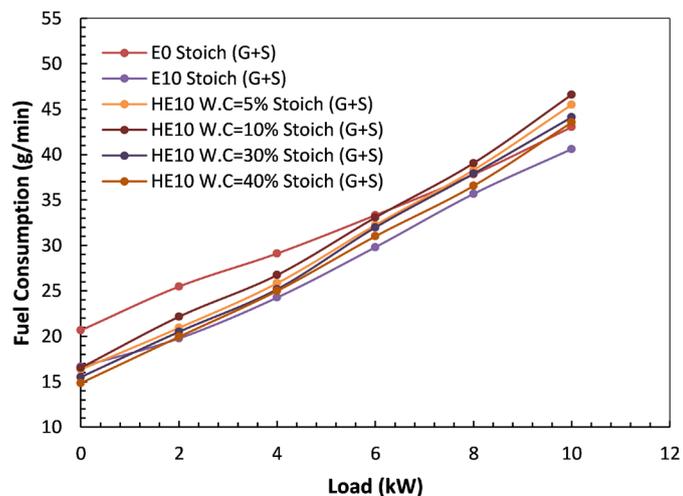


Figure 20. Fuel consumption of E0-E5-HE5-Gasoline 95 octane number with different water concentrations at a stoichiometric mixture with syngas.

blended fuel (E5 and E10) and hydrous ethanol-gasoline (HE5 and HE10 with water concentrations = 5%, 10%, 30% and 40%) for two types of fuel: RON91 and RON95 on the emissions content and performance of SI engine operated at a stoichiometric mixture regime. The experimental results demonstrated a significant total reduction in NO_x emissions and a slight change in fuel consumption—including fuel supplied to the plasma-assisted converter—when mixing gasoline (RON 91 or RON 95), ethanol (E5 and E10) and hydrous ethanol (HE5 and HE10) with syngas. The main finding regarding the plasma system and the engine operations can be summarized as follow:

1) Mixing gasoline, anhydrous ethanol and hydrous ethanol with and without syngas while supplying the engine had a positive effect on emissions content, where No_x was dramatically reduced and fuel consumption was slightly increased.

2) Blending gasoline (RON95 or RON91) with 5% ethanol (E5) and 10% ethanol (E10) resulted in a considerable reduction in No_x content, where (E10) gave more reduction than (E5).

3) Blending gasoline (RON95 or RON91) with hydrous ethanol (HE5, HE10) at water concentrations of 5%, 10%, 30% and 40% resulted in a considerable reduction in No_x content.

4) As the water concentration increased in the hydrous ethanol-gasoline blend, No_x content decreased at the stoichiometric regimes of the engine for both cases of with and without syngas.

5) As the water concentration increased in the hydrous ethanol-gasoline blend, fuel consumption decreased, in general, at the stoichiometric regimes of the engine for both cases of with and without syngas.

6) Maximum No_x emissions reduction for blends of gasoline + ethanol + hydrous ethanol was found to be at water concentration 40 %, for both fuel types (RON91 or RON95) and both ethanol volume percentage (5% and 10%).

7) Water concentration 5% has a negative effect on No_x emissions content and fuel consumption for both HE5 and HE10 compared to those for E5 and E10, while they (No_x and fuel consumption) trend again, positively, as the water concentration is increased (10%, 30% and 40%) for both gasoline types (RON91 or RON95) with and without syngas.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Gupta, P., Sae-wang, V., Kanbua, P. and Laoonual, Y. (2011) Impact of Water Contents Blended with Ethanol on SI Engine Performance and Emissions. *Journal of Research and Applications in Mechanical Engineering*, **1**, 7-11.
<https://www.tci-thaijo.org/index.php/jrame/article/view/150231>
- [2] Truyen, P.H., Tuyen, P.H., Tuan, P.M. and Tuan, L.A. (2012) Influence of E10, E15 and E20 Fuels on Performance and Emissions of In-Use Gasoline Passenger Cars. *ASEAN Engineering Journal Part C*, **4**, 33-40.
<http://seed-net.org/wp-content/uploads/2015/12/INFLUENCE-OF-E10-E15-AND-E20-FUELS-ON-PERFORMANCE-AND-EMISSIONS-OF-IN-USE-GASOLINE-PASSENGER-CARS.pdf>
- [3] Masum, B.M., Masjuki, H.H., Kalam, M.A., Fattah, I.R., Palash, S.M. and Abedin, M.J. (2013) Effect of Ethanol-Gasoline Blend on NOx Emission in SI Engine. *Renewable and Sustainable Energy Reviews*, **24**, 209-222.
<https://doi.org/10.1016/j.rser.2013.03.046>
- [4] Pal, A. (2014) Blending of Ethanol in Gasoline: Impact on SI Engine Performance and Emissions. *International Journal of Thermal Technologies*, **4**, 1-5.
<https://inpressco.com/wp-content/uploads/2014/03/Paper11-52.pdf>
<https://doi.org/10.14741/ijtt/mar.2014.01>
- [5] Volpato Filho, O. (2008) Gasoline C Made with Hydrous Ethanol. *XVI SIMEA Simpósio Internacional de Engenharia Automotiva*, São Paulo, 17 September 2008.
https://www.researchgate.net/publication/309564235_GASOLINE_C_MADE_WITH_HYDROUS_ETHANOL
- [6] Munsin, R., Laoonual, Y., Jugjai, S. and Imai, Y. (2013) An Experimental Study on Performance and Emissions of a Small SI Engine Generator Set Fuelled by Hydrous Ethanol with High Water Contents up to 40%. *Fuel*, **106**, 586-592.
<https://www.sciencedirect.com/science/article/pii/S0016236112011039>
<https://doi.org/10.1016/j.fuel.2012.12.079>
- [7] El-Faroug, M., Yan, F., Luo, M. and Fifi Turkson, R. (2016) Spark Ignition Engine Combustion, Performance and Emission Products from Hydrous Ethanol and Its Blends with Gasoline. *Energies*, **9**, 984. <https://doi.org/10.3390/en9120984>
- [8] De Melo, T.C.C., Machado, G.B., Belchior, C.R., Colaço, M.J., Barros, J.E., de Oliveira, E.J. and de Oliveira, D.G. (2012) Hydrous Ethanol-Gasoline Blends-Combustion and Emission Investigations on a Flex-Fuel Engine. *Fuel*, **97**, 796-804.
<https://doi.org/10.1016/j.fuel.2012.03.018>
- [9] Huang, D.Y., Lin, B.F. and Jang, J.H. (2015) Emission of Internal Combustion with Low Temperature Plasma Reformer. *Energy Procedia*, **75**, 3036-3041.
<https://doi.org/10.1016/j.egypro.2015.07.618>
- [10] Opaliński, M., Rek, P. and Skrobek, W. (2014) Reforming Gaseous Fuels as a Method of Engine Combustion Process Improvement.
http://sdpg.pg.gda.pl/pij/wp-content/blogs.dir/133/files/2014/12/01_2014_22-opalinski_mar.pdf
- [11] Lee, J. and Castaldi, M.J. (2010) A Study on Performance and Emissions of a 4-Stroke IC Engine Operated on Landfill Gas with Syngas Addition. In: *18th Annual North American Waste-to-Energy Conference*, American Society of Mechanical Engineers Digital Collection, Orlando, 11-13 May 2010, 61-67.
<https://doi.org/10.1115/NAWTEC18-3565>
- [12] Green Jr., J.B., Domingo, N., Storey, J.M.E., Wagner, R.M., Armfield, J.S., Bromberg, L., Alexeev, N., *et al.* (2000) Experimental Evaluation of SI Engine Operation

