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Improving SI Engines Performance to Obtain Lower Operating Cost and Emissions Using In-situ Produced HHO Gas

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Abstract: Adding hydroxy (HHO) gas to the fuel of spark ignition (SI) engine is an effective way to improve the engine performance and to reduce its emissions due to several advantages of HHO gas over gasoline fuel. In the present study, a simple dry fuel cell was developed and tested. Sodium hydroxide and potassium hydroxide were used as catalysts in two different cells A and B. Each cell was connected to the intake manifold of single cylinder air-cooled SI engine that drives 32-m head centrifugal water pump. The engine performance was evaluated under different speeds and fully open water discharge throttle in three cases with and without adding HHO gas. The measured parameters considered were fuel consumption, pump flow rate, water head, exhaust temperature, intake air mass flow rate, and engine emissions including HC and CO gases. The results showed that cell B gave higher HHO production rate allocated with lower electric current compared to cell A. On average at different engine speeds, the engine efficiency increased by 20% and 23% by adding HHO gas from cell A and cell B, respectively. Moreover, adding HHO gas from cell A and B, respectively reduced brake specific fuel consumption by average values of 15% and 17%, increased relative air/fuel ratio by 12.72% and 13.76%, reduced CO emissions by 35.2% and 43.7%, and reduced HC emissions by 15.55% and 20%. The total operating costs when running the blended engine by HHO gas for 10,000 hours reduced to about 143 $ (cells A) and 195 $ (cells B).

Keywords: Emissions; Engine performance; Fuel cell; Gasoline engine; Hydroxy (HHO).

1. INTRODUCTION

The increasing demand for fossil fuel associated with limited non-renewable stored quantities resulted in huge increase in crude oil prices in the last few years [1]. Many researchers focused on finding new effective alternative sources. Hydroxy (HHO) gas resulted from the water electrolyzer, is considered one of the best effective solutions when hybridized with an internal combustion engine. The effect of blending HHO gas on the performance of the gasoline engine was studied and investigated [2]. It was concluded that adding HHO gas increased the thermal efficiency by 10%, reduced the fuel consumption by 34%, the NOx emissions by 15%, the CO emissions by 18% and reduces the HC emissions by 14%. Sharma et al. [3] studied the effect of hydroxy (HHO) gas addition on the performance of a two-cylinder SI engine working on a four-stroke cycle. Their experimental results showed that, the average engine brake power increased by 11.5%, the specific fuel consumption decreased by 6.35%, thermal efficiency increased by 10.26% and the exhaust temperature of the engine reduced by 4%, which resulted in a significant reduction in NOx emissions. Su et al. [4] studied the effect of hydrogen addition on idle engine performance. They reported that hydrogen addition into the combustion chamber of the engine improved the idle stability which reduced the emissions. The addition of pure hydrogen in internal combustion engine had a significant effect on the performance of the engine. Furthermore, the performance and emissions of internal combustion engines using pure hydrogen were studied in literatures [5-7]. Wang et al. [8] studied the effect of adding different volume fractions of HHO on the performance of a gasoline engine. Wang et al. [9] studied also the effect of utilizing hydrogen and hydroxy on SI engine at a speed of 1400 rpm. They stated that, after hydrogen addition, the fuel flow rate decreased, but it increased with HHO blending, hydrocarbon (HC) emissions decreased, whereas NOx increased with the increase of hydrogen and hydroxy, CO emissions increased after adding hydrogen but decreased with using hydroxy. Baltacioglu et al. [10] studied the emissions and performance of compression ignition (CI) engine upon using pure hydrogen, biodiesel and HHO gas. They reported that, brake power, brake torque, and brake specific fuel consumption (BSFC) increased with HHO addition more than pure hydrogen compared with the diesel fuel, but pure hydrogen gave better values than HHO in engine emissions.

