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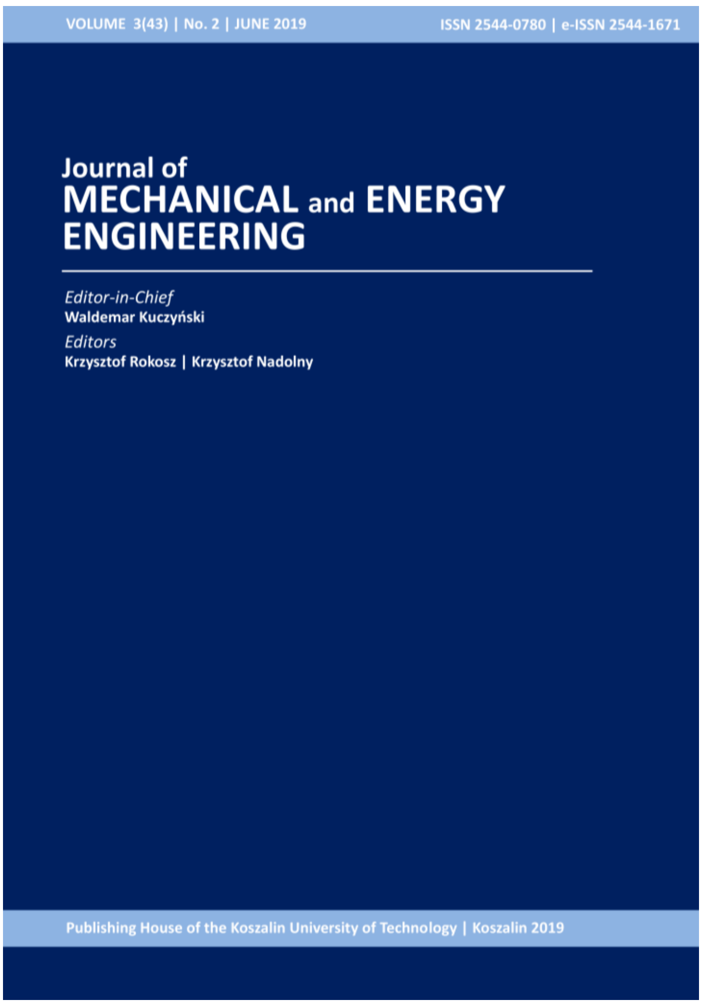

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IMPACT OF ADDITION OXY-HYDROGEN GAS (HHO) ON VEHICLE ENGINES PERFORMANCE AND EMISSIONS

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Abstract: The electrolysis process of water produces oxy-hydrogen (HHO) gas that can be used as an energy source to solve the shortage problem of fossil fuel and reduces the exhaust emissions of greenhouse gases from vehicles engines. In this study, HHO dry cell generator was designed, fabricated and tested experimentally to investigate its performance. The hybrid internal combustion engines using HHO gas is considered one of the most important studied applications. The vehicle engines performance and gas emissions are investigated for two different engines; 150CC with carburetor and 1300CC with Electronic Control Unit (ECU). The results recorded the consumption of the fuel is reduced by 14.8% for 150CC engine and 16.3% for 1300CC engine. HHO gas reduced the emission gases by 33% and 24.5% reduction in CO and 27.4% and 21% reduction in HC for 150CC and 1300CC engines respectively. HHO gas can be efficient used as a secondary fuel for vehicle engines.

