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Optimization of oxyhydrogen gas flow rate as a supplementary fuel in compression ignition combustion engines

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ABSTRACT

In this study, Oxyhydrogen (HHO) gas produced by electrolysis process using Potassium hydroxide (KOH) was introduced as a supplementary fuel into a four-cylinder, four -stroke Compression Ignition (CI) engine.
In the first part, the throttle of the engine is held to its full, half and quarter position. The field voltage (brake load) is varied to obtain different engine speeds. In the second part, the field voltage of the electric dynamometer is held constant while the throttle of the engine is varied. Power, torque, Brake Specific Fuel Combustion (BSFC) and efficiency improvements depend on the HHO gas flow rate supplied to the engine and can be enhanced by 14.2, 4.8, 10.6 and 8.8 percent, respectively. A curve that relates engine speed with the optimum HHO gas flow rate was plotted to maximize the enhancement of the engine performance. Optimum HHO gas flow rate depends on the engine speed; being 1.4 L/min at low speeds, and increases with speed increase to reach 2.1 L/min at intermediate speeds, while at high speeds, to maximize the enhancement of power and torque, it is recommended to mix diesel with HHO flow rate of 3.0 L/min.

Keywords: HHO, Optimization, CI Engine, Engine Performance.

1. INTRODUCTION

The huge consumption of fossil fuels has caused visible damage to the environment in various forms [1]. The search for alternative energy sources is strongly rooted in the realization that the conventional energy sources are polluting and they are not renewable and thus limited. The potential of renewable energy sources is enormous as they can in principle meet many times the world's energy demand. Renewable energy sources such as biomass, wind, solar, hydropower, and geothermal can provide sustainable energy services, based on the use of routinely available, indigenous resources. It is becoming clear that future growth in the energy sector is primarily in the new regime of renewable, and to some extent natural gas-based systems, and not in conventional oil and coal sources [2]. The improvement of diesel engines performance and reducing emission was considered a very hot research topic which was studied by several researchers in the last few years. For context, Sendilvelan and Sundarraj studied diesel engine performance and emission when a modified LPG Diesel dual fuel engine with diesel as primary fuel and liquefied petroleum gas as secondary fuel by providing a venturi at the inlet manifold for better performance at all loading conditions. [3]. Another important point which influence the combustion and emission characteristics of diesel engine is Spray characteristics. A simulation model of diesel engine spray is established to study the development of spray process, study the influence of the different working condition on spray penetration, droplet sauter average diameter and spray cone angle [4]. The Impact of diagonal swirler vane angle on combustion dynamic and NOx formation characteristic in a hybrid industrial combustor is numerically studied using a full compressible large eddy simulation approach. Increase the diagonal swirler vane angle will have relatively smaller impacts on compressing the NOx emission due to the confinement of combustion chamber [5]. For a long time, hydrogen has been known as a suitable alternative fuel for its unique and highly desirable properties, for performing as a fuel in an engine [6]. There are several reasons for applying hydrogen as an additional fuel to accompany diesel fuel in CI engine. Firstly, it increases the H/C ratio of the entire fuel. The amount of energy released is dependent on the oxidation state of the carbons in the hydrocarbon which is related to the hydrogen/carbon ratio. The more hydrogen per carbon, the lower the oxidation state and the more energy that will be released during the oxidation reaction. Thus the greater the H/C ratio, the more energy release on combustion. Secondly, injecting small amounts of hydrogen to a diesel engine could decrease heterogeneity of a diesel fuel spray due to the high diffusivity of hydrogen which makes the combustible mixture better premixed with air and more uniform [7].