Baltacioglu [11] manufactured electronic control system to generate various hydroxy gas production flow rates using pulse width modulation (PWM) according to the demand of engine operating conditions. The effect of SI engine HHO fuel cell‘s anodes-cathodes inter-distances was investigated [12]. It was concluded that the hydrocarbons and carbon monoxide emissions at 10 mm inter distance were reduced to about 40% at different engine speeds and maximum reduction occurs at 5 mm gap. Ismail et al. [13] used a 1500 cc spark ignition (SI) engine supplied with 0.375 L/min of HHO gas. Their results showed that, fuel consumption reduced by 17% and reductions of 17%, 27% and 15% were achieved in the emissions of CO, HC, and CO_2 respectively. Yilmaz et al. [14] studied the effect of introducing HHO gas on CI engine upon using different electrolytes such as KOH, NaOH and NaCl with an electronic control unit using PWM in order to control the production rate of the gas. The influence of adding hydrogen on methanol engine's performance at lean fuel and partially loaded conditions was studied [15]. Dual-fuel injection system at engine speed of 1400 rpm with two hydrogen volume fractions in the intake air of 0% and 3% was used. The results showed that brake efficiency had been enhanced after hydrogen addition, besides, HC and CO emissions reduced.

Nabil and Dawood [16] experimentally tested the hydroxy gas which was generated by a dry fuel cell in two different engines; 150 cc with carburetor and 1300 cc with Electronic Control Unit (ECU). Their results showed that the emissions reduced by 27.4% and 21% in HC and 33% and 24.5% in CO for 150 cc and 1300 cc engines respectively. Bari and Esmaeil [17] studied the effect of addition of mixture of H_2 and O_2 resulting from water electrolysis process on the thermal efficiency of a CI engine. They stated that under constant engine speed and different additions of equivalent H_2/O_2 to make a mixture with diesel with percentages 4.84%, 6.06%, and 6.12%, the engine brake thermal efficiency increased by 2.6%, 2.9% and 1.6% respectively. Also, using loads of 19 kW, 22 kW and 28 kW respectively, led to 15.07%, 15.16% and 14.96% fuel reductions and a decrease in HC, CO_2 and CO emissions, however, NOx emission increased. Being an important factor in engine design, the possibility of reduction of HC emissions was also studied at the beginning of the engine run (cold start) [18], exhausted gas recirculation (EGR) system was tested in the CI engine [19] and with using a thermodynamic model, NO_X emissions could be studied [20].

In this study, a simple fuel dry cell was manufactured and tested using two catalysts, sodium hydroxide, denoted as cell A and potassium hydroxide, denoted as cell B. The cells A and B are connected to a small gasoline engine to investigate the effect of blending HHO gas when mixed with gasoline fuel. The operating costs of running the engine largely reduced, as well as the performance improved and the consumption of fuel and exhaust gas emissions reduced. To the best of our knowledge, no one of the previous researchers studied the effect of HHO gas on the same engine type, the economic impact of blending HHO gas with engine intake, or tested the small gasoline engine for speed above 2500 rpm.

2. EXPERIMENTAL SETUP

2.1 HHO Generator

The cell used in this experiment is a dry fuel cell which is shown in Figure 1. It contains 24 plates (made of stainless steel-grade 304L) with dimensions of 15 × 15 cm and 0.2 cm thickness (stainless steel plates were used for its good electric conductance and its chemical corrosion resistance), insulated from each other by rubber gasket insulators with a thikness of 0.2 cm. Two reinforced wood plates of dimensions 20 × 20 cm and a thickness of 2 cm were used as the cover and were followed by two plates of 20 × 20 cm with 0.2 cm thickness made of stainless steel which were inserted between the two sides of the arranged plates. The pipes used for water supply were connected to the wood plates. The plates were arranged as shown in Figure 1 in an alternative form (+, 4N,-), where (+) represents the positive electrode, (N) is the neutral, and (-) is the negative electrode. Current flows from the negative plate through the neutral plates to the positive plate [21] and the cell contains two ports; upper port for water droplets and HHO gas exit, and the second port is located at the bottom of the cell for water feed.

The two ports are connected to a separation tank as shown in Figure 2. The HHO gas, generated in the cell, flows up with some water droplets to the separation tank. The water droplets fall down to the bottom of the separation tank and flow back to the cell. The HHO gas is delivered from the separation tank to a small water tank (a bubbler) to achieve safe cell operation and to avoid fire flashback of the engine. The electrolytes used are NaOH for cell A and KOH for cell B with a concentration of 10 g/L of distilled water to increase water conductivity. The cells A and B were tested before being connected to the engine. The engine was supplied with a 13.5 V external voltage source and then allowed to run for about 90 minutes, the HHO production rate, current drawn and water temperature were measured. The cell was then connected to the engine.