Keywords: HHO gas; engine performance; gas emissions

1. INTRODUCTION

World demand of energy is very high relative to the supply amount from the traditional sources especially the fossil fuel which is considered the start point of world crisis [1-3]. Increase in fossil fuel consumption results in decreasing its save amount, environmental pollution, global warming with climate change and health thread impacts [4-6]. So researchers studied the fossil fuel usages, applications and claimed it can be reduced by replacing it with another fuels and renewable energy sources or supporting it by secondary fuels as a hybrid system [7-11]. Hydrogen as a hybrid with fossil fuel; gasoline, diesel and LPG, had attention in research field and also commercially (BMW company) due to its combustion advantages [12, 13]. Hydrogen has limited applications due to its explosion nature causing a catastrophe. HHO gas is a mixture of hydrogen and oxygen gases with theoretical ratio 2:1 produced from water electrolysis process. HHO gas used in the last years as a hybrid with internal combustion engine fuels instead of hydrogen due to it is more safe in use with good combustion properties and easy to be created onboard. Oxy-hydrogen, hydroxyl, H_2/O_2, Rhodes gas and Browns gas, all these are alternative names for HHO gas. Oxy-hydrogen gas is considered a cornerstone in reducing the fuel consumption and at sometimes completely dispensed with as a cradle energy source. HHO gas can be obtained from dry cell and wet cell through electrolysis process [14]. Wet cell designed as plates submerged in water, while in dry cell the water runs through the plate. Wet cells have higher gas production but it required more current nevertheless dry cell more adapted to operate with moving engines since the electrolyte volume content is smaller and sealed [15].

Electric power (amperage and voltage), metal plates (charged terminals and neutrals); number, area and material, electrolyte type and percentage; these are main components of HHO generator responsible for the electrochemical ionization reactions and splitting the bonds in H2O molecule to form HHO gas [16, 17].

All researchers in the field of hybrid vehicle engines with HHO gas claimed lower fuel consumption, higher engine performance and lower gas emission than individual gasoline or diesel engines [18-27].

By this way, Wang et al. [28] improved the performance of gasoline engine by hydrogen-oxygen mixture addition. They compared the addition of hydrogen and hydroxygen with three volume fraction (0, 2% and 4%) with excess air ratio variation on the engine performance and engine emission at 1400 rpm and a MAP of 61.5 kpa under lean conditions. After adoption of ECU, the blending of hydroxygen with gasoline engine results in higher percentage of the thermal efficiency, the brake mean effective pressure and NOx emission than the conventional engine and hybrid gasoline with hydrogen engine at lean conditions with lower CO emission.

EL-Kassaby et al. [29] designed, optimized and fabricated HHO dry cell. They studied the effect of variation of the catalyst type and its quantity. They used two catalyst materials, sodium hydroxide and potassium hydroxide. The effect of HHO gas on the performance of Skoda Felicia 1.3 GLXi (1300CC) engine and the exhaust gas emissions was studied. They produced 18 l/h of HHO gas from their designed generator. The engine performance enhanced after HHO gas addition with fuel such that 10% increase in thermal efficiency and 34%, 18%, 14% 15% reduction in fuel consumption, carbon monoxide, hydrocarbons, and nitrogen oxides.

Vemula [30] investigated the performance and emission of 149CC, 4stroke spark ignition single cylinder engine with HHO gas at low engine speeds from 700 to 1500 rpm. Specific fuel consumption and total fuel consumption of the engine are decreased from 5% to 12% with addition of HHO gas. Brake thermal efficiency increased by 5-10%. Carbon monoxide decreased by 20% and NOx decreased by 62%. Rajasekaran et al. [31] investigated 150CC single cylinder engine fueled by gasoline engine and liquefied petroleum gas. This investigation was extended to introduce HHO gas to these engines. In both experiments the incorporation of HHO gas results in decrease in fuel consumption and emissions. Experimental results show introducing HHO to gasoline and LPG engines results in decrease in fuel consumption by 9.6% and 15.7%, CO concentration reduction by 27.5% and 52.1%. Sunil Raj et al. [32] studied a single cylinder air cooled 100CC spark ignition petrol engine conducted by HHO gas. They observed smooth and stable operation of the engine with HHO gas and a reduction in carbon monoxide and hydrocarbons percentage.

Musmar and Al-Rousan [33] studied the gasoline engine emissions with effect of HHO gas. The tