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Experimental Investigation of Performance and Emissions of Spark Ignition Engine Fueled with Blends of HHO Gas with Gasoline and CNG

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Abstract

Fossil fuels are widely used all over the world to power the motor vehicles. Due to superfluous consumption of these fuels, their reservoirs are depleting continuously. The huge demand of crude oil has caused the unprecedented price rise, environmental pollution, and global warming which directly affects the living beings as well as the surroundings in which they are surviving. Alternative fuels can suffice the demand with less adverse effects on the environment through the means of different sustainable technologies. Hydroxy gas (HHO) can be effective source of energy to combat these prominent issues. This work covers the experimental analysis of different parameters related to advantages and disadvantages of using HHO as a blend with gasoline and CNG fuel mixture. The analysis is based on engine performance and emissions. The experiments were performed on engine model fueled with a mixture of fuel and HHO gas. HHO was used as a fuel supplement. A compact HHO gas kit was installed in the engine compartment. A 219cc, four stroke, single cylinder spark ignition engine was used. No modifications were required in the engine design as HHO was used as a fuel supplement. The production of HHO was accomplished by the electrolysis of double distilled water in the presence of KOH(aq.) as an electrolyte. Products of water electrolysis consisted of H_2 and O_2 in the ratio of 2:1 by volumetric basis. Performance enhancement in overall engine characteristics such as brake power, specific fuel consumption, and overall efficiency was observed. Furthermore, a significant reduction in the emissions of unburnt hydrocarbons, carbon monoxide, and carbon dioxide was noticed. However, due to lean air-fuel mixture and tremendous peak combustion temperature the amount of NO_x was increased.

Keywords: *hydroxy gas, HHO, fuel blend, engine performance, exhaust emissions*

1. Introduction

The internal combustion engine (ICE) is defined as the heat engine operating in a cycle that develops mechanical energy from a supply of heat energy. Firstly, it converts the chemical energy of the fuel into heat energy and later this heat energy transforms into mechanical energy. ICEs have two main types: reciprocating and rotary engines, but mostly used type is the reciprocating internal combustion engine. In reciprocating ICEs piston moves linearly (have to- and fro- motion) in engine cylinder and transmit power via connecting rod to the engine crankshaft. This reciprocating engine with one or more cylinders operates on either four-stroke or two-stroke cycle. In a four-stroke engine, piston has four movements over two revolutions of crankshaft for each cycle and in a two-stroke engine piston has four movements over one revolution of crankshaft for each cycle [1]. Various improvements in the ICEs have been done in the past two decades in terms of the size reduction and improvement in the overall efficiency. In 1885 Gottlieb Daimler developed a modern gasoline engine prototype by mixing of fuel into air ignited by spark plug. Presently, due to increasing demand of motor vehicles spark ignition engines are used in automobile industry as well as for other applications, e.g., in motorcycles, cars, in lawn mowers in home, in portable power generators and chain saws. During its operation SI engine uses

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air and fuel mixture, compresses it, and ignites it by using spark plug to produce combustible products of high pressure. These high pressure products produce some amount of work during expansion. However, the combustible products of petroleum produce large amount of pollutant emissions. The petroleum based automobiles produce HC and NO_x as well as CO emissions [2]–[5]. This has led the researchers' to focus on using alternative fuels which are environmentally friendly and also to enhance engine performance and reduce pollutant emissions [6]–[8].

Due to depletion of fossil fuels at an alarming rate alternative fuels have received great attention of researchers for use in internal combustion engines. As global concerns have increased about global warming and climate change linked with fossil fuel based emissions. The limited reserves of fossil fuels have created a need for fossil fuels. In improving fuel economy and reducing exhaust emissions a lot of research is used. Hydrogen is an excellent alternative and renewable energy source to meet the environmental control of exhaust emissions [9]. Therefore, hydrogen and natural gas can be used as carbon free alternative fuels in ICEs to decrease greenhouse gases and also compensate the consumption of conventional liquid fuels. The use of these two fuels in ICEs also causes some problems, e.g., the utilization of hydrogen leads to pre-ignition and blowback due to low ignition energy of hydrogen. The utilization of hydrogen additionally creates low power yield and to constrain the working load range because of low density of hydrogen, keeping in mind the end goal to diminish the engine volumetric efficiency [10]. The utilization of hydrogen only as a fuel entails the problem of modification in the engine and also abnormal combustion.

From last many years' natural gas (NG) is being used in internal combustion engines instead of conventional gasoline. It is used as a compressed natural gas (CNG) or liquefied natural gas (LNG). Worldwide different sources for natural gas have been discovered. It is cleaner fuel gas with high hydrogen to carbon ratio. The use of natural gas produces some problems like lower burning speed, poor lean burning quality, higher ignition energy, higher quenching distance, and lower calorific value [11]. Due to these problems and long combustion duration natural gas engine becomes less efficient [12]. By using substantial quantity of hydrogen, lean operation of spark ignition engines could be increased [13]. Hydrogen can be used as a supplementary fuel in SI engines due to its good burning properties. The hydrogen and oxygen produced by water electrolysis increases combustion period of hydrocarbon fueled internal combustion engines [14]. Properties of H_2, CNG, and petrol (gasoline) are given in Table 1.

Table 1: Comparison of properties of hydrogen, CNG, and Petrol

Properties	H_2	CNG	Petrol
Relative air to fuel ratio	34.3	17.2	14.7
Density (kg/m^3)	0.085	0.748	719.7
Octane number	<130	120	88-100
Lower calorific value (MJ/kg)	120	50	120
Auto-ignition temperature (°C)	536	600	501-744
Laminar burning velocity (cm/s)	265-325	37-45	30-42
Flame quenching distance (mm)	0.64	2.03	2
Flammability in air (% vol)	4-75	5.3-15	1-7.8

Irrespective of the CNG's advantages there are some drawbacks due to its distinct physiochemical properties and combustive properties such as lower burning speed, lower calorific value, higher ignition energy, narrow flammability range, and higher quenching distance. All these properties can be improved by using hydrogen as a supplementary fuel with CNG [15]. As the percentage of hydrogen increases in fuel it improves combustion thermal efficiency. It also reduces emissions of CO_2, HC, and CO due to lack of carbon content in fuel composition as compared to pure CNG.

2. Experimental approach

Many researchers have performed experiments on internal combustion engines by using different blends and their ideas are given below. Falahat et al. [16] investigated the performance of a 197CC, 4-stroke, single cylinder air cooled SI engine operated with gasoline and HHO gas. They obtained break thermal efficiency of 23%. They observed that torque increased by 12.6% with addition of HHO gas. At 2 liter per minute flow rate specific fuel consumption decreased by 16.9%. CO and HC emissions also decreased by HHO gas addition. Experiments performed by El-Kassaby et al. [17] on Skoda Felicia 1.3 GLXi 1.3L (1289CC) in-line 4-cylinder engine with hydroxy gas. Their results showed that thermal efficiency increased by 10%, fuel consumption decreased by 34% and CO, HC, and NO_x emissions decreased by 18%, 14%, and 15%, respectively. They found that KOH with 6 g/L concentration was the best catalyst for electrolysis. Experimental study on combustion emissions of G200 (197CC single cylinder engine) by using HHO gas, air and gasoline mixture was carried out by Musmar and Al-Rousan [18]. They reported that using HHO gas with air/fuel mixture gives reduction in fuel consumption. In their results, concentration of CO and NO_x decreased by 20% and 54%, respectively. Brayek et al. [19] performed experiments on Honda GX100 (98CC, single cylinder, 4-stroke, air cooled SI engine. The engine was operated at various loads (0, 0.3, 0.75, 1.2, and 1.5kW). They investigated results by using 5 L/min HHO gas as supplementary fuel and compared results with pure gasoline. Their results showed a decrease in brake specific fuel consumption (BSFC), HC, CO, CO_2, and NO_x emissions by 7.8%, 18%, 31.8%, 30%, and 26%, respectively. Investigation carried out by Iliev [20] on four stroke single cylinder S.I engine by using hydrogen and oxygen mixture without modification in engine. He reported an increase in engine performance in terms of mechanical efficiency, break thermal efficiency, volumetric efficiency and indicated thermal efficiency. Also, a reduction of 6.7& in HC emissions was reported.

