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ORIGINAL ARTICLE

Effect of hydroxy (HHO) gas addition on gasoline engine performance and emissions

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KEYWORDS
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Abstract The objective of this work was to construct a simple innovative HHO generation system and evaluate the effect of hydroxyl gas HHO addition, as an engine performance improver, into gasoline fuel on engine performance and emissions. HHO cell was designed, fabricated and optimized for maximum HHO gas productivity per input power. The optimized parameters were the number of neutral plates, distance between them and type and quantity of two catalysts of Potassium Hydroxide (KOH) and sodium hydroxide (NaOH). The performance of a Skoda Felicia 1.3 GLXi gasoline engine was evaluated with and without the optimized HHO cell. In addition, the CO, HC and NO_x emissions were measured using TECNO TEST exhaust gas analyzer TE488. The results showed that the HHO gas maximum productivity of the cell was 18 L/h when using 2 neutrals plates with 1 mm distance and 6 g/L of KOH. The results also showed 10% increment in the gasoline engine thermal efficiency, 34% reduction in fuel consumption, 18% reduction in CO, 14% reduction in HC and 15% reduction in NO_x.

1. Introduction

A trending global concern, toward lowering fuel consumption and emissions of internal combustion engines, is motivating researchers to seek alternative solutions that would not require a dramatic modification in engines design. Among such solutions is using H_2 as an alternative fuel to enhance engine efficiency and produce less pollution [1]. This is not feasible from a commercial point view; building a system that generates H_2 and integrating it with the engine system yield an expensive manufacturing cost [2] and impact the vehicle market price. Another option is blending H_2 with Natural Gas (NG) [3–12]. Ma et al. showed that the H_2/NG mixture achieved shorter flame development and propagation periods, and so, the combustion efficiency is enhanced and emission levels were lower [3]. Musmar and Al-Rousan have designed, integrated and tested a compact HHO generating device on a gasoline engine. Their results showed that nitrogen oxides (NO_x), carbon monoxide (CO), and fuel consumption were reduced by 50%, 20%, and ~30%, respectively, with an addition of HHO gas [13,14]. The effect of HHO addition on CI engines was studied by Yilmaz et al.; their results reported an increase in engine torque by an average of 19.1%, a reduction in CO and Hydrocarbons (HC) emissions, and Specific Fuel

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Consumption (SFC) by averages of 13.5%, 5%, and 14%, respectively [15]. Ji et al. [16] have studied the effect of H_2 enrichment on a SI methanol-fueled engine, and reported an increase in Brake Mean Effective Pressure (B_{mep}) and both the thermal and volumetric efficiencies, with 3% of H_2 by volume of the intake air.

Shivaprasad et al. [17] have experimented on a single cylinder SI gasoline engine while injecting H_2 in the intake manifold in volumetric fractions (V_f) of the intake air between 5% and 25%. The results reported a continuous increase in B_{mep} and thermal efficiency, and a decrease in both HC and CO emissions, with an increase in H_2 fraction. Unfavorably, a corresponding increase in NO_x was reported with the rise in H_2%. Wang et al., have conducted a number of experiments [18–23] on a SI 4-cylinder gasoline engine to investigate the performance of H_2/gasoline blends. In most of the experiments, the engine was operated in a city driving condition of 1400 rpm. Results in [24] outlined the general qualities offered by H_2 without any other modifications to the engine. Notably, the spark timing of the original gasoline operation was not modified, despite the predictable fast combustion of H_2/gasoline. The results demonstrate a most profound enhancement in B_{mep} and thermal efficiency in lean conditions, and an increase in peak cylinder pressure and an advance in the corresponding crank angle (CA) with the increase in H_2%.

Advantages of CO_2, CO and HC reduction, while NO_x increased, with higher H_2 %, would be reasoned as follows: reduction of these 3 was attributed to enhanced combustion kinetics, as H_2 combustion produces the oxidizing species of OH and O radicals that benefit the chemistry of Hydrocarbons (HCs) combustion. Besides, gasoline fuel flow was reduced with H_2 enrichment – to maintain constant global mixture equivalence and compare the engine performance with pure gasoline – so, lesser HCs content is in the fuel, which cuts the formation of CO, CO_2 and HC and promotes economic fuel consumption. Furthermore, hydrogen has a higher diffusion coefficient than that of the gasoline, and so, the gaseous H_2 can disperse thoroughly in the charge and allow for greater mixture homogeneity and combustion completeness. On the other hand, NO_x increase was attributed to the higher adiabatic flame temperature of hydrogen [24].