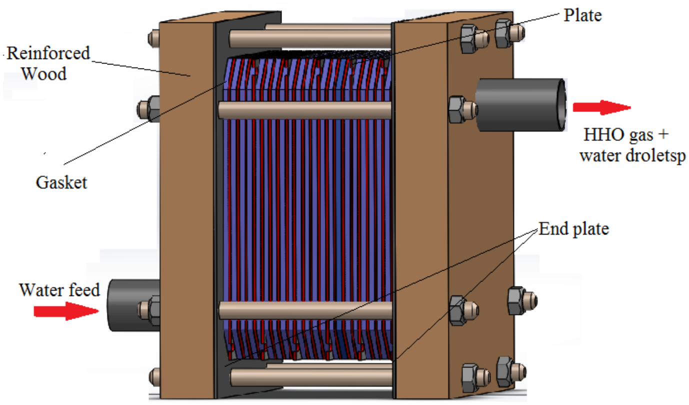

Figure 1. HHO dry fuel cell construction

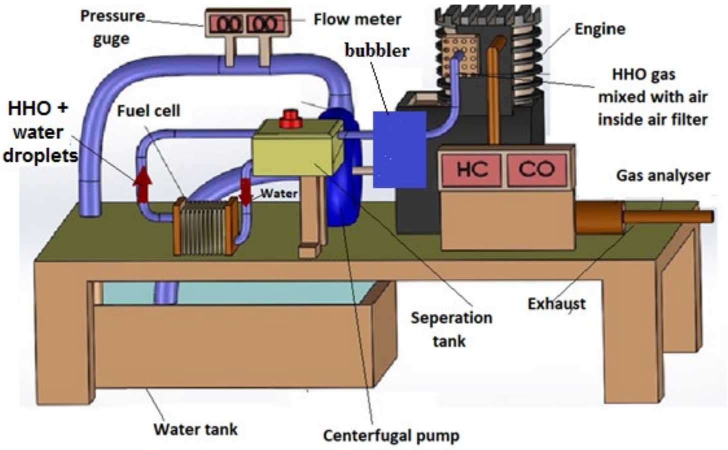

Figure 2. Experimental test rig

2.2 Engine Test Rig

The experimental test rig is shown in Figure 2. The engine used in this experiment is Robin EY 20-3, a single-cylinder air-cooled of 183 cc, fed with a carburetor and the load used is a centrifugal pump (model: PTG210) of a maximum delivery flow rate of 520 L/min, and maximum head of 32 m. The fuel used is commercial gasoline with 80 octane number.

The experimental tests were carried out under different engine speeds of 1200, 1500, 2000, 2500 and 3000 rpm with fully open pump water discharge. Three cases of the experimental work were done, running the engine without HHO gas is the first case to compare the performance of the engine with and without the cells. Then, connecting cell A in the second case and cell B in the third case respectively to the intake air manifold of the engine without any modification in the engine construction. Then measuring the parameters of the engine; fuel consumption (by calculating the time of consuming a fixed volume of gasoline fuel for different operations), pump water flow rate, water head, engine speed, and emissions. The uncertainty of HHO production rate, cell electric power, engine power, HC emissions, and CO emissions are ± 0.07%, ± 0.13%, ± 0.23%, ±10 ppm, and ± 0.05 % respectively.

In the present work, the total efficiency of the system is considered; (engine + pump) regardless of the efficiency of the pump itselfe. It is known that the efficiency of the centrifugal pump changes dramatically with the changes of the impeller speed. From the experimental test, for example, at 1500 rpm engine speed, the efficiency of the pump will be the same if the engine runs with gasoline only or hybridized with HHO gas. Therefore, the output power from the system is assumed to be the hydraulic power delivered by the pump (Equation (1)). For simplicity and for achieving a comparison between gasoline and gasoline + HHO, the thermal break efficiency of the engine is calculated based on the load delivered by the pump as

$$p = P \times Q \tag{1}$$

where p is engine power (W), P is water pressure (Pa) and Q is water volume flow rate (m^3/s). The density of water is taken as 1000 kg/m^3. The system efficiency, η is calculated as:

$$\eta = \frac{p}{\dot{m}_f \times C.V} \tag{2}$$

where η is engine thermal efficiency, $\dot{m}_f$ is fuel consumption rate (kg/s) and $C.V$ is Gasoline calorific value (44000 kJ/kg). The BSFC is calculated as

$$BSFC = \frac{\dot{m}_f}{p} \tag{3}$$

Engine intake air is presented as the ratio of actual air-fuel ratio to the theortical air-fuel ratio which is called the relative air/fuel ratio, λ. It can be obtained as

$$\lambda = \frac{(A/F)_{actual}}{(A/F)_{stoic}} \tag{4}$$

3. RESULTS AND DISCUSSION

3.1 HHO Generator

As mentioned earlier, each cell must be tested separately for a time of 90 minutes before connecting to the intake air of the engine. At the beginning of operation the average production rate of cell A is relatively lower than that of cell B, but after 60 minute of operation, the production rates of cells A and B increase rapidly as shown in Figure 3. Increasing the production rates for the two cells with time subsequently increases the drawn electric current and water temperature (Figures 4 and 5), respectively. Cell B shows more stability and more compatibility with metallic components compared to cell A. Nevertheless, it is caustic and dangerous if it is not handled carefully [21]. Part of the electric power is consumed in water heating which increases the water temperature, increases the ionic conductivity of the electrolyte and leads to surface reaction [22].