Aminy et al. [21] performed tests on Z24 (2389CC, four cylinders) spark ignition engine by adding HHO gas to the fuel. They showed that addition of HHO gas increased both torque and power by 5.5% at full load condition. CO and HC emissions reduced about 21% and 19%, respectively. Hora and Agarwal [15] conducted experiments on a single cylinder SI 948CC engine by using different compositions of H_2 and CNG mixture. They noticed that the overall engine performance improved by using hydrogen and CNG mixture. Also, they found that the best composition mixture was 30HCNG (30% H_2 by volume and 70% CNG by volume). This composition showed benefits of optimum engine performance and emissions between the tested HCNG mixtures. Their results showed improvement in break thermal efficiency by addition of hydrogen with CNG. Emissions also improved with addition of hydrogen with CNG owing to lesser quenching gap of hydrogen and lesser hydrogen to carbon ratio of CNG. An experimental study on single cylinder 948CC prototype spark ignition engine after modifications in engine was performed by Verma et al. [22]. Experiments were conducted for fuels with various H/C ratios and H/C ratio varied from 4 to infinity at constant 1500 rpm. They concluded that brake thermal efficiency was maximum for test fuel with H/C: 4.5/1. Higher NO_x emissions were noticed with H/C: 4.22/1 and NO_x value was highest with H/C: 4.5/1 at full load.

Yue [23] performed experiments on ZS1100M (903CC, 4-stroke, air cooled, single cylinder) spark ignited CNG engine using low heat value gas (mixture of NG 60% to 80% by volume and nitrogen 20% to 40% by volume) mixed with H_2 in a modified engine. They reported that with increasing N_2, emissions of CO and NO_x decreased but HC emissions increased. They also noticed that engine power decreased with increasing amount of N_2. Ma et al. [24] performed experiments on in-line six cylinders spark ignition engine at different operating conditions such as spark timing, excess air ratio, and manifold pressure in a lean burn NG engine with H_2 addition. They reported that engine efficiency increased with 55% hydrogen addition by optimizing spark timing. Experimental investigation on emissions and performance of 6-cylinder engine with compression ratio of 10.5, by using H_2 and NG mixture was performed by Akansu et al. [25] Their results showed decrease in NO_x emissions by 80% with retarded spark timing for hydrogen and CNG mixture. Experimental study carried out by [26] on 1796CC, 4-stroke, 4-cylinder SI engine with compression ratio of 10:1 by using H_2 in methane (0%, 10%, 20% and 30% by volume) by changing equivalence ratio from 0.6 to 1.2 at 2000 rpm and at constant load condition. They found that for lean mixture (equivalence ratio less than 0.75) HC, CO, and CO_2 emissions decreased and brake thermal efficiency increased by increasing H_2.

From the above cited literature, it can be observed that the addition of hydrogen to the fuel in ICEs has beneficial outcomes as it increases engine performance and decreases harmful emissions. Therefore, further tests need to be performed to find the optimum ratio of hydrogen with each fuel that can be used in ICEs. This work is an attempt to continue the knowledge in this field as it may help the engineers to design an engine that can operate on hydrogen-blended fuel in order to protect the environment. The following section briefly explains the experimental setup and methodology used, followed by results and discussion. Conclusions are presented at the end.

3. Experimental Setup and Methodology

This section explains the experimental setup and the methodology used to record and analyze the results.

3.1 Experimental Setup

Fig. 1 shows the experimental setup used. The specifications of the engine are given in Table 2. Experimental procedure to is summarized in Fig. 2.

Fig. 1. Engine model setup

Table 2. Engine specifications

No of strokes	4
No of cylinders	1
Cooling system	Water cooled
Displacement	219cc
Bore	67mm
Stroke	62mm
Compression Ratio	10.5
Max. Power	3.51 HP@1800 rpm
Max. Torque	10.873 lb.ft@1600 rpm

3.2 HHO Production Unit

Presence of oxygen makes HHO more combustible than purified H_2 gas. HHO gas production cell was built with the help of a battery with 12V DC Power Supply. An external battery which was already integrated to the vehicle was used to supply 12V direct current. The mixture of an electrolyte and water that constituted an electrolytic solution was poured in to the HHO cell storage tank. Depending upon better chemical performance of electrolytes, KOH was used. Potentiometer divider was used to control 24V from step down transformer for varying different resistances and thus voltages as well. As per demand, the HHO was allowed to enter into a carburetor. The amount of hydroxy gas (HHO) produced was directly proportional to the amount of applied voltage or potential difference. It should be noted that purified and double distilled water was required for the production of hydroxy gas.

3.3 Specifications of HHO dry cell

In this study HHO dry cell with following specifications was used:

- 4x4 inches/9 plates/8 cells
- 12V DC to 24V DC
- Generation Capacity: approx. 1.5 LPM (liters every minutes) @ 15A (with 12V DC) Maximum Capacity: 3 LPM @ 35A (with all accessories)
- Simple mounting plates
- No overheating and no spilling (sealed shut framework)
- shaded wing nuts
- high tough dark end plates
- 10 EPDM Flat Gaskets
- 9 plates (materials as picked)
- 2 point spouts (3/8, 90^o)
- 4 stainless steel nuts and bolts, 10 stainless steel washers

4. Results and Discussion

Experiments were conducted on 4-stroke, single cylinder, 219cc, water cooled spark ignition engine in automotive research center at University of Engineering and Technology (UET) Lahore, to study the effect of HHO gas addition in CNG. Effect of HHO gas and CNG mixture was experimentally analyzed at varying engine speed. The rate of production of HHO was set at 2 standard cubic feet per hour (SCFH). Experimental evaluation of performance and emission characteristics was performed. The results are given in the following sub-sections.

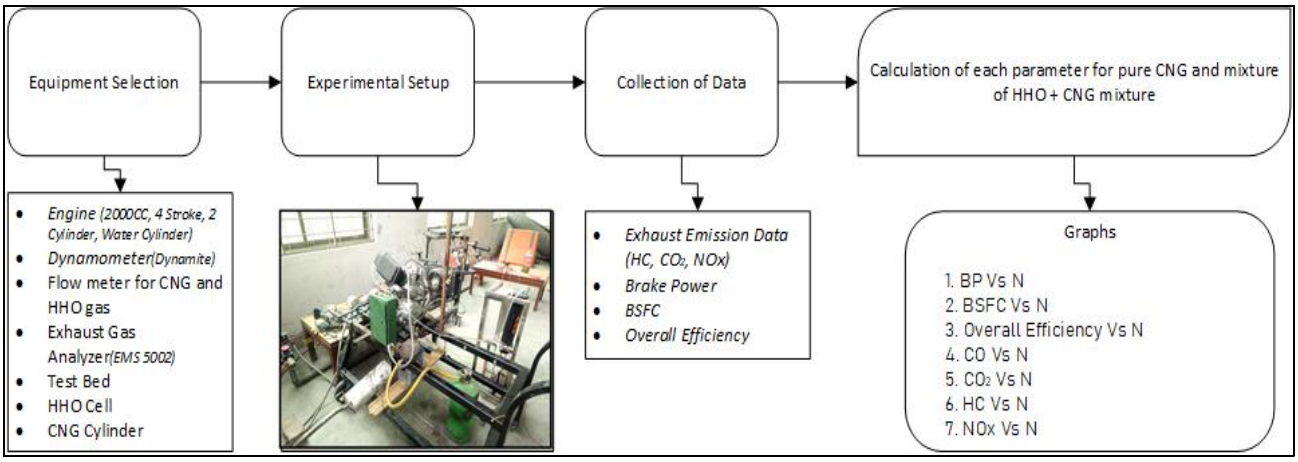

Fig. 2. **Schematic sketch of Experimental Setup**

4.1 Engine Performance characteristics

4.1.1 Brake Power

Brake power is the power available at engine crankshaft to do external work and is expressed as:

$$BHP = T\frac{N}{5252} \quad (1)$$

where BHP is the brake horsepower (HP), T is the torque (ft-lb), and N is the revolution per minute.

Fig. 3 illustrates the comparison of brake horsepower for different fuels: gasoline, gasoline+ HHO mixture, CNG, and CNG + HHO mixture. It is observed from figure that there is direct connection between engine BHP and rpm. By increasing rpm of an engine brake horsepower also increases until a maximum is reached. Further increase in rpm decreases BHP. It can be observed that BHP for blend of gasoline and HHO is slightly greater than the gasoline alone. The difference is more observable at higher rpm rather than at low rpm. The mixture resulted in producing higher BHP as compared to CNG or gasoline alone. It was observed that a maximum of 3.1% increase in brake horsepower was achieved with the mixture of CNG + HHO instead of using CNG alone. Compared to gasoline, 17.99% decrease in brake horsepower occurred when CNG is used in gasoline engine. When CNG and HHO gas mixture is used in gasoline engine there is 15.6% decrease in brake horsepower as compared to gasoline alone. Gasoline + HHO mixture produces highest power while the CNG produced the least power.

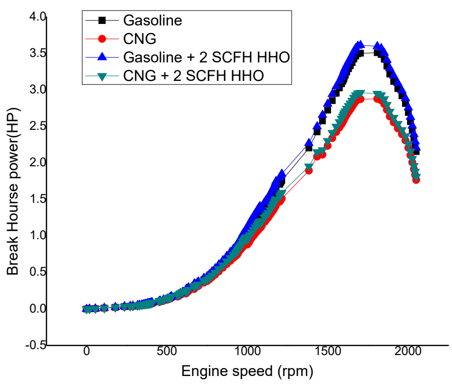

Fig. 3. BHP vs engine speed for gasoline, CNG, gasoline + HHO, and CNG + HHO mixtures

4.1.2 Specific Fuel Consumption

Specific fuel consumption (SFC) is the mass stream rate of fuel required to deliver a unit measure of energy yield. It shows how effectively an engine is utilizing the fuel provided to deliver the work. It is measured in kg/kWh. Fig. 6 compares the results of specific fuel consumption for four fuels: gasoline, gasoline+ HHO mixture, CNG, and CNG + HHO mixture. It is observed that inverse relation occurs between engine speed and specific fuel consumption. By increasing rpm of an engine SFC decreases until a minimum is reached and then increases. Specific fuel consumption for gasoline and HHO gas mixture is lower than the gasoline alone. Hence blend of gasoline and HHO gas reduced the SFC. A maximum decrease of 23.25% in SFC was observed when gasoline and HHO gas mixture was used in gasoline engine. A maximum decrease of 22.9% in SFC was observed with mixture of CNG and HHO as compared to CNG alone. CNG + HHO gas mixture gave lowest value of SFC of 0.25 kg/kwh while gasoline + HHO gas mixture gave 0.3 kg / kWh. Blend of CNG + HHO gas is superior in SFC perspective than the blend of gasoline + HHO gas