Hydrogen has higher flame speed and its gasoline blend can be combusted faster. Still, as H_2 addition widen the mixture flammability limit to leaner fuel equivalence, the reaction rate will be reduced and combustion would be prolonged in lean conditions. That is why the effect of spark timing was investigated in [25]; both of the highest thermal efficiency and indicated mean effective pressure (I_{mep}) were achieved at a significantly retarded CA, compared to pure gasoline at the same equivalence. The effect of H_2 on allowing a leaner operation was studied in [26]; H_2 was added at a constant V_F, while gasoline flow rate was gradually reduced until the lean limit (LL) was reached. LL was remarkably extended to an equivalence of 2.55, instead of 1.45 with unblended gasoline. In [18], the cyclic variations in I_{MEP} were studied statistically, and H_2 was found to smoothen engine operation as identified by a limited scatter in both the I_{mep} and CA durations of heat release, when plotted against the number of cycles. This smooth operation effect was found to prevail in cold starting conditions, as reported in [19]. Reduction in flames development and heat release periods was attributed to the lower ignition energy of H_2 and its higher flame speed [24], compared to gasoline. In [20], reported is an interesting study of combining the benefits of lean combustion with H_2 injection to achieve load control. The results reported a significant reduction in NO_x at low and part-load conditions and an increase in the thermal efficiency for all loads. On the other hand, this H_2-assisted lean operation at low loads suffered an increase in the CA combustion duration, which compromised the engine stability.

As perhaps in a next step, the use of standard hydroxygen gas (HHO) – produced by water electrolysis and consisting of H_2 and O_2 in 2:1 volume ratio – was investigated in [21,22] and compared with H_2 enrichment at the same V_F of the intake air. Collectively, it was found that HHO-gasoline blends can provide a comparable performance to H_2 blends, if not better. HHO was claimed to grant a greater enhancement in thermal efficiency and B_{mep} and notably extend the stable LL of H_2-gasoline blends. HHO was reported to reduce the CA of heat release duration. Such is desirable as it yields, combined with optimized spark timing, the heat release process to start-and-end in almost constant volume conditions (state of an ideal thermodynamic cycle), and so, enhancements in engine efficiency would be more pronounced. Notably in [21], standard HHO addition was calculated to increase the energy flow to the engine, contrary to H_2, as it gets to higher V_F while maintaining a constant global equivalence. Therefore, a higher B_{mep} realized with HHO compared to H_2. On the other hand, HHO was reported to raise NO_x to levels even higher than that of H_2, which are already higher than these of the original gasoline fuel. Easier as it seems, adding H_2 in the intake manifold substitutes some of the combustion air. Such can be thought to deteriorate combustion at some point if the hydrogen content got very high such that the charge entering the cylinder did not have sufficient O_2 concentration to promote combustion completeness. Moreover, H_2 lower density might dramatically inflect the engine volumetric efficiency (less mass in cylinders). Another study [23] attempted to investigate the effect of a variable H_2 content in HHO gas, and reported an almost constant CO emission irrespective of the hydrogen fraction as it changed within 0–100%, and that H_2 fraction would control the diameter of particulate emissions.

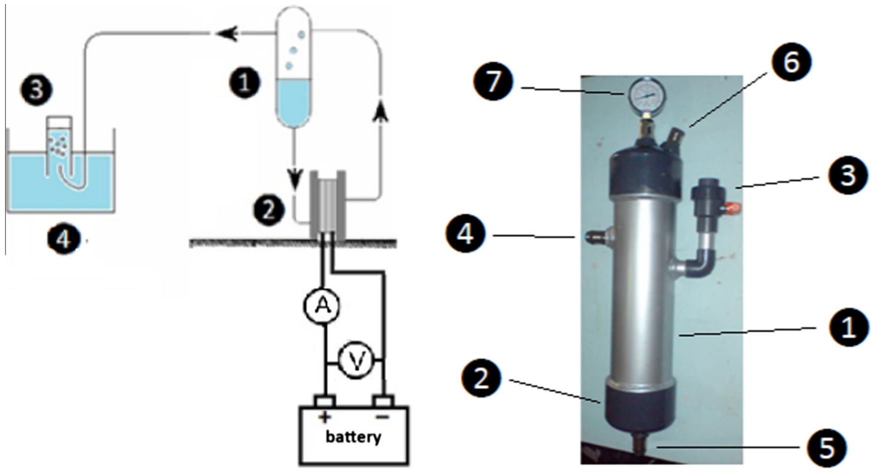
There is more to be learned regarding the use of H_2 or HHO in gasoline engines. The goal is to emphasize the great qualities they offer such as increased efficiency and peak pressure, and alleviate the drawbacks of higher NO_x and reduced mass of the cylinder charge. The first step in this endeavor is to design a hydrogen generator capable of delivering the required flow for optimum performance, and to be at an acceptable size and weight for installation on a passenger vehicle. This would be the main objective of the present study.