HHO or Hydroxyl or brown gas is in brown color and the form of un-separated hydrogen and oxygen generated by the electrolysis process of water (NaOH, KOH or NaCl additives for more HHO production and optimum molality to keep electrical resistance-conductivity balance) by a unique electrode design. Hydrogen and oxygen did not form into O_2 and H_2 molecules. They were in their monoatomic state (a single atom per molecule). Water was split by electricity to form its various elements, oxygen and hydrogen. When HHO mixture was ignited, both explosion and implosion occurred to form water, releasing the energy that was found in the bonds of the two elements in the form of heat. In the monoatomic portion, there weren't any atomic bonds needed to be broken (the bonds of the H_2 and O_2 respectively) before turning back into water. The key difference of HHO gas was the fact that some of the hydrogen and oxygen never go into a diatomic state. Hence, HHO gas had more energy because these bonds were never made [8]. HHO gas has many good characteristics that give it the potential of being used as a fuel supplement; its efficient and easy production in good amounts using a simple electrolyzer with a small size and cheap cost is an advantage when using it for ICE's. Furthermore, it contains oxygen by itself so it does not require oxygen for combustion and will not produce harmful emissions when combusted since it produces pure water when combusted [9]. Selvi Rajram et al, experimentally examined introducing Brown's gas into a direct injection diesel engine in order to study its effect on performance, emissions and combustion characteristics. However results showed that the induction of oxyhydrogen gas resulted in increasing brake thermal efficiency by 11%. Carbon monoxide emissions were reduced by 15.4%, whereas HC emissions were reduced by 18.2%. On the other hand, carbon dioxide increased by 6 % while NOx emissions had an 11.2% increase [10]. Similarly, Bari and Esmaeil tested a four cylinder, direct injection water cooled diesel engine by using on-board hydrogen-oxygen generator in order to produce H_2/O_2 mixture through water electrolysis. At a constant speed and variable load and H_2/O_2 amounts, experimental results showed that by using 4.84%, 6.06% and 6.12% total diesel equivalent of H_2/O_2, an increase in brake thermal efficiency from 32% to 34.6% at 19 kW, whereas increasing from 32.9% to 34.7% at 22 kW, compared to an increase from 34.7% to 36.3% at 28 kW load [11]. Sa'ed A. Musmar and Ammar A. Al-Rousan integrated a 197 cc single cylinder SI engine with a system that can generate HHO gas in order to test the effect of the gas on emissions and fuel consumption. At various speeds, results showed that NOx emissions have been reduced to about 50% when HHO was introduced, while carbon monoxide was reduced by 20%. In addition to that, fuel economy tests concluded that a deduction of 20% to 30% was observed in fuel consumption [12]. Mohamed M. EL-Kassaby et al, constructed a simple innovative HHO generation system and evaluated the effect of hydroxyl gas HHO addition, as an engine performance improver, into gasoline fuel on engine performance and emissions [13].

In this study, a four-stroke CI, 1.5L four-cylinder engine was used to test the effect of varying HHO gas flow rate on the engine performance. HHO gas in this test will be produced by electrolysis process using KOH as an electrolyte in a dry cell Hydrogen generator (electrolyzer). Experiments were conducted at 3 dynamometer speeds; 3800 RPM, 2875 RPM and 2000 RPM. This is followed by another set of experiments in which the field voltage is held constant.

2. EXPERIMENTAL

In this study, HHO gas, which is produced in the electrolyzer, is supplied directly to the intake manifold of a four stroke, four-cylinder diesel engine without any modification. A photograph of the experimental setup is shown in figure 1. Before being supplied to the manifold, the gas passes through a safety system consisting of a 5-liter water tank called the bubbler and a flashback arrestor to prevent explosion in the case of backfire. The HHO generator is made of 43 plates of 316L stainless steel separated by 16 high temperature silicon gaskets. The end plates are made of high tensile strength CPVC, which can resist high pressures, and a wide range of operation temperature. The generator is designed so the voltage between two successive plates is 2.3 volts. This is achieved by placing five neutral plates between every positive and negative plate. Technical specifications of the water electrolyzer are presented in table 1. As shown in Figure 2 a bubbler is located above the electrolyzer to supply it with water electrolyte mixture for the electrolysis process. HHO gas produced from the electrolysis process is sent back to the water mixture. HHO bubbles escaped to the surface of the water in the bubbler passes to the flashback arrestor A second bubbler is inserted after the flash back arrestor and is connected to the engine intake manifold. The second bubbler is used to condense water vapor so that the engine is supplied with pure HHO gas. A four-stroke, four-cylinder, water cooled and direct- injection engine was used in this study. The engine specifications are listed in table 2. Specific fuel consumption of the diesel engine is measured by recording the time required for 50ml of diesel to flow in the engine for all speeds. Then the consumption is converted to g/kWh. A BKB trademark DC machine is used to test the power output of the diesel engine. The maximum speed the dynamometer is 4200 rpm; however, the belt reduction drive connecting it to the engine allows a maximum engine speed of 7000 rpm. The dynamometer has a load control switch on its casing. With the switch in the half position, the dynamometer will handle speeds up to 1800 rpm and in the full position it will handle speeds up to 4200 rpm. Torque reaction of the dynamometer is measured by a spring balance and a torque arm attached to the generator. When the dynamometer is balanced, the torque generated from the weight added to the balance is equal to the torque of the dynamometer. The speed of the dynamometer was obtained by using a PROVA trademark noncontact digital tachometer having a speed range from 10 to 99999 RPM and an accuracy of .04%.