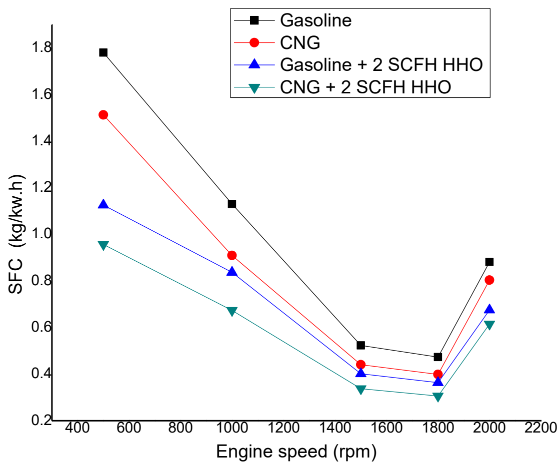

Fig. 4. SFC vs engine speed for gasoline, CNG, gasoline + HHO, and CNG + HHO

4.1.3 Overall efficiency

Overall efficiency (η) of an engine is defined as the ratio of the final output mechanical energy to the input energy of fuel. It is expressed as:

$$\eta = \text{Energy output / energy input} \quad (2)$$

The comparison of overall efficiency for the fuels tested in this study is presented in Fig. 14. It is observed that the trend of the overall efficiency is similar to the trend of BHP in Fig. 3. Increasing engine speed increased overall efficiency for all the fuels until a maximum at 1800 rpm after which a decrease was observed. The mixture of CNG + HHO showed best results with highest overall efficiency, whereas gasoline alone showed the worst results in terms of overall efficiency. An increase of 68% in overall efficiency was observed with gasoline + HHO mixture as compared to gasoline alone. CNG + HHO gas mixture produced maximum overall efficiency of 30% while gasoline + HHO gas mixture produced 28%. Interestingly, 6.06% increase in overall efficiency was observed when CNG was used instead of gasoline.

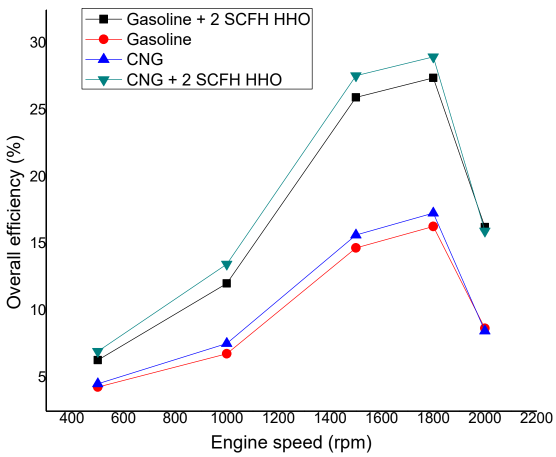

Fig. 5. Overall efficiency vs engine speed for gasoline, CNG, gasoline + HHO, and CNG + HHO

4.2 Emission characteristics

4.2.1 Unburnt hydrocarbon (HC) emission

Fig. 6 shows the unburnt hydrocarbon emissions along engine speed for the fuels analyzed in this work. Gasoline produces the most HC emission at all rpm. Addition of HHO to gasoline decreases HC emissions. CNG produces even less emissions and the least amount of emission is produced by CNG + HHO mixture making it the most environmentally friendly fuel. It is observed that HC emissions decrease with increasing engine speed for all the fuels until a minimum is reached. This decrease is due to the high engine temperature inside the cylinder at higher engine speeds which leads to combustion of more HCs. The emissions reduced a maximum of 57.8% when HHO gas was used with gasoline as compared to gasoline alone. Whereas 59.1% maximum decrease was observed with CNG + HHO mixture as compared to CNG alone. It is also noticed that the 57.1% decrease in HC emissions occurs when CNG is used in gasoline engine. When CNG + HHO gas mixture is used in gasoline engine there was 76.32% decrease in HC emissions. These values are in comparison with gasoline fuel.