2. Experimental setup and test procedure

2.1. HHO generator

2.1.1. System description

HHO generator used in this study is shown in Fig. 1. It consists of separation tank (1) which supplies the HHO cell (2) with continuous flow of water to prevent the increase in the temperature inside the cell and to provide continuous hydrogen generation.



(a) (b)

Figure 1 (a) Schematic diagram of the HHO gas generation system. (b) HHO separation tank components.

Oxygen–hydrogen mixture generated from the dry cell will be back to the top of the tank with some water droplets.

$2H_2O \rightarrow 2H_2 + O_2$

Water droplets will separate and fall to the bottom of the tank with the rest of the water, while hydrogen and oxygen gases are directed to the engine intake manifold.

The HHO flow rate was measured by calculating the water displacement per time according to the setup shown in Fig. 1. The HHO gas leaves the separation tank and flows into the water open pool (4) bushing the water down of the inverted graduated cylinder (3). The volume of gas collected in the graduated cylinder per unit of time was measured as the HHO flow rate. Therefore, the cell productivity can be calculated from the following equation:

$$\text{HHO productivity} = \frac{\text{volume}}{\text{time}}$$

2.1.2. HHO dry cell

Stainless steel tumblers were used as the electrodes. There are 16 electrodes 16 × 20 × 0.2 cm thickness, configured as shown in Fig. 2 in alternate form (+,2N,−), where (+) represents the positive electrode, (N) is neutral, and (−) is the negative electrode. Amperage flows from the negative battery terminal through the neutral plates to the positive plate and onto the positive terminal. Neutrals reduce the plate voltage, share the same amperage and increase surface area for HHO production. The gap between adjacent tumblers was limited to 1 mm using rubber gaskets. In addition, 20 × 24 × 1 cm thickness cover plates were made of acrylic to provide visual indication of electrolyte level. HHO cell is supplied by electrical energy from the engine battery which is recharged by the engine alternator.

The cell productivity was tested without being connected to the engine with 2 different catalysts, KOH and NaOH, to find the best electrolyte with best concentration experimentally. The calculation was done based on the following equation:

- $m_{H2} = \frac{V}{\text{V/Kmole}} \times M$

  V: Hydrogen volume collected = 1/9 displaced volume of the cylinder 3.

  V/Kmole : Volume occupied by one kmole = 22.4 m^3/Kmole

  M: Molecular weight of hydrogen = 2
- Energy gained = $m_{H2} \times LHV_{H2}$

  LHV_{H2} = 121,000 kJ/kg
- Energy consumed = Volt × Ampere × Time
- HHO cell efficiency = $\frac{\text{Energy gained}}{\text{Energy consumed}}$

2.1.3. HHO separation tank

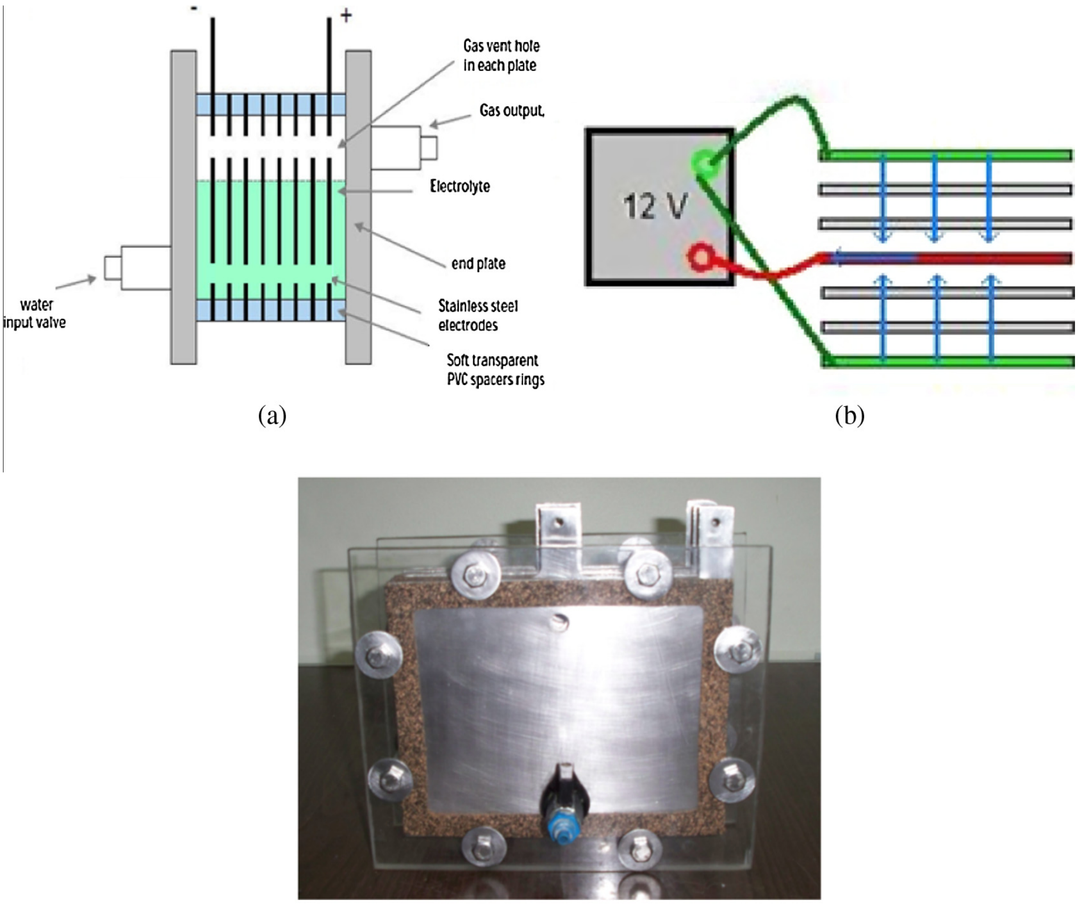
The HHO separation tank and its components are shown in Fig. 1b. It was constructed from 3.5 in PVC pipe (1) with a capacity of 2.2 L. A standard 4 in PVC end caps (2) were used to seal the top and bottom. A 0.5 in PVC ball valve (3) was used to refill the tank with Distilled water with dissolved catalyst. Hoses were used for water inlet (4) and HHO gas outlet from the cell, the condensed water and dissolved catalyst are carried to the cell through outlet (5) and HHO gas outlet (6) to the engine. It is equipped by a Pressure gauge (7) with vacuum range 0–1 bar and a spring loaded vacuum breaker.

2.2. Engine and test bed description

These research experiments were performed on Skoda Felicia engine whose specifications are shown in Table 1; tests were carried out at engine speeds of 1500, 2000 and 2500 rpm with different loads.

Different engine parameters are measured, on a test rig which is illustrated in Fig. 3. Engine load was measured by Froude hydraulic dynamometer (2), engine speed and air flow rate by Vag-Com Diagnostic Systems (VCDS) (3), engine fuel consumption is measured by self-build inclined manometer (4), and engine emission by exhaust gas analyzer model TE488 (5).

The testing is conducted for the taken engine operated with gasoline as base fuel without using the HHO cell and with using HHO cell connected to the inlet manifold. A constant speed test at variable load has been performed on this engine. The engine is tested and the measured data are collected at the



(a) (b)

(c)

Figure 2 HHO fuel cell. (a) A schematic diagram of HHO cell. (b) Plates' arrangement (using 2 neutral plates). (c) HHO dry cell with Water inlet and gas outlet ports.

Table 1 Engine specifications.

Engine model	Skoda Felicia 1.3 GLXi1.3 L (1289 cm^3)
Engine type	In-line, 4-cylinders
Fuel system	Multi point fuel injection
Compression ratio	9.7:1
Max. power	67.66 HP @ 5500 rpm
Max. torque	102 Nm @ 3750 rpm

same operating conditions for both cases of HHO/gasoline and gasoline fuel only.

For the safety purpose, HHO generation system is connected to the engine intake manifold through two flash-back arrestors which close gasoline engine in event of the intake manifold flashback. Fig. 4 shows the schematic diagram of the HHO system with safety component installed to the engine.

3. Results and discussion

3.1. HHO cell results

Fig. 5 shows the effect of KOH concentrations on the HHO cell average efficiency. It is found that 6 g/L of KOH as catalyst gives better efficiency at different engine speeds. It is also found that 4 g/L of NaOH gives better highest thermal efficiency compared to other NaOH concentration at different engine speeds as shown in Fig. 6.

Fig. 7 compares the results of 6 g/L of KOH with those of 4 g/L of NaOH, and it is found that 6 g/L KOH gives highest efficiency at different motor speeds (see Fig. 7).