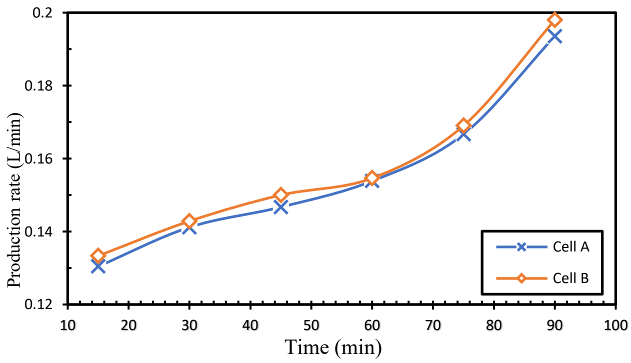

Figure 3. HHO production rate over time

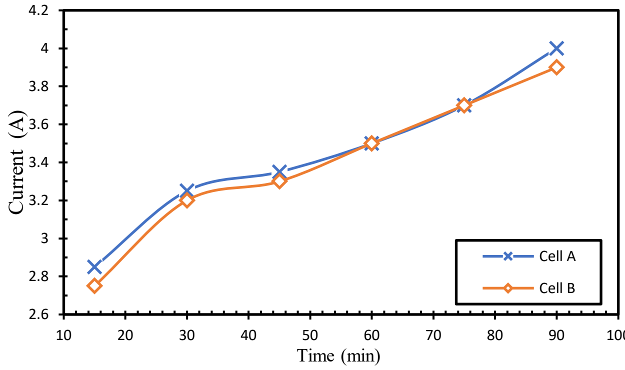

Figure 4. Variation of drawn cell current with time

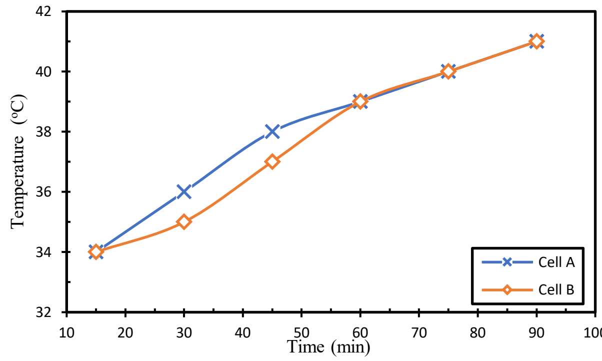

Figure 5. Variation of cell temperature with time

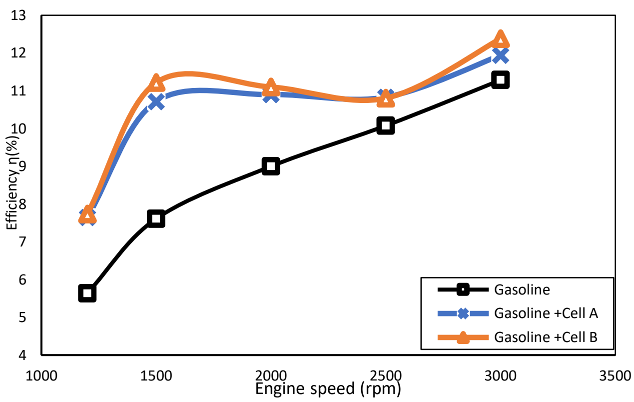

Figure 6. Variation of thermal efficiency with engine speed

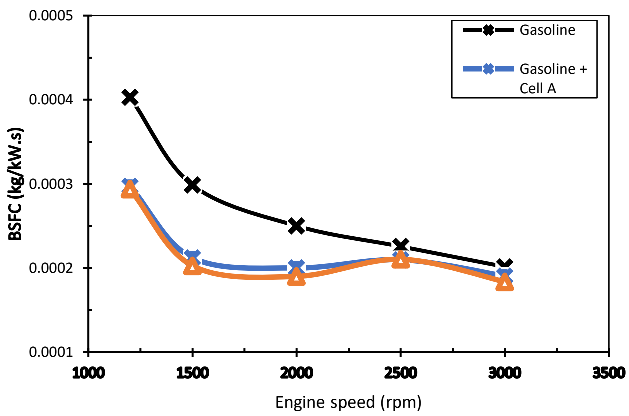

Figure 7. Effect of HHO gas on BSFC for different engine speeds

3.2 Engine Performance

The effects of HHO gas addition on the engine efficiency and BSFC are shown in Figures 6 and 7, respectively. The general trend of the curves indicates an improvement in engine efficiency for different engine speeds. HHO gas enhances the average thermal efficiency by average values of 20% and 23% and reduces the BSFC by average values of 15% and 17% for cell A and cell B respectively. At low engine speed range, the value of BSFC is relatively high as a result of low load at these speeds.

Engine thermal efficiency and BSFC represent the economy of the engine. HHO gas enhances these two parameters results for having several advantages over gasoline fuel. Specifically, HHO increases the octane rating of any fuel, which means how much the fuel can be compressed before it ignites [13]. The increase of the octane rating will increase the engine's thermal efficiency because the combustion will be much closer to the top dead center of the cylinder [1].

3.3 Engine Emissions

Introducing HHO gas into the gasoline engine causes a significant effect on engine exhaust emissions. HHO gas leads to more excess air entering the engine as is clear from Figure 8. Adding HHO gas increases the relative air fuel ratio by average values of 12.72% and 13.76% for cells A and B respectively. Figure 9 shows the variation of CO emissions with engine speed. Generally, there is an average reduction of 35.2% and 43.7% in CO emissions for cells A and B respectively. The variation of HC with engine speed is shown in Figure 10, and the average reductions of HC at different engine speeds obtained for cell A and cell B were 15.55% and 20% respectively. Reducing the emissions level of the engine leads to a significant effect on decreasing air pollutants which negatively affects the environment and human health. The reduction of engine emissions occurs as a result of the good chemical structure of HHO gas rather than gasoline. Hydrogen and oxygen gases exist in HHO as single two atoms per combustible units with an independent cluster, while gasoline fuel consists of thousands of large molecules of hydrocarbons [22]. In addition, HHO gas has a higher flame velocity than gasoline.

4. ECONOMIC POINT OF VIEW

The cost, safety, economic operation, and life time are considered the most important factors that the consumers are looking for and taking into consideration in any new project. As mentioned earlier, introducing HHO gas into the engine has a significant effect on enhancing the performance of the engine. Adding HHO gas to SI engine will improve the thermal efficiency and reduce the fuel consumption and the exhaust emissions of the engine. Cost performance analysis mentioned herein is based on the schematic diagram shown in Figure 11. It is imposed that, an electric generator; run with gasoline, is used to deliver the cell with the required electric power. The total efficiency of the generator, η_g was assumed to be 25%. See Equation (5) where $P_{electric}$ is the electric power delivered by the generator. A part of the fuel saved from the use of HHO gas will be delivered to the gasoline electric generator in order to supply the cell with the required electric power and the rest of the fuel saved is considered to be the "net saved fuel" as shown in Figure 11. The net saved fuel is calculated as $net\ savedfuel\ = saved\ fuel\ - fuel\ consumed\ in\ generator$ (kg/s). The fuel consumed can be obtained as

$$fuel\ consumed\ in\ generator = \frac{P_{electric}}{\eta_g \times C.V} \tag{5}$$

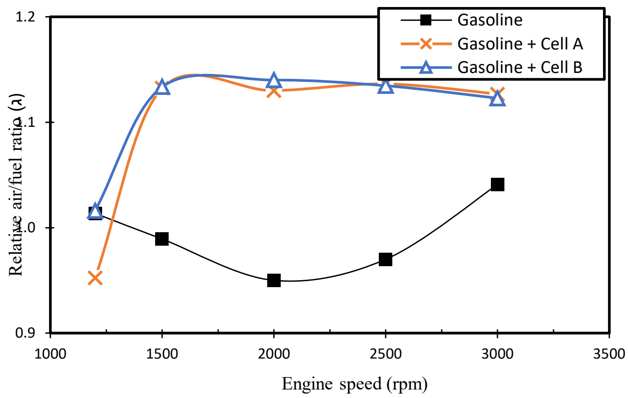

Figure 8. Variation of relative air/fuel ratio, λ with engine speed

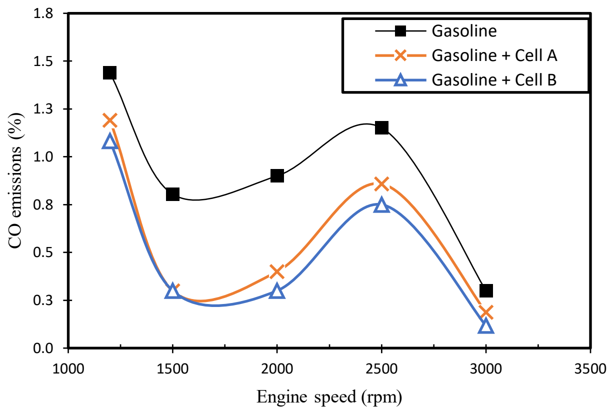

Figure 9. Effect of HHO gas on CO emissions

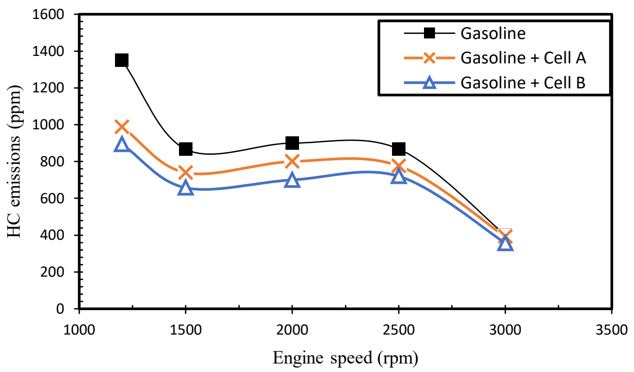

Figure 10. Effect of HHO gas on HC emissions

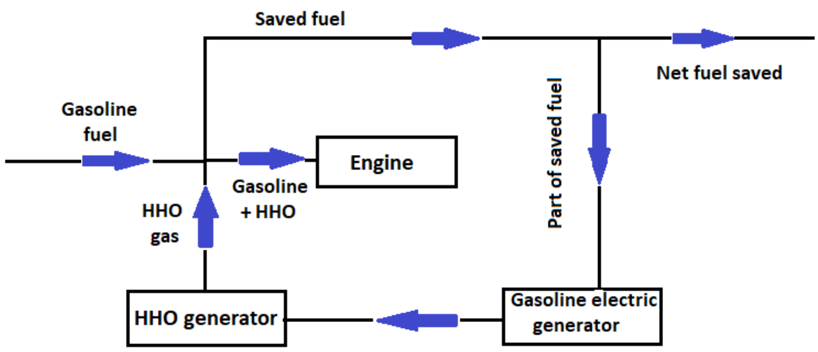

Figure 11. Schematic diagram used for calculating the amount of fuel and money saved