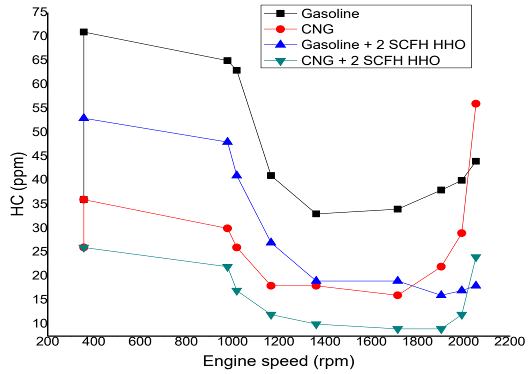

Fig. 6. HC emission vs engine speed for gasoline, CNG, gasoline + HHO, and CNG + HHO

4.2.2 Carbon monoxide (CO) emission

The carbon monoxide emission for the four fuels is represented in Fig. 7 along engine speed. The general trend observed is that CO emissions decrease with increasing engine speed. Gasoline produces most CO emissions followed by CNG, gasoline + HHO mixture, and CNG + HHO mixture. The addition of HHO gas to the base fuel decreases CO emissions. This is due to the fact that HHO gas contains extra oxygen which helps in oxidizing carbon monoxide to carbon dioxide. It is observed that a maximum of 73.34% decrease in CO emissions occurred when gasoline + HHO gas mixture is used instead of gasoline alone. Whereas a maximum of 53.34% decrease in CO emissions when mixture of CNG + HHO gas was used as compared to CNG alone, and the decrease was 76.67% when compared to gasoline alone.

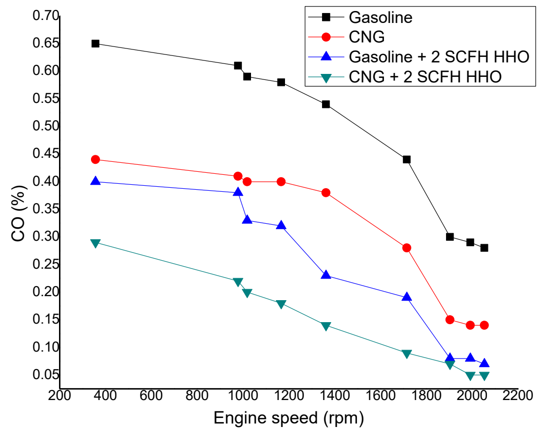

Fig. 7. CO emission vs engine speed for gasoline, CNG, gasoline + HHO, and CNG + HHO

4.2.3 Carbon dioxide (CO_2) emission

The carbon dioxide emission for the four fuels used is presented in Fig. 8. It can be observed that the emission of CO_2 (Fig. 8) is somewhat inverse of the emission of CO (Fig. 7). At higher engine speeds CO emissions decrease whereas CO_2 emissions increase. When blend of fuel and HHO gas is used emission of CO_2 is reduced due to higher hydrogen to carbon proportion and higher in-chamber temperature. A maximum decrease of 25.5% in CO_2

emission was observed when gasoline + HHO mixture was used instead of gasoline alone. Whereas a decrease of 26.4% was observed when CNG + HHO mixture was used as compared to CNG alone. Comparing to gasoline, a decrease of 35.6% and 52.6% in CO_2 emissions was observed when using CNG and CNG + HHO mixture, respectively.

