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Emissions control and performance evaluation of spark ignition engine with oxy-hydrogen blending

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ABSTRACT

Fast depletion of fossil fuels and their detrimental effect to the environment is demanding an urgent need of alternative fuels for meeting sustainable energy demand with minimum environmental impact. Expert studies indicate hydrogen is one of the most promising energy carriers for the future due to its superior combustion qualities and availability. The use of hydrogen in spark ignition internal combustion engine may be part of an integrated solution to the problem of depletion of fossil fuels and pollution of the environment. The broader flammability limits and fast flame propagation velocity of hydrogen ensures complete combustion of fuel and allows engine to be operated at lean ranges. Lean burn operation comparatively maintains NOx, CO and HC emissions at a very low level. In the present work oxyhydrogen (HHO) gas is produced in leak proof plexiglass reactor by electrolysis of water using potassium hydroxide as electrolyte. The HHO gas generator is attached to a spark ignition engine, currently operating on the road without any modifications of the engine. The HHO gas produced is then added to the air which is being drawn into the engine. Experiments were conducted on a 4-stroke single cylinder natural air cooled spark ignition engine to determine total fuel consumption, specific fuel consumption, air fuel ratio, brake power and brake thermal efficiency and emissions CO, CO_2, O_2, NOx, HC at different loads with and without addition of HHO gas to gasoline for lower speeds ranging from 700 rpm to 1500 rpm. Also mileage tests were conducted to find the speed at which the fuel consumption is optimum.

1. INTRODUCTION

Now a days it is very common to use alternative fuels in Internal Combustion (IC) engines to enhance the engine performance and to reduce the engine emissions. Recent innovations mainly use hydrogen as secondary fuel in IC engines to increase the efficiency. This fuel has a great property of decreasing the emissions caused by the IC engines, essentially no carbon monoxide or hydrocarbon in the exhaust as there is no carbon in the fuel and produces only water during combustion. The availability of fuel is high, as it can be produced in different ways including hydrolysis of water using different electrolytes like KOH, NaOH and NaCl. Use of conventional fuels such as petrol and diesel fuels could not be eliminated completely due to their widespread dependence and difficulties in getting other alternatives. The most promising alternative is to supplement hydrogen gas produced on board by electrolysis of water to gasoline without much change in engine design. Also combustion factors such as flame speed, lean burn ability, diffusivity and flammability limits will improve with the addition of HHO gas.

Dugler and Ozcelik [1] conducted experiments on gasoline engines of various types and sizes by using oxyhydrogen (HHO) gas produced on board from electrolysis process. They demonstrated that the fuel consumption and exhaust emissions are reduced with the addition of HHO gas without any change in acceleration, torque and maximum power. Andrea et al. [2] carried out an experimental investigation on the performance of gasoline fuelled Spark Ignition (SI) engine by adding hydrogen up to 66% by volume with little modification to the engine. They found increase in work output and a reduction in burn duration due to the addition of hydrogen. They also concluded that the exhaust emissions CO, NO and O_2 are reduced with the addition of hydrogen. Saravanan and Nagarajan [3] did experimental investigation to determine the optimal injection parameters of the fuel for a manifold injected hydrogen-operated engine using diesel fuel as an ignition source for hydrogen. They found 9% increase in brake thermal efficiency at 30^0 crank angle from top dead center for a hydrogen flow rate of 7.5 l/min. They also found decrease in smoke, CO emissions and increase in exhaust gas temperature with hydrogen injection at all the load conditions compared with diesel fuel. Saravanan et al. [4] conducted experiments on a diesel engine with diesel as an ignition source for hydrogen. Hydrogen was injected into the intake port, while diesel was injected directly inside the cylinder. They observed maximum brake thermal efficiency of 29.4% at 10 l/min flow rate and great reduction in NOx emissions and smoke with port injected hydrogen. Saravanan et al. [5] conducted experiments on a single cylinder, 4-stroke, water-cooled, direct injection diesel engine by adopting exhaust gas recirculation technique to supply hydrogen-enriched air during suction stroke. Their results showed increase in thermal efficiency and decrease in specific fuel consumption (SFC), smoke level, particulate and NOx emissions.