Table 1. Specifications of water electrolyzer

Length	25.4 cm (fittings included)
Width, Height	11.43 cm, 20.32 cm
Rated voltage	12V-14V
Rated current	40A-120A
Number of plates	43 316L Stainless steel
Number of gaskets	44 High Temp Silicon

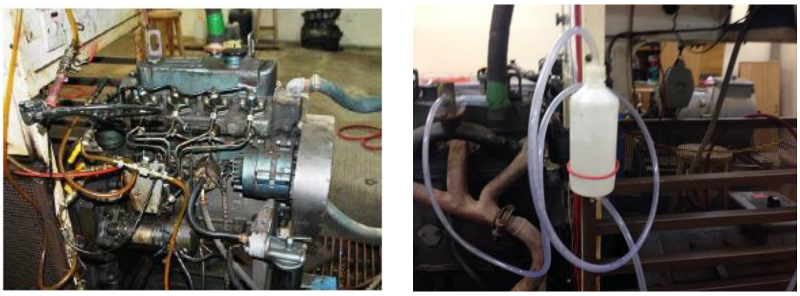


Figure 1. Experimental setup (Engine, Second bubbler)

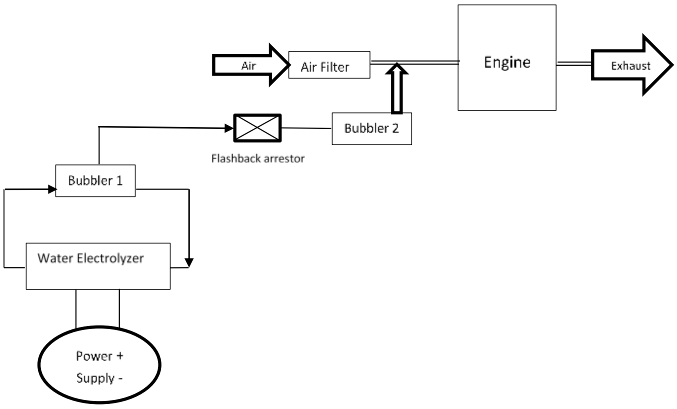


Figure 2. Schematic for the experimental apparatus

Table 2. Test engine specifications [14]

Type	Automotive 30 test bed
Bore	72.25 mm
Stroke	88.18 mm
Number of cylinders	Four cylinder
Type of injection	Direct injection
Type of cooling	Water cooled
Swept volume	1450 cc
Compression ratio	21.5
Intake valve diameter	34.51 mm
Exhaust valve diameter	28.49 mm
Connected rod length	155.8 mm

The rate of HHO production was measured by recording the time required to produce 140ml. The procedure was repeated with different electrolyte concentration (KOH). The voltage across the electrolyzer electrodes is 13.8 V which is equal to the engine alternator voltage. Electrolyzer was operated using water at ambient temperature. The flow rates were calculated and summarized in table 3.

Table 3. Electrolyzer performance analysis

Time required for HHO to fill 140 ml (Second)	Flow Rate (L/min)
6	1.4
4	2.1
2.8	3.0

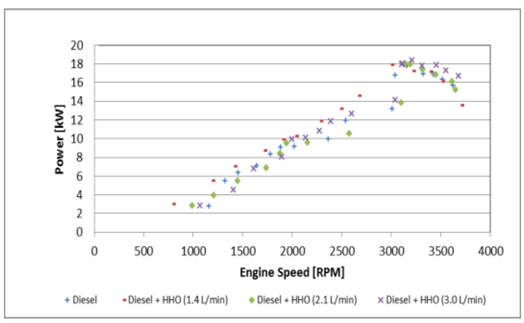
In the first part of the study, the throttle of the engine is held to its full, half and quarter position.

The field voltage (brake load) is varied to obtain different engine speeds; 3800 RPM, 2875 RPM, and 2000 RPM. In the second part, the field voltage of the electric dynamometer is held constant while the throttle of the engine is varied to achieve the desired speed. This test is done to simulate real life driving pattern, while the driver controls the engines speed. Engine tests were done using three different HHO gas flow rates; 1.4, 2.1 and 3 L/min in order to find the optimum flow rate that should be supplied to the intake manifold at different speeds and under different load conditions.

3. RESULTS

3.1 Engine performance with variable field voltage and constant throttle (full, half and quarter) with and without HHO.

The majority of typical Brown's gas is in the form of stable H_2 and O_2 gasses, by a ratio of 2:1 by volume. Hydrogen gas burns at higher speed of diesel. It acts as a powerful accelerant in the combusting of the HC fuel. The major contribution of HHO gas to the combustion process is with its ability to make the dominant HC fuel more effective within the allotted window of time.



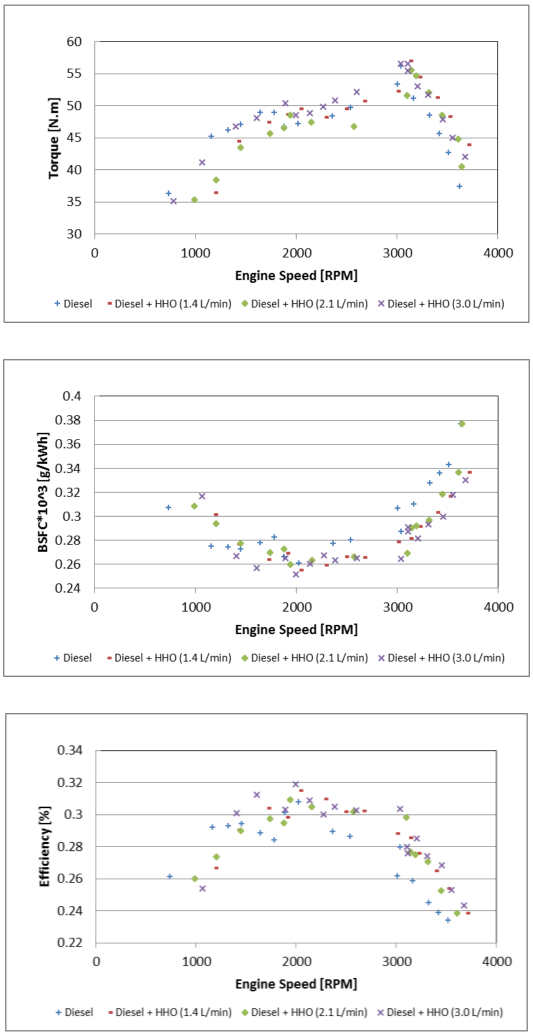


Figure 3. Power, torque, BSFC and efficiency as a function of engine speed (Dynamometer speed=3800)

From figure 3, we can conclude that compared to pure diesel, power showed an increase by an average of 5.2%, 0.03% and 10.7% for HHO flow rates of 1.4, 2.1 and 3.0 L/min respectively; while an average increment of 1.58% in torque was observed at a flow rate of 1.4 L/min. However, an average decrement of 2.24% in torque was observed during testing the intermediate HHO flow rate (2.1 L/min). As the flow rate of HHO increased to 3.0 L/min, torque increased to reach 3.91%. The increase in power is due to oxygen concentration of HHO gas which yield enhanced combustion. High flame velocity of HHO yields shorter combustion period that provides lower heat losses, much closer to ideal constant-volume combustion which results increased compression ratio and thermal efficiency. HHO has a low ignition energy and fast flame speed, consequently, the HHO-diesel mixture is more easily ignited and quickly combusted than the pure diesel fuel. This is positively reflected on torque at high speeds. Also, it is noticed that the maximum power and torque at 3800 RPM dynamometers occur at engine speeds of (3000-3100 RPM). At high operational speeds, power and torque were improved with the addition of the highest HHO gas flow rate (3.0 L/min), while at low engine speeds HHO flow rate of 1.4 L/min achieved the highest improvement albeit not notably noticed. BSFC achieved an average reduction of 2.5%, an increase of an average of 0.2%, and a reduction on an average of 4.4% at 1.4, 2.1 and 3.0 L/min flow rates respectively. At each flow rate tested, BSFC and efficiency achieved good augmentations, with the highest being at a flow rate of 3.0 L/min and this is due to the increase of power at the same brake load

Brake thermal efficiency is noticed to achieve an increase during testing the three HHO flow rates, with the highest being at 3.0 L/min with an average of 4.4%, and the lowest being at 2.1 L/min with an average of 0.2%. However, an intermediate improvement of 2.81% was achieved at 1.4 L/min HHO flow rate.

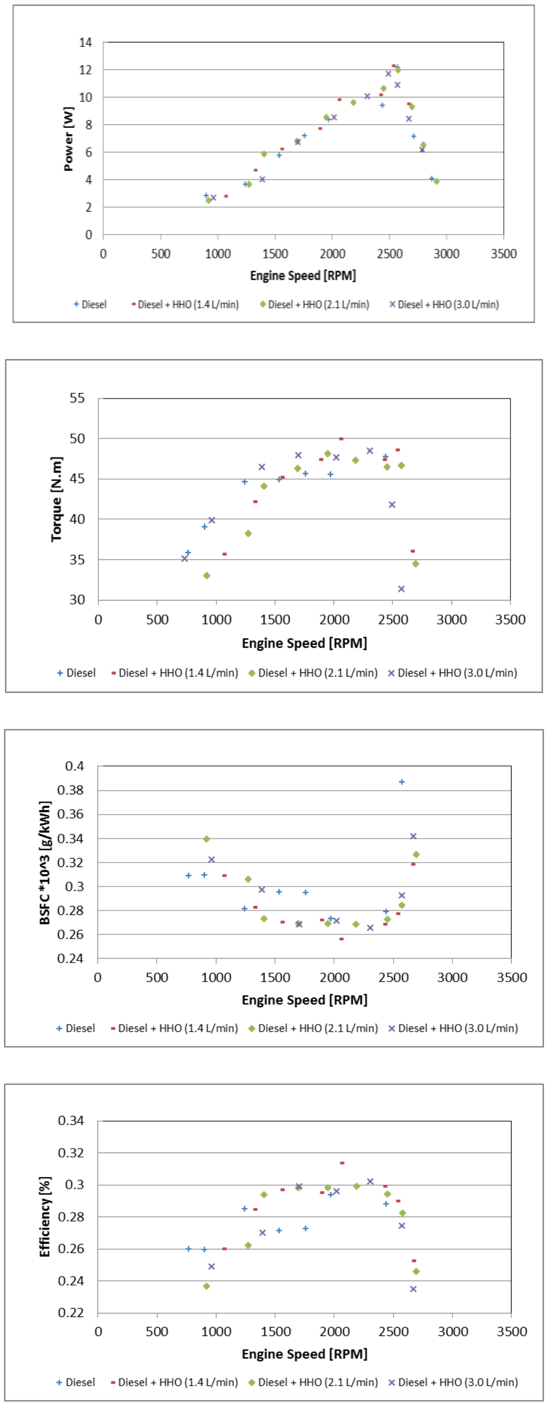


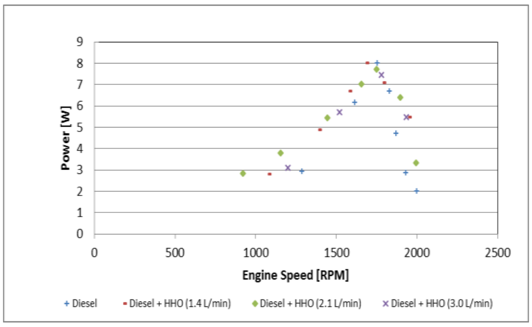
Figure 4. Power, torque, BSFC and efficiency as a function of engine speed (Dynamometer speed =2875 RPM)

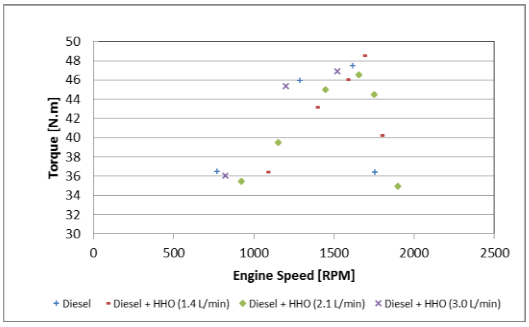
Figure 4 shows the results obtained for 2875 RPM dynamometer speed. Power increased by an average of 14.2%, 6.7% and 4.1% for HHO flow rates of 1.4, 2.1 and 3.0 L/min respectively, while an average increment of 0.7%, 0.04% and 4.8% in torque was observed at the respective flow rates, with all being compared to pure diesel operation.