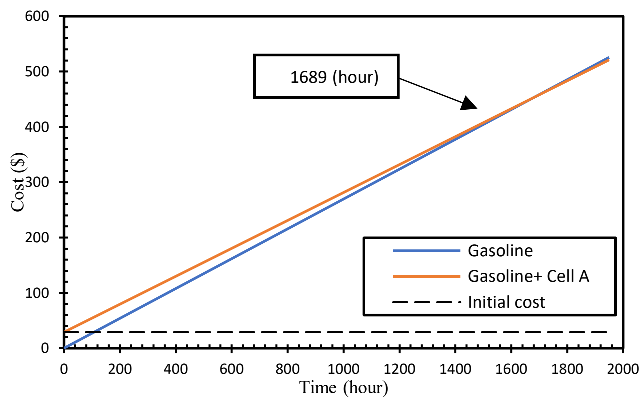

Figure 12. Total cost of cell A compared to gasoline only (initial cost of cell A = 29 $, average running cost = 0.252 $/h of gasoline + cell A and average running cost of gasoline = 0.2696 $/h)

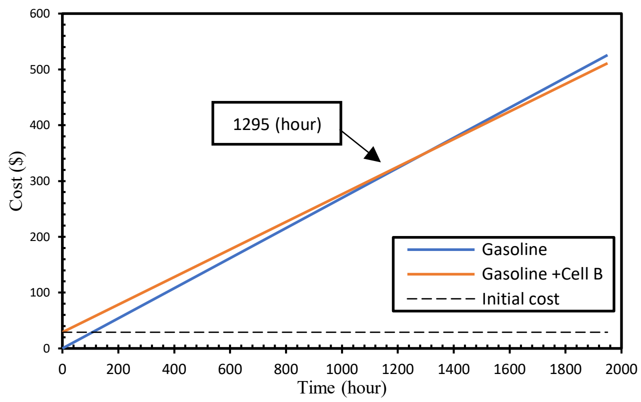

Figure 13. Total cost of cell B compared to gasoline only (initial cost of cell B = 29 $, average running cost = 0.247 $/h of gasoline + cell B and average running cost of gasoline = 0.2696 $/h)

The results of the total cost (initial cost + average running cost) for cell A and cell B compared to gasoline-only are illustrated in Figures 12 and 13 respectively. The initial cost of the HHO system is calculated and is found to be 29 $. It may be noticed from Figures 12 and 13 that cell B is better than cell A as it recovers its cost after 1,295 hours of engine running rather than cell A which required 1,689 hours to recover its cost. Besides, cell B gives better results in terms of engine performance (thermal efficiency, fuel consumption rate and engine emissions). If the engine is allowed to run for a period of 10,000 hours with the aid of HHO gas, the saved money will be 143 $ and 195 $ for cell A and cell B respectively. The benefit from using HHO gas may be relatively small but it is accepted for this small-size SI engine (183 cc) which was used in this study. The benefit will increase if the gas is used with larger scale engines.

5. COMPARISONS

It is worth mentioning that these results were obtained by using a new manufactured dry cell for generating HHO gas and blending it into a small engine with the previously mentioned specifications at different speeds. The results showed a significantly high improving efficiency, low gas emissions, and low operating costs. This work is not obtained by any other researchers till now as shown in Table 1, which represents the brief conclusions and comparisons between the present study and some of the previous studies.