Saravanan and Nagarajan [6] found an increase in engine performance with less pollution by conducting experiments on stationary diesel engine using hydrogen-enriched air. They also noticed reduction in NOx emissions. Szwaja and Rogalinski [7] made an experimental investigation on compression ignition (CI) engine using hydrogen gas and combination of hydrogen gas and diesel. They concluded that with the addition of hydrogen about 5% the engine provides better combustion and the engine durability increases. Yilmaz et al. [8] conducted experiments on CI engine using HHO gas produced from electrolysis process. By using HHO gas the engine torque was increased by 19.1% compared to diesel operation, there is an average gain of 14% was obtained in SFC by using hydroxyl gas and also increase in brake thermal efficiency for the hydroxyl enriched compression ignition engine at high speed conditions. There was an average reduction in 5% of HC emission at higher engine speed and 13.5% CO emissions at mid and higher engine speeds. Al-Rousan [9] conducted experiments on a single cylinder gasoline engine by attaching a compact HHO generating device to the engine. He has shown that this can increase fuel efficiency, engine torque and reduce harmful exhaust emissions. Musmar and Al-Rousan [10] conducted experiments on a single cylinder SI engine using mixture of air, HHO and gasoline. They noticed 50% reduction in NOx emissions, 20% reduction in CO emissions and 20% to 30% reduction in fuel consumption. Wang et al. [11] conducted experiments to investigate the effect of oxyhydrogen blends on the performance of gasoline engine equipped with electronically controlled hydrogen and oxygen injection systems. Their results showed an increase in brake thermal efficiency and decrease in SFC. They also found decrease in CO and HC emissions with the addition of 2% and 4% volume fractions of oxyhydrogen to the gasoline. Vino et al. [12] conducted experiments on single cylinder, 4-stroke and 150 cc petrol engine using petrol and petrol-HHO separately on engine. They found around 20% reduction in fuel consumption with petrol-HHO gas compared to petrol. They also noticed appreciable reduction in emissions such as CO and unburned hydro-carbons particularly during the idle condition. Wang et al. [13] investigated experimentally the effect of the variable hydrogen content in a oxyhydrogen gas on a 1.6 liters gasoline engine, and reported that the HC, CO, NOx emissions were decreased with the increase of hydrogen volume fraction in the oxyhydrogen gas. They also observed the decrease in particulate emissions with the increase in hydrogen gas volume fraction in the oxyhydrogen. Wang et al. [14] found significant reduction in HC and CO emissions, and slight increase in NOx emissions with addition of hydrogen from the experiments conducted on gasoline engine operating at high loads and lean combustion conditions. They also observed an improvement in engine stability with hydrogen blending.

Shivaprasad et al. [15] made an experimental study to find the effect of hydrogen addition on combustion performance and emission characteristics of spark ignition high speed gasoline engine. They observed increase in brake thermal efficiency up to 20% fraction of hydrogen in gasoline. Beyond this, the brake thermal efficiency is decreased due to reduction in air quantity. They also found decrease in HC and CO emissions with an increase in percentage of hydrogen. Abhilash et al. [16] investigated experimentally the performance of a diesel engine with the addition of oxy-hydrogen gas generated through water electrolysis at different electrolyte concentrations. The brake thermal efficiency of the engine at 75% of rated load with the supplement of oxyhydrogen gas generated using sodium hydroxide electrolyte was 53%. It was 4% more compared to conventional SI engine with gasoline only as a fuel. Jadhav et al. [17] carried out experiments on a single cylinder petrol engine under constant speed with varying load conditions using oxyhydrogen gas. From the experimental investigation at full load the total fuel consumption is reduced by 18.87%, brake thermal efficiency increased by 3.72%, brake SFC decreased by 19.48%, the concentration of HC reduced by 28.33% by volume and CO is reduced 0.28% by volume with the addition of oxyhydrogen gas compared to conventional SI engine with only gasoline as a fuel. Sendilvelan and Sundarraj [18] carried out experimental work on a modified liquefied petroleum gas dual fuel engine with diesel as primary fuel and liquefied petroleum gas as secondary fuel by providing a venturi at the inlet manifold for all load conditions. They observed considerable reduction in diesel fuel consumption and slight reduction in brake thermal efficiency for the dual fuel engine compared to conventional engine with only diesel as a fuel. They also found that the CO and HC emissions were reduced at higher loads for the dual fuel engines. Recently Sakhrieh et al. [19] did experimental work on a four cylinder, 4-stroke CI engine to find optimum flow rate of oxy-hydrogen gas. They conducted experiments at different speeds and under different load conditions for three different flow rates of HHO gas. Results showed that the performance of the engine is higher at lower speeds compared to higher speeds with the addition of HHO compared to conventional CI engine with only diesel as a fuel. To the author's knowledge no work has been reported in the literature on the performance evaluation and emission control of Spark Ignition (SI) engine with HHO gas addition at lower speeds. Hence in the present work experimental investigation was made on 4-stroke single cylinder natural air cooled SI engine at different loads with and without the HHO blending at low speeds. The HHO gas was produced by the process of water electrolysis. Total fuel consumption, SFC and brake thermal efficiency were determined from the experiments conducted. Also emissions such as NOx, CO, CO_2, HC and O_2 were measured using five gas analyzer.