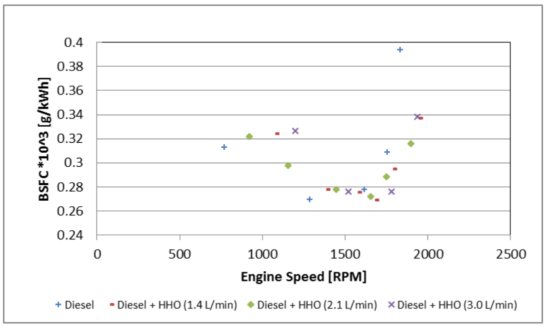
Also, it is noticed that the maximum power and torque at 2875 RPM dynamometer speed at engine speeds of (2400-2500 RPM). At operational speeds between (2400-2900 RPM), each power and torque were improved with the addition of the intermediate HHO gas flow rate (2.1 L/min), while at low engine speeds (below 2000 RPM), HHO flow rate of 1.4 L/min achieved the highest improvement albeit not notably noticed. BSFC achieved an average reduction of 10.6%, 0.6% and 9.7% for 1.4, 2.1 and 3.0 L/min respectively. Brake thermal efficiency is noticed to achieve an increase during testing the three HHO flow rates, with the highest being at 1.4 L/min with an average of 8.83% and the lowest being at 2.1 L/min with an average of 1.8%. However an intermediate improvement of 8.4% was achieved at 3.0 L/min HHO flow rate. When comparing each HHO flow rate enhancements at the same speed, it is noticed that BSFC and efficiency achieved almost equal percentages.

As shown in Figure 5, power increased by an average of 22.01%, 9.28% and 13.73% for HHO flow rates of 1.4, 2.1 and 3.0 L/min respectively, while an average increment of 31.8%, 21.8% and 28 % in torque was observed at the respective flow rates, with all being compared to pure diesel operation.

As we can notice, the maximum power and torque occur at engine speeds of (1500-1600 RPM). In the whole range of speed tested for the 2000 RPM dynamometer speed, each power and torque were improved with the addition of the least HHO gas flow rate (1.4 L/min).







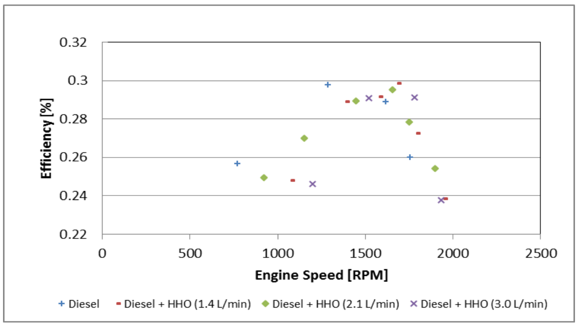


Figure 5. Power, torque, BSFC and efficiency as a function of engine speed (Dynamometer speed= 2000 RPM)

BSFC achieved an average reduction of 24.6%, 18.1% and 22.3% for 1.4, 2.1 and 3.0 L/min respectively. Brake thermal efficiency is noticed to achieve an increase during testing the three HHO flow rates, with the highest being at 1.4 L/min with an average of 20.52% and the lowest being at 2.1 L/min with an average of 14.01%. However an intermediate improvement of 17.85% was achieved at 3.0 L/min HHO flow rate. The existence of hydrogen in the mixture increases the rate of chain reactions after the start of the diesel ignition. Also the high energy content of the hydrogen in the gas mixture results in BSFC reduction.