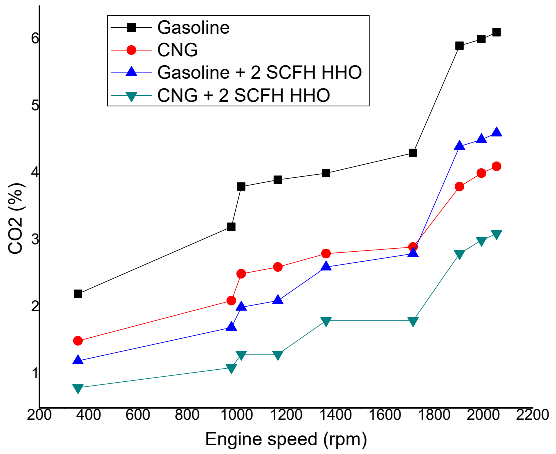

Fig. 8. CO_2 emission vs engine speed for gasoline, CNG, gasoline + HHO, and CNG ,HHO

4.2.4 Nitrogen oxides (NO_x) emission

The emissions of NO_x from the engine exhaust when using four fuels is displayed in Fig. 9. The general trend of all the fuels is that at higher engine speeds NO_x emissions increase. Using blended fuel rather than the base fuel decreased NO_x emissions slightly. A maximum decrease of 1.1% in NO_x emissions was observed when gasoline + HHO mixture was used instead of gasoline alone. Comparing to gasoline, when CNG was used NO_x emissions increased abruptly. The most NOx emissions were observed with CNG fuel, followed by CNG + HHO mixture, and gasoline, whereas the least NO_x emissions were observed with gasoline + HHO mixture.

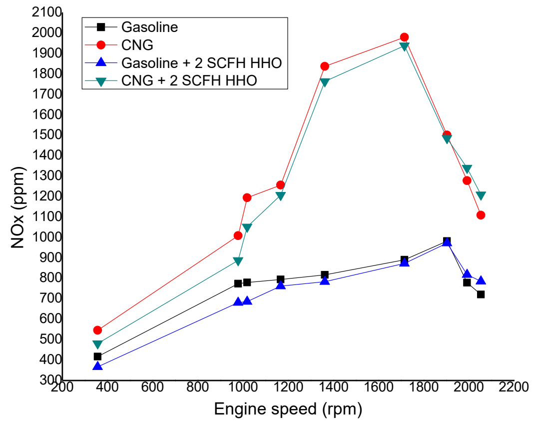

Fig. 9. NO_x emission vs engine speed for gasoline, CNG, gasoline + HHO, and CNG + HHO

5. Conclusion

This study was dedicated to observe the effect of addition of HHO gas to the base fuels such as CNG and gasoline in spark ignition engine. This work also presented comparison between gasoline and CNG in gasoline engine. The analysis was performed on the basis of engine performance and exhaust emissions. It was observed that the addition of HHO gas to the base fuels resulted in better engine performance and lower exhaust emissions. The HHO gas upon combustion only produces H2O and CO_2 therefore the harmful unburnt hydrocarbon emissions are totally eliminated. Comparing CNG to gasoline, CNG produced lower power but increased brake thermal efficiency and decreased specific fuel consumption. Emissions of HC, CO_2, and CO also decreased, however CNG produced higher NO_x emissions. The addition of HHO gas to the base fuel increased the engine performance as it increased engine output power and overall efficiency and decreased specific fuel consumption. Apart from improving the engine performance, HHO gas also reduced engine emissions such as unburnt HCs, CO_2, CO, and NO_x. Therefore, fuel + HHO mixture is not only beneficial in terms of engine performance but is also environmentally less harmful.

Nomenclature

HHO	Hydroxy or oxy-hydrogen gas
CNG	Compressed natural gas
NG	Natural gas
HCNG	Hydrogen and CNG mixture
H_2	Hydrogen
O_2	Oxygen
N_2	Nitrogen
A/F	Air-fuel ratio
BHP	Brake horsepower
HP	Horsepower
SFC	Specific fuel consumption
SCFH	Standard cubic feet per hour
ppm	Parts per million
CC	Cubic centimeter
KOH	Potassium hydroxide
NaOH	Sodium hydroxide
CI	Compression ignition engine
SI	Spark ignition engine
DC	Direct current
rpm	Revolution per minute
CO_2	Carbon dioxide
CO	Carbon monoxide
HC	Hydrocarbons
NO_x	Oxides of nitrogen
η	efficiency

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