2. EXPERIMENTAL SETUP

The schematic layout of experimental setup is shown in Fig. 1. The HHO gas was produced in a leak proof plexiglass reactor (hydrogen generator) of diameter 2 inches and 5 inches height by electrolysis of water using potassium hydroxide electrolyte. A small orifice is made in air filter and a hose pipe is inserted in orifice such that there is an interference fit. The hose pipe is pushed until it has reached the carburetor. The other end of the hose pipe is connected to the HHO gas generator. The diluted solution is prepared by adding 900 ml of distilled water to 50-60 ml of electrolyte. The generator is filled with the diluted solution of the electrolyte and mounted on the engine. When electric current is passed through the diluted solution, the generator produces 0.6 liters of HHO gas per minute. HHO gas produced has more energy because the hydrogen and oxygen molecules formed are in their monoatomic state [8]. The flow of HHO gas is measured using a calibrated flow meter. The gas produced is introduced into the air suction pipe. Technical specifications of the engine used in the experimental study are given in Table 1.

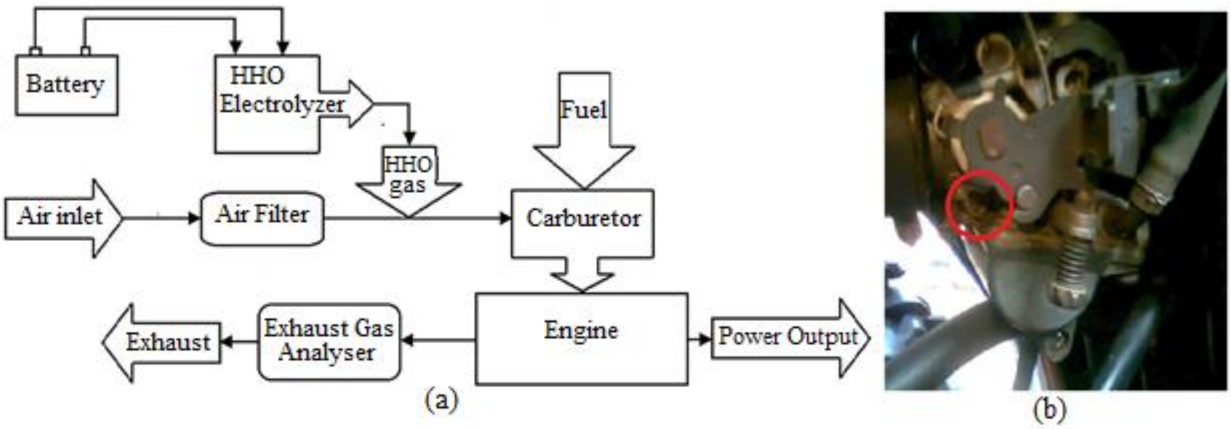

Figure 1. (a) Schematic layout of experimental setup (b) Photographic view of experimental setup (Engine)