3.2. Engine performance

Figs. 8 and 9 show the effect of introducing HHO gas to the combustion on both thermal efficiency and specific fuel consumption. It is noted that HHO gas enhances the combustion process through increasing engine thermal efficiency and reducing the specific fuel consumption. Comparing HHO gas to commercial gasoline fuel, HHO is extremely efficient in terms of fuel chemical structure. Hydrogen and oxygen exist in HHO as two atoms per combustible unit with independent clusters, while a gasoline fuel consists of thousands of large molecules hydrocarbon. This diatomic configuration of HHO gas (H_2 and O_2) results in efficient combustion because the hydrogen and oxygen atoms interact directly without any ignition propagation delays due to surface travel time of the reaction. On ignition, its flame front flashes through the cylinder wall at a much higher velocity than in ordinary gasoline/air

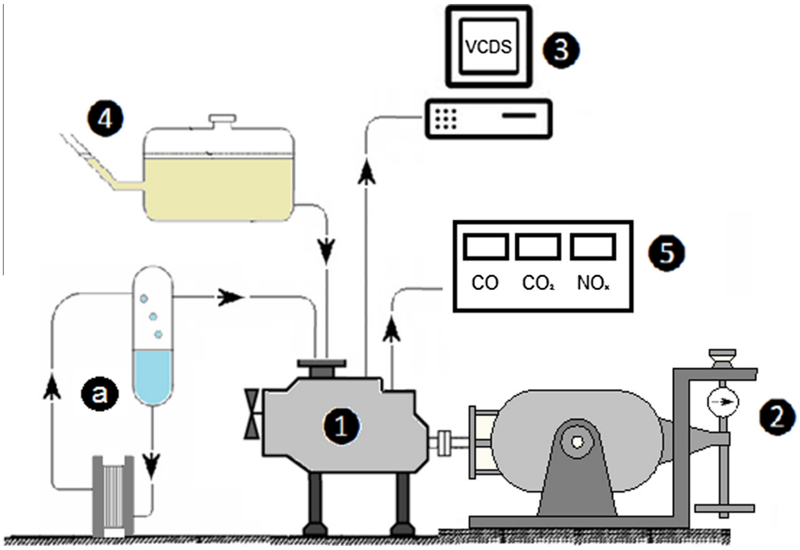


Figure 3 Schematic diagram of engine and test bed description.

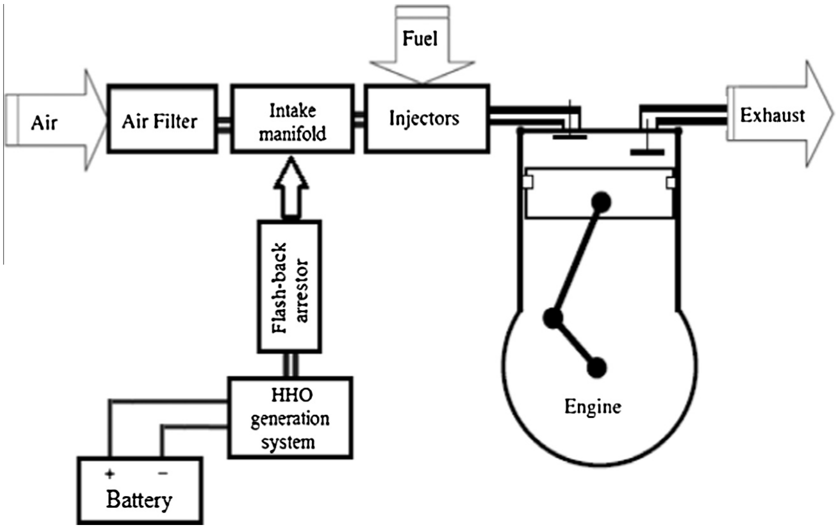


Figure 4 Schematic illustration of the HHO system with safety component installed on the engine.

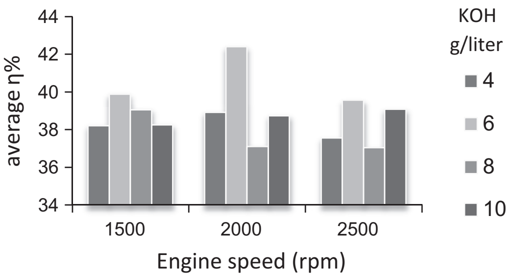


Figure 5 Average efficiencies for using different concentrations of KOH at different engine speeds.