Supplemented by Hydrogen Rich Gas from a Compact Plasma Boosted Reformer. *SAE (Society of Automotive Engineers) Transactions*, **109**, 1875-1882.

https://www.jstor.org/stable/44634357?seq=1#page_scan_tab_contents

<https://doi.org/10.4271/2000-01-2206>

- [13] Bromberg, L., Cohn, D.R., Rabinovich, A. and Heywood, J. (2001) Emissions Reductions Using Hydrogen from Plasmatron Fuel Converters. *International Journal of Hydrogen Energy*, **26**, 1115-1121.
[https://doi.org/10.1016/S0360-3199\(01\)00049-0](https://doi.org/10.1016/S0360-3199(01)00049-0)
- [14] Al-Harbi, A.A., Alenazey, F.S., Migoun, A.N., Dmitrenko, Y.M. and Zhdanok, S.A. (2016) Reducing Pollution Emissions by Adding Syngas Generated by a Plasma-Assisted Gasoline Converter in the Intake Manifold of a Gasoline Engine with Electronic Fuel Injection System. *Heat Transfer Research*, **47**, 1073-1082.
<http://www.dl.begellhouse.com/journals/46784ef93dddf27,4d60ef1c722bb89b,1cd68edd53d20305.html?sgstd=1>
<https://doi.org/10.1615/HeatTransRes.2016016579>
- [15] Alenazey, F.S., Al-Harbi, A.A., Chernukho, A.P., Dmitrenko, Y.M., Migoun, A.N. and Zhdanok, S.A. (2016) Syngas Production from Propane—Butane Mixtures Using a High-Voltage Atmospheric Pressure Discharge Plasma. *Heat Transfer Research*, **47**, 1057-1072. <https://doi.org/10.1615/HeatTransRes.2016016411>
<http://www.dl.begellhouse.com/journals/46784ef93dddf27,4d60ef1c722bb89b,184c68f36e91f90d.html>
- [16] Hoang, A.T., Tran, Q.V., Al-Tawaha, A.R.M.S., Pham, V.V. and Nguyen, X.P. (2019) Comparative Analysis on Performance and Emission Characteristics of an In-Vietnam Popular 4-Stroke Motorcycle Engine Running on Biogasoline and Mineral Gasoline. *Renewable Energy Focus*, **28**, 47-55.
<https://www.sciencedirect.com/science/article/pii/S1755008418301236>
<https://doi.org/10.1016/j.ref.2018.11.001>
- [17] Deng, X., Chen, Z., Wang, X., Zhen, H. and Xie, R. (2018) Exhaust Noise, Performance and Emission Characteristics of Spark Ignition Engine Fuelled with Pure Gasoline and Hydrous Ethanol Gasoline Blends. *Case Studies in Thermal Engineering*, **12**, 55-63. <https://doi.org/10.1016/j.csite.2018.02.004>
<https://www.sciencedirect.com/science/article/pii/S2214157X17302708>
- [18] Binjuwair, S. and Alkudsi, A. (2016) The Effects of Varying Spark Timing on the Performance and Emission Characteristics of a Gasoline Engine: A Study on Saudi Arabian RON91 and RON95. *Fuel*, **180**, 558-564.
<https://doi.org/10.1016/j.fuel.2016.04.071>