Table 1. Engine specifications

Configuration	4-Stroke, single Cylinder, 2 Valve Petrol Engine
Bore x Stroke	58 mm x 56.4 mm
Engine Displacement	149 cc
Compression Ratio	9.5 : 1
Type of Cooling	Natural air cooled
Type of Ignition	Digital Twin Spark Ignition
Max. Power	11.1kW at 9000 rpm
Max. Net Torque	12.45 Nm at 6500 rpm

Eddy current dynamometer is used to load the engine. The fuel is fed to the engine by gravity through a burette. The gasoline fuel consumption is read by graduated burette over a specified time period. Effect of HHO gas addition to the fuel on exhaust emissions and engine performance under different load conditions for lower speeds ranging from 700 rpm to 1500 rpm were investigated. Exhaust gas emissions were measured using Nextech NGA 6000 automotive gas analyser [20]. Exhaust gas and ambient temperatures were monitored using K-type thermocouples. The thermocouple used to measure the exhaust gas temperature is inserted into the exhaust manifold ensuring that it does not touch the exhaust side walls. An orifice plate that was developed in-house used to measure the consumption of air. This was implemented using an Arduino Uno prototyping platform. The same unit was also used for data logging and for controlling power supply to the hydrogen generator. The pulse width modulation function on the Arduino was used as the input signal to change the duty cycle for the supply to the generator. The change in duty cycle resulted in a change of current supplied to the HHO generator.

3. RESULTS AND DISCUSSION

The tests are performed on a 4-stroke single cylinder natural air cooled SI engine at different speeds and loads to determine total fuel consumption, specific fuel consumption, air fuel ratio, brake power and brake thermal efficiency. The experiments are conducted with pure gasoline and hydrogen-gasoline mixture. The readings are taken for loading conditions ranging from 40 N to 140 N at speeds of 700, 1000 and 1500 rpm. Tachometer was used to measure the engine speed. The engine performance parameters such as total fuel consumption, specific fuel consumption, air fuel ratio, brake power, brake thermal efficiency are calculated using the procedure given by Heywood [21]. A five gas analyzer is used to estimate the concentrations of NO_X, HC, CO, CO_2, and O_2 in the exhaust stream.

3.1 Variation of SFC and TFC with BP

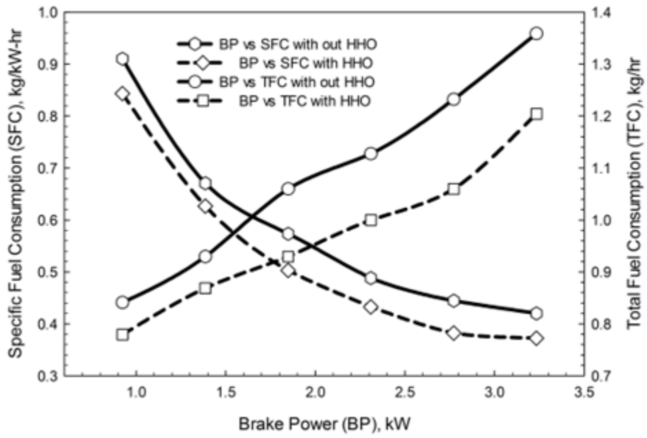

Figure 2. Variation of SFC and TFC with BP at engine speed 1500 rpm

Fig. 2 shows the variation of Brake Power (BP) with SFC and Total Fuel Consumption (TFC) at a constant engine speed of 1500 rpm with and without HHO gas blending. The SFC is decreased by using gasoline with HHO gas compared to gasoline. This is due to the uniform mixing of HHO gas with air as well as oxygen content present in the HHO, which helps in complete combustion. The combustion efficiency also increases with HHO supplement due to low ignition energy and high flame speed of HHO gas. The decrease in SFC with HHO-gasoline mixture ranges from 7-12 % compared to pure gasoline at 1500 rpm. The brake power is in the range of 0.9-3.25 kW. Figures 3 and 4 show the variation of SFC and TFC with BP at lower engine speeds of 1000 rpm and 700 rpm respectively. TFC reduced in the range of 7-11% at 1000 rpm and 6-9% at 700 rpm. The TFC is reduced due to decrement in fuel consumption for same output of power at all engine speeds and loads. This is due to the high diffusivity of hydrogen gas as well as oxygen index of HHO gas which assists combustion process and yields better combustion. The experiments showed that the reduction in SFC and TFC is more pronounced at higher engine speeds with addition of HHO gas to gasoline. Since HHO gains high flame speed and wide flammability, the addition of hydrogen would help the gasoline to be burned faster and complete at high speed conditions. The same can be observed from the figures 2, 3 and 4.

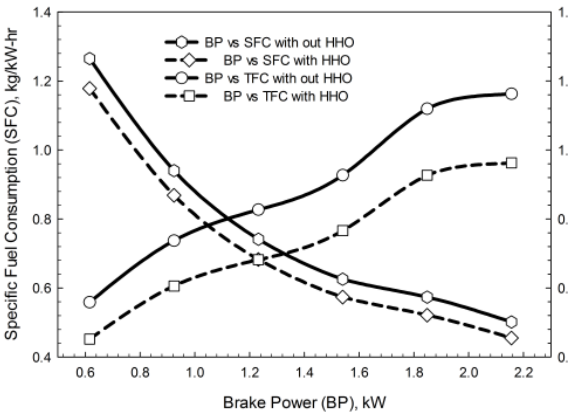

Figure 3. Variation of SFC and TFC with BP at engine speed 1000 rpm

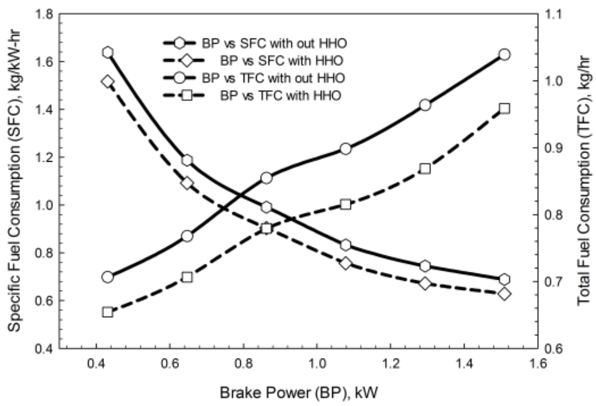

Figure 4. Variation of SFC and TFC with BP at engine speed 700 rpm

3.2 Variation of brake thermal efficiency and A/F with BP

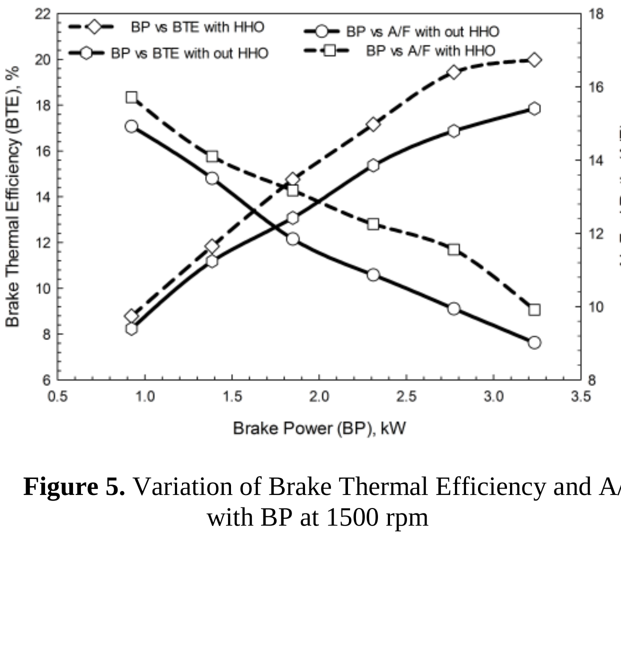

Figure 5. Variation of Brake Thermal Efficiency and A/F with BP at 1500 rpm

Fig. 5 shows the variation of brake thermal efficiency and Air-Fuel ratio (A/F) with BP at the engine speed of 1500 rpm. It has been observed that there is an increment in the A/F from 17 to 18.2 at same brake power of 0.92 kW with the addition of HHO gas to gasoline compared to pure gasoline at the speed of 1500 rpm. This is due to the oxygen index in HHO gas which results in increment of air-fuel ratio. The brake thermal efficiency also increased with HHO-gasoline mixture compared to pure gasoline due to decrement in heat supplied. The heat supplied is low due to better mixing of HHO with air and fuel and high energy content of the hydrogen in HHO gas. Also the heat losses from the combustion chamber are lower due to shorter combustion period with the addition of HHO gas. The increase in brake thermal efficiency ranges from 5 % to 12 % with the addition of HHO gas for the brake power ranges from 0.9-3.25 kW. Figures 6 and 7 show the variation of brake thermal efficiency and Air-Fuel ratio with BP at engine speeds of 1000 rpm and 700 rpm respectively. It is observed that there is slight decrease in brake thermal efficiency due to the reduced fuel energy flow rate as the energy density of hydrogen on volume basis is much lower than that of gasoline.

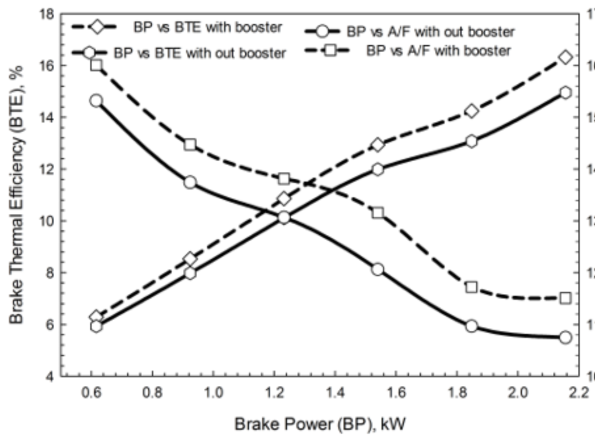

Figure 6. Variation of Brake Thermal Efficiency and A/F with BP at 1000 rpm

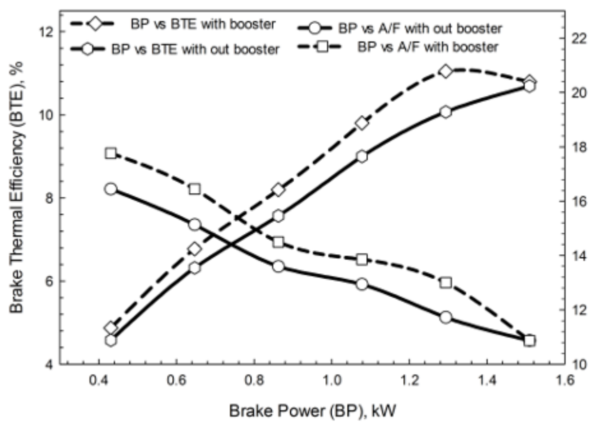

Figure 7. Variation of Brake Thermal Efficiency and A/F with BP at 700 rpm

3.3 Variation of CO and O_2 with Brake Power

Fig. 8 shows the variation of CO and O_2 emissions with BP with and without the addition of HHO gas to gasoline at the engine speed of 1500 rpm. It was observed that CO emissions decreased significantly due to the complete combustion as the HHO gas contains additional oxygen. By adding the HHO gas to gasoline enriches the air fuel ratio and there is no delay in the ignition propagation. An average reduction of 20% is achieved in CO emissions with HHO gas mixture compared to pure gasoline operation at 1500 rpm. It is also observed that O_2 emissions decreased with increase in brake power. This is due to the complete combustion which takes place by the addition of HHO gas with gasoline. The same variation can be observed at a lower speed of 700 rpm from Fig. 9. It can be concluded that decrease in oxygen in exhaust is a sign of better combustion characteristics. Also hydrogen in the charge accelerates the flame front for better combustion.