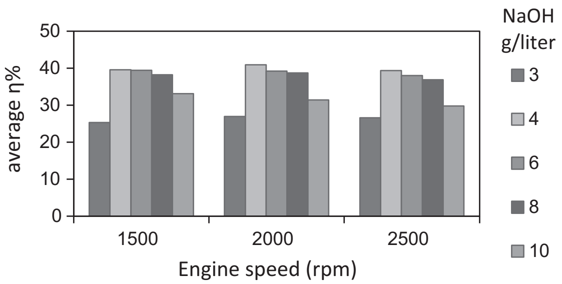


Figure 6 Average efficiencies for using different concentrations of NaOH at different engine speeds.

combustion [3]. The released heat of HHO facilitated breaking of the gasoline molecules bonds and hence increasing reaction rate and flame speed and then combustion efficiency is increased.

It is also noted that introducing HHO gas to the fuel/air mixture has a positive impact on the octane rating of gasoline fuel. Therefore the engine compression ratio can be raised and more gain in the efficiency can be obtained. In addition the

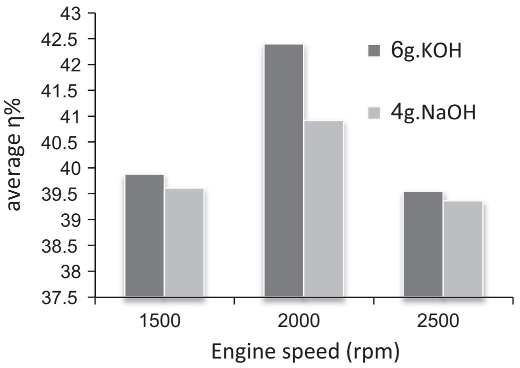


Figure 7 Average efficiencies for using concentrations of 6 g KOH and 4 g NaOH per liter at different engine speed.

ignition advance could be increased to maximize the engine torque without knocking of engine.

3.3. Engine emissions

The effect of supplying the gasoline engine with HHO gas on the carbon monoxide CO, unburned hydrocarbon HC and nitrogen oxides NO_x is presented in Figs. 10–12 respectively.

CO is highly affected by the fuel to air ratio of the engine, so using a blend of HHO gas reduces significantly the presence of carbon monoxide in the exhaust due to decreasing the gasoline fuel consumption.

In Fig. 11, it is clear that, at fixed speed the unburned hydrocarbon increases as the load increases. This is due to more fuel is introduced to achieve the desire engine torque and hence it leads to increase in HC emission. It also noted that there is a reduction in HC emission when the engine runs with HHO/gasoline than gasoline fuel only. This is owing to the high O_2 % in HHO gas being injected into the intake manifold which in turn enhances the fuel oxidation process and reduces the HC emission.

High NO_x emission is usually increased with high flame temperature and excess air. Introducing HHO into the intake manifold results in reducing the amount of gasoline which leads to lean mixture and hence, resulting in reduction in the flame temperature. Therefore, lower NO_x emission is obtained as shown in Fig. 12. HHO gas shifts all emission curves downward, since it enhances the combustion characteristics and consequently reduces the fuel consumption at any speed. The obtained results from this work have comparable trend as those for reference [21–26].

The voltmeter and ammeter were calibrated at the electrical laboratory and the dynamometer was calibrated in

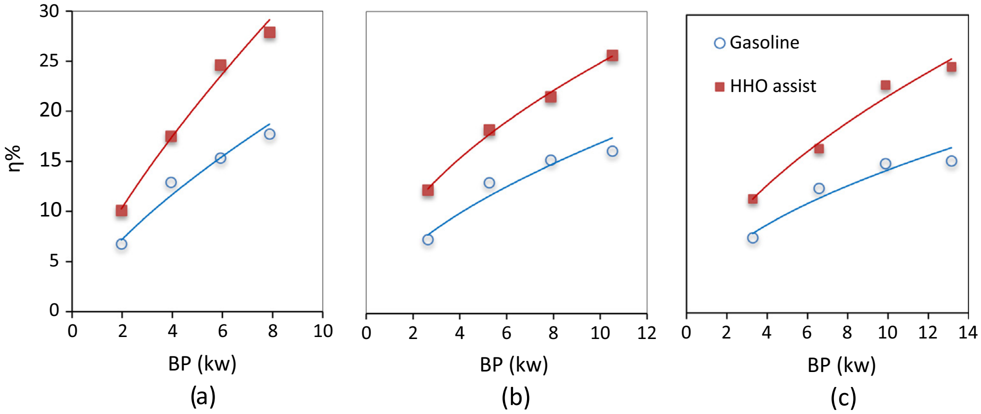


Figure 8 Overall thermal efficiency improvement with HHO over pure gasoline fuel at different engine speeds; (a) 1500 rpm, (b) 2000 rpm, and (c) 2500 rpm.