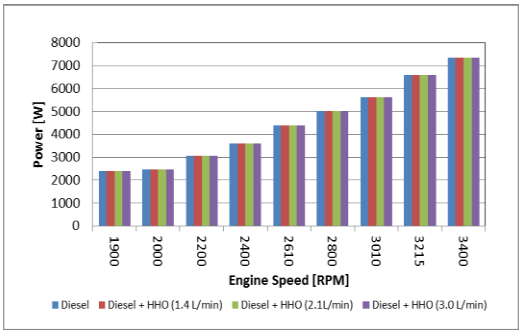
This improvement in power and torque is due to high oxygen concentration with the presence of HHO and better mixing with the fuel which leads to more efficient combustion. The high flame speeds are a result of the fast and thermally neutral branching chain reactions of H_2 as compared to the relatively slower endothermic and thermally significant chain reactions associated with hydrocarbon fuel combustion [15]. Also Heat release rates from H_2-diesel fuel combustion tend to be higher than those for diesel fuel combustion, resulting in a shorter duration of combustion with less heat transfer to the surroundings, and can improve thermal efficiencies [16-18].

In addition, the low ignition energy of HHO yields to a diesel-HHO mixture which can be easily combusted and ignited compared to diesel fuel.

3.2 Engine performance with variable dynamometer speed and constant field voltage of 30V with and without HHO

In this test the field voltage of the electric dynamometer is held constant. This test is done to simulate the real-life driving pattern.

Figures 6 show the variation of engine performance at constant field voltage test at different HHO flow rates.



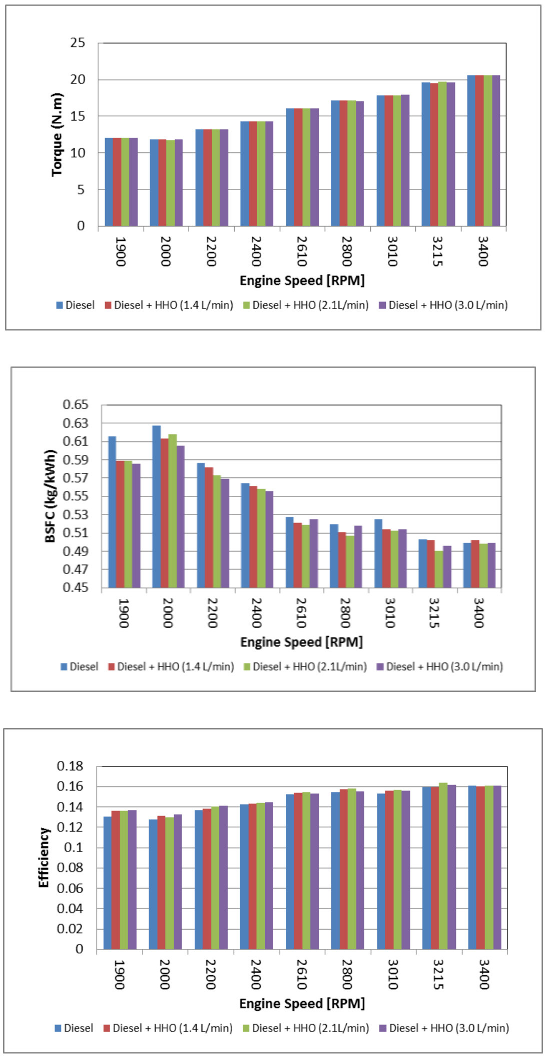


Figure 6. Power, torque, BSFC and efficiency as a function of engine speed (variable dynamometer speed)

It is noticed that power and torque remain constant during variable dynamometer speed. BSFC achieved an average reduction of 2.67%, 2.42% and 2.23% for 1.4, 2.1 and 3.0 L/min respectively. Brake thermal efficiency is noticed to achieve an increase during testing the three HHO flow rates, with the highest being at 1.4 L/min with an average of 3.17%, and the lowest being at 3.0 L/min with an average of 2.29%. However, an intermediate improvement of 2.67% was achieved at 2.1 L/min HHO flow rate.

When comparing each HHO flow rate enhancements at the same speed, it is noticed that BSFC and efficiency achieved almost equal percentages. At high operational speeds, BSFC improved with the addition of the highest HHO gas flow rate (3.0 L/min), while at low engine speeds HHO flow rate of 1.4 L/min achieved the highest improvement. In both tests, the high diffusivity of HHO leads to a better mixing with air, also the high oxygen index of HHO assists the diesel fuel during combustion and results in enhanced combustion especially at high speeds when the fuel is not completely burnt due to poor mixing and lower volumetric efficiency.

Although the variable dynamometer speed tests resulted in higher increment in power and torque with the addition of HHO in comparison with the constant dynamometer tests, the brake specific fuel consumption showed better improvement in both 2875 RPM and 2000 RPM dynamometer speed tests. This is due to higher volumetric efficiency of the engine at low dynamometer speeds, because of lower engine speed allowing more HHO to enter the cylinder.

3.3 HHO flow rate optimization

Based on the results obtained from the constant dynamometer speed test figures, a curve relates the engine speed with each power and torque was plotted. The curve was obtained by choosing a suitable polynomial trend line for power and torque curves versus speed for diesel only and at each HHO flow rate. Other curves were conducted by subtracting each

HHO flow rate trend line equation from the diesel one to get the increase in both power and torque at each speed. By taking the value of HHO flow rate that gives the maximum value of the increase in each power and torque, a set of points were plotted of the obtained flow rate against speed for each parameter. Then two suitable polynomial trend lines were obtained from those points, which relate the optimum HHO flow rate at each speed. The obtained curves are presented in figures 7 and 8, respectively.

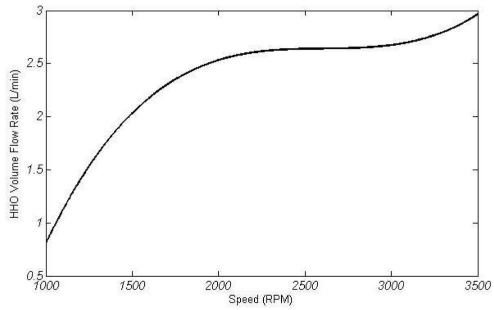


Figure 7. Power based optimum HHO flow rate at each speed

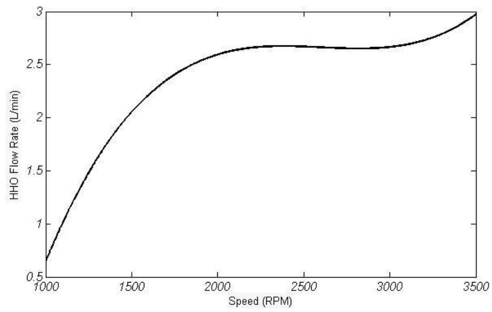


Figure 8. Torque based optimum HHO flow rate at each speed

As it can be seen, the optimum HHO gas flow rate depends on the engine speed; being 1.4 L/min at low speeds, and increases with speed to reach 2.1 L/min at intermediate speeds, while at high speeds, to maximize the enhancement of power and torque, it is recommended to mix diesel with HHO flow rate of 3.0 L/min.

From the knowledge of errors in the measured variables the probable error in the result WR is the error of the results is calculated using

$$W_R = \pm\sqrt{\left(\frac{\partial R}{\partial X_1} W_{x1}\right)^2 + \left(\frac{\partial R}{\partial X_2} W_{x2}\right)^2 + \left(\frac{\partial R}{\partial X_3} W_{x3}\right)^2 + \cdots} \quad (1)$$

where Wx1, Wx2, Wx3, …are the uncertain or errors in the independent variables and WR is the error in the results. To find the value of uncertainty percentage:

Percentage analysis=W_R/R*100%

Using the above mentioned equations it was found that the minimum and the max torque uncertainties are 1.95% and 2.13% respectively.

4. CONCLUSIONS

The results of the test can be concluded as follows:

- The performance of the electrolyzer depends on the electrolyte concentration; as it increases, time required for HHO gas to replace water in a test decreases, which leads to an increase in the gas flow rate.
- At low speed operation, it was noticed that a low HHO flow rate will lead to a better engine performance, and that is because of the higher volumetric efficiency which allows more HHO gas to enter the cylinder, while at high engine speeds, a high HHO flow rate is needed to maximize the engine performance due to a reduced volumetric efficiency.
- The enhancement in performance of the engine with the addition of HHO is noticed to be higher at lower dynamometer speeds compared to high dynamometer speeds.
- In the variable dynamometer speed operation, it was observed that the addition of HHO gas will cause a notable reduction in the BSFC, an increase in the brake thermal efficiency, while the power and torque remain constant.

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