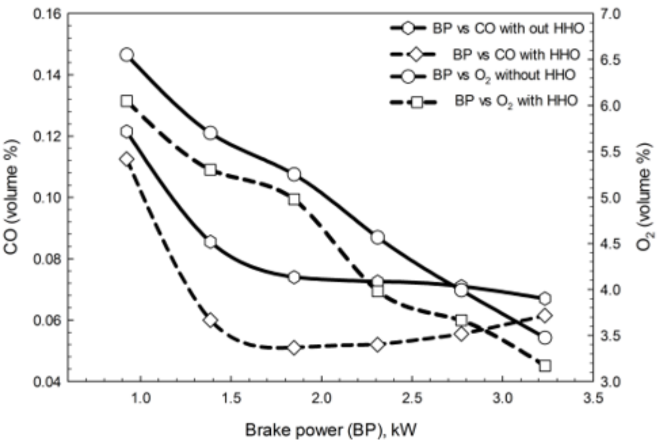

Figure 8. Variation of CO and O_2 with BP at 1500 rpm

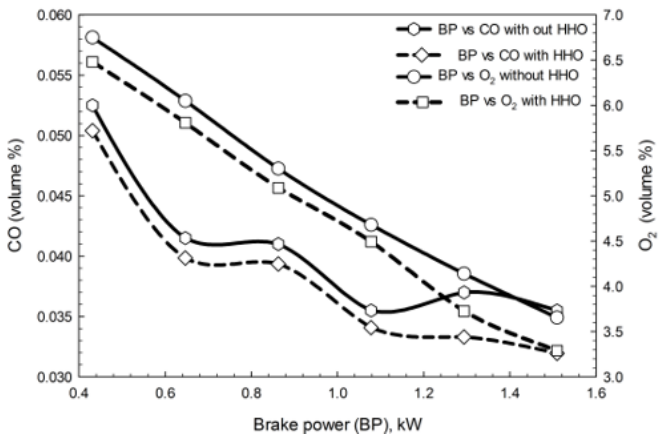

Figure 9. Variation of CO and O_2 with BP at 700 rpm

3.4 Effect of NOx and HC emissions on Brake Power

Fig. 10 shows the variation of un-burnt hydrocarbon emissions with brake power at the speed of 1500 rpm. An average reduction of 11.5% is obtained in HC emissions with the addition of HHO gas to gasoline compared to only gasoline as a fuel. In pure gasoline engine operation the fuel is incompletely burnt due to short opening time of manifold. With the addition of HHO gas the heat losses from the combustion chamber is reduced due to short quenching distance and wide flammability range of hydrogen. Fig. 10 also shows the variation of NOx emissions with brake power at the speed of 1500 rpm, with and without addition of HHO gas to gasoline. With the addition of HHO gas to gasoline an average reduction of 10.3% is obtained in NOx emissions due to low exhaust gas temperature. From the figure 11, it has been observed that there is nearly 62 % reduction in NOx emissions in exhaust gas due to the addition of HHO gas to gasoline at the lower engine speed of 700 rpm as the exhaust gas temperature is directly related to the engine speed. It has also been observed from the figure 11 that the reduction in HC emissions are better at higher speeds compared to lower speeds with the addition of HHO gas. At low engine speeds, due to high volume occupation of HHO, required amount of air cannot be taken into the cylinder which prevents gasoline fuel to be combusted completely.