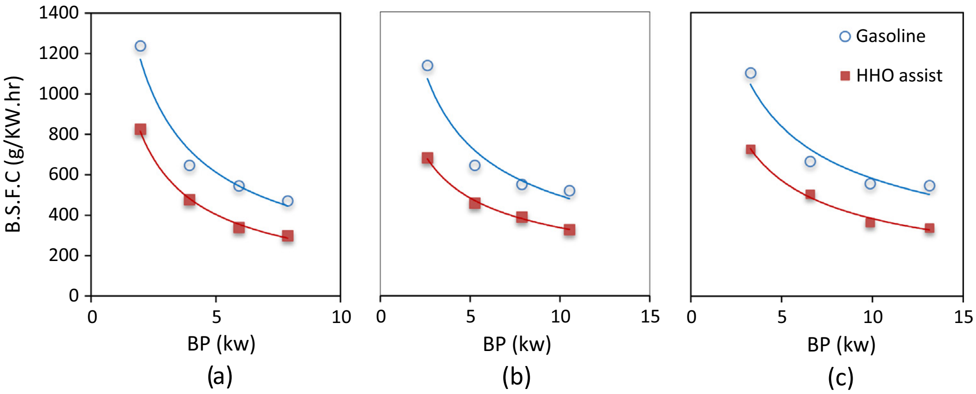
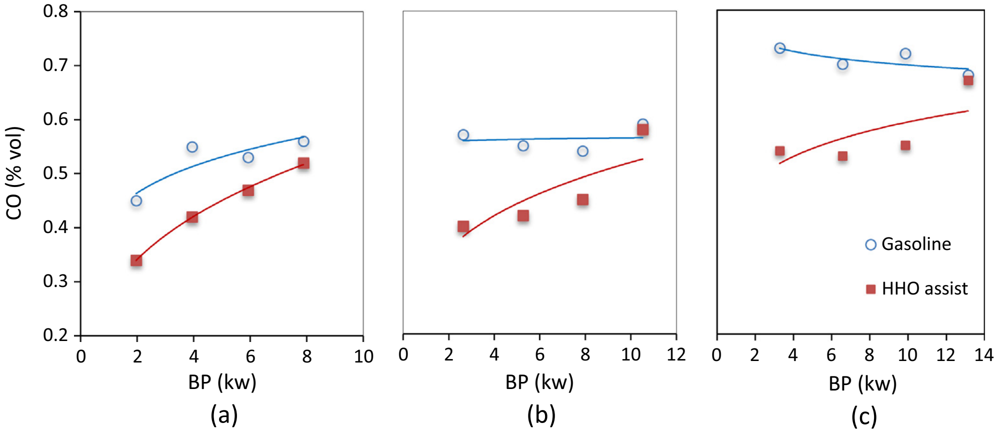
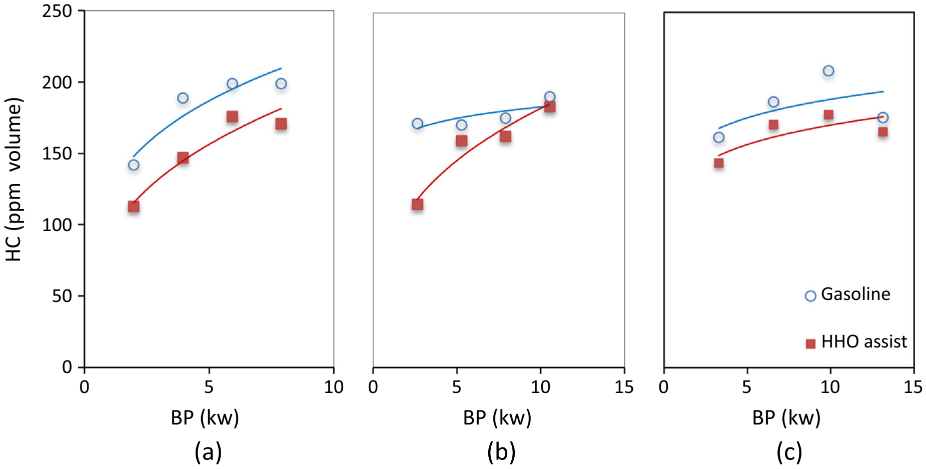


Figure 9 Effect of varying the engine dynamometer load on BSFC; (a) 1500 rpm, (b) 2000 rpm, and (c) 2500 rpm.