Table 1. Comparison between the present study and some of the previous studies

Authors	Gasoline Engine Type	Type of cell and catalysts	RPM	Results
Present work	Robin Air-cooled,4-stroke, Gasoline engine183 cc	Dry cell Potassium Hydroxide (KOH) and Sodium Hydroxide (NaOH).	1200 to 3000	1. KOH gave higher production rate rather than NaOH, 2. HHO gas increased the thermal efficiency at different engine speeds by average values of 20% and 23% for cell A (NaOH) and cell B (KOH)

				respectively and reduced the BSFC by average values of 15% and 17% for cells A and B respectively. 3. Relative air/fuel ratio increased at different engine speeds by average values of 12.72% and 13.76%. 4. CO emission is reduced at different engine speeds by average values of 35.2% and 43.7% for cells A and B respectively. 5. HC emission reduced at different engine speeds by average values of 15.55% and 20% for cells A and B respectively. 6. Cell B is better than cell A as it recovered its cost after 1,295 hours of engine running compared to cell A which required 1,689 hours to recover its cost.
M. M. El-kassaby et al. [2]	Skoda Felicia 1.3 GLXi gasoline engine (1289 cc) In-line, 4-cylinders	Dry cell Potassium Hydroxide (KOH) and Sodium Hydroxide (NaOH).	1500 to 2500	By using KOH catalyst (6 g/L), two neutrals cell and 1 mm plates distance, the maximum HHO gas production rate (18 L/h) was obtained. In addition, the engine thermal efficiency improved by 10%, the fuel consumption reduced by 34%, and the CO, HC, and NOx emissions reduced by 18%, 14%, 15% respectively.
Sharma et al. [3]	Four stroke, four cylinder, Inline, DOHC, MPFI petrol Engine (1197 cc)	Wet cell Potassium Hydroxide (KOH) and Sodium Hydroxide (NaOH).	1500	Mixing of HHO gas with fuel of the petrol engine led to increase of the brake power and the brake thermal efficiency by an average of 11.5% and 10.26% respectively and reduced the specific fuel consumption and the exhaust gas temperature by an average of 6.35% and 3.9% respectively.
Ismail et al. [13]	Gasoline engine (Chevrolet, Lanos, 1500 cc, model 2012)	Dry cell Sodium Hydroxide (NaOH)	1000 to 2400	The blended HHO gas to the petrol engine led to the reduction of fuel consumption by 15%, reduction of CO and HC emissions by 17%, and 27% respectively, and increased the CO_2 and O_2 emissions by 15% and 1% respectively.
Nabil and Dawood [16]	Dayune 150 cc Single cylinder, 4- strokes, air-cooled and Mitsubishi 1298 cc Lancer 1.3 GL 4 cylinders, 4 e strokes, water-cooled.	Dry cell Sodium Hydroxide (NaOH)	1100 to 2500	The fuel consumption reduced by 14.8% for 150 cc engine and 16.3% for 1300 cc engine. The CO and HC emissions reduced by 33% and 27.4% for 150 cc engines respectively, and reduced by 24.5% and 21% for 1300 cc engines respectively.

6. CONCLUSION

A simple fuel dry cell was manufactured and tested using two catalysts: (NaOH) and (KOH). Then it is connected to a 183 cc single-cylinder air-cooled engine (Robin EY 20-3) to study the effect of HHO gas on the performance, emissions and economics of SI engines. The following conclusions were obtained:

1. KOH gives a relatively higher production rate than NaOH because it has more stability and compatibility with metallic components.
2. Addition of HHO gas enhances the combustion properties at different engine speeds, this leads to the increase of thermal efficiency by 20% and 23% and reduced the BSFC by 15% and 17 for cells A, and B respectively.
3. In high engine speed range between 2500 and 3000 rpm, introducing HHO gas leads to an increase in the thermal efficiency by 16.9% and 18.7% and reducing the BSFC by 6.3% and 7.8%, thus leading to a reduction of 7.9% and 15% in HC emissions and 27.9% and 40.3% in CO emissions for cells A, and B respectively.
4. CO emission is reduced at different engine speeds by average values of 35.2% and 43.7% and HC is reduced by average values of 15.55% and 20% for cells A and B respectively.
5. Cell B is better than cell A as it recovers its cost after 1,295 hours of engine running compared to cell A which required 1,689 hours to recover its cost.

6. Upon running the tested (183 cc) engine for 10,000 hours, using HHO gas will reduce the total cost of cells A and B by 143 $ and 195 $ respectively. The benefit (cost reduction) will increase upon using a larger engine.
7. According to the experimental results, it is recommended to use cell B with the engine because it gives a higher efficiency with less fuel consumption rate and low emissions level.

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