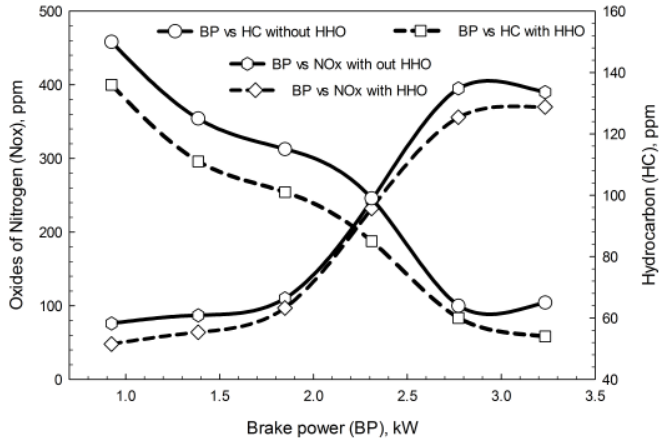

Figure 10. Effect of Nox and HC on Brake Power at 1500 rpm

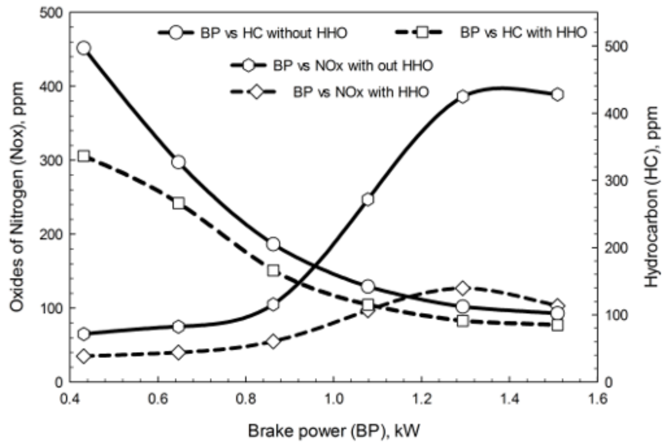

Figure 11. Effect of Nox and HC on BP at 700 rpm

3.5 Mileage test

The fuel economy of an automobile is the fuel efficiency relationship between the distance travelled and the amount of fuel consumed by the vehicle. So mileage tests were conducted on the same engine with on board HHO gas generator to determine the fuel consumption at higher speeds ranging from 2000 to 6000 rpm. The bike was given for maintenance check before the mileage test was conducted. The front and rear tire pressures were set at 172.37 kPa (25 psi) and 195.81 kPa (28.4 psi) respectively as prescribed by the manufacturer. Thorough inspection was done to check for any leaks and oil levels. The mileage test was conducted on a test track with driver of weight around 75 kg. To know the fuel economy at higher speeds the tests were conducted at constant rpm of the engine starting with 2000 rpm, and incrementing 1000 rpm with and without the HHO gas generator. The gas generator was refilled with the electrolyte just before the tests began so that correct amount of HHO gas is generated. The test results are given in the table 2 for a fuel quantity of 1000 ml.

Table 2. Mileage test results

Speed (rpm)	Mileage with HHO gas generator (kmpl)	Mileage without HHO gas generator (kmpl)	% improvement in mileage
2000	70	65	7.69
3000	62	55	12.72
4000	54	47	14.89
5000	45	40	12.50
6000	39	35	11.42

An improvement ranging from 7.69% to 14.89% in fuel consumption is found from the mileage tests conducted with the addition of HHO gas to gasoline compared to pure gasoline operation. The change in mileage can be seen maximum at around 4000 rpm, which is in consistent with specifications of the manufacturer.

4. CONCLUSIONS

Experiments have been carried out to investigate the effect of HHO gas on the engine performance and emission parameters. The following conclusions are made from the results obtained.

1. Specific Fuel Consumption (SFC) and Total Fuel Consumption (TFC) of the engine are decreased with addition of HHO gas to gasoline-air mixture due to uniform mixing of HHO gas with air as well as oxygen content of HHO stimulate combustion. The SFC and TFC are decreased approximately from 5% to 12% for the engine speeds ranging from 700 to 1500 rpm.
2. The brake thermal efficiency of the engine has been increased about 5-10% due to high energy content of hydrogen in HHO gas. The air-fuel ratio also improved due to oxygen content in HHO gas.
3. The average concentration of carbon monoxide has been reduced to almost 20% with addition of HHO gas to gasoline compared to pure gasoline operation. The O_2 emissions have been reduced due to complete combustion of fuel with the presence of HHO gas
4. With HHO gas addition to gasoline engine, the NOx concentration has been reduced to about 62% at the engine speed of 700 rpm. HC emissions have also decreased with the addition of HHO gas. But it is highly affected by the engine speed.
5. From the mileage tests conducted on the engine it is found that the fuel consumption has been decreased at all speeds ranging from 700 rpm to 6000 rpm with the addition of HHO gas.

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