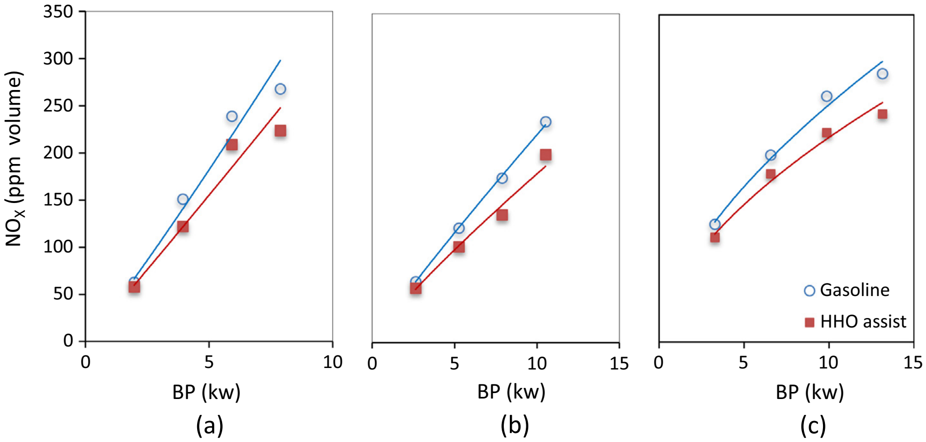
(a) (b) (c)

Figure 10 Effect of varying the engine dynamometer load on CO emission; (a) 1500 rpm, (b) 2000 rpm, and (c) 2500 rpm.



(a) (b) (c)

Figure 11 Effect of varying the engine dynamometer load on HC emission; (a) 1500 rpm, (b) 2000 rpm, and (c) 2500 rpm.



(a) (b) (c)

Figure 12 Effect of varying the engine dynamometer load on NO_x emission; (a) 1500 rpm, (b) 2000 rpm, and (c) 2500 rpm.

the internal combustion laboratory, both laboratories are located in Alexandria University. It was found that the error is less than 1%. The error analysis, which is given below, shows the uncertainty of the measured data.

$$U_{\text{volt}} = \pm 0.01 \text{ volt} \quad U_{\text{amp}} = \pm 0.01 \text{ amp}$$

$$U_{\text{Engine load}} = \pm 0.125 \text{ ib} \quad U_{\text{Engine rpm}} = \pm 50 \text{ rpm}$$

$$U_{\text{Engine volumetric fuel consumption}} = \pm 0.025 \text{ cm}^3$$

$$U_{\text{Engine power}} = \sqrt{\left(\frac{\partial P}{\partial L} \times U_{\text{Engine load}}\right)^2 + \left(\frac{\partial P}{\partial N} \times U_{\text{Engine rpm}}\right)^2}$$

$$U_{\text{Engine power}} = \sqrt{\left(\frac{N}{2800} \times 0.125\right)^2 + \left(\frac{L}{2800} \times 50\right)^2}$$

Engine power	min engine rpm 1500	max engine rpm 2500
Uncertainty	min engine load 5 ib	max engine load 20 ib
	±0.11	±0.37

$$U_{\text{HHO cell power}} = \sqrt{\left(\frac{\partial P}{\partial V} \times U_{\text{volt}}\right)^2 + \left(\frac{\partial P}{\partial I} \times U_{\text{amp}}\right)^2}$$

$$U_{\text{Engine power}} = \sqrt{(I \times 0.01)^2 + (V \times 0.01)^2}$$

HHO cell power	min HHO cell volt	max HHO cell volt
Uncertainty	min HHO cell amp	max HHO cell amp
	±0.13	±0.135

4. Conclusion

Laboratory experiments have been carried out to investigate the effect of HHO gas on the emission and performance of a Skoda Felicia 1.3 GLXi engine. A new design of HHO fuel cell has been performed to generate HHO gas required for engine operation. The generated gas is mixed with a fresh air in the intake manifold. The exhaust gas concentrations have been sampled and measured using a gas analyzer. The following conclusions can be drawn.

1. HHO cell can be integrated easily with existing engine systems.
2. The engine thermal efficiency has been increased up to 10% when HHO gas has been introduced into the air/fuel mixture, consequently reducing fuel consumption up to 34%.
3. The concentration of NO_x, CO and HC gases has been reduced to almost 15%, 18% and 14% respectively on average when HHO is introduced into the system.
4. The best available catalyst was found to be KOH, with concentration 6 g/L.
5. The proposed design for separation tank takes into consideration the safety precautions needed when dealing with hydrogen fuel.

It is recommended for the future work to study the effect of both compression ratio and ignition advance on the engine performance and emissions with introducing HHO gas into the gasoline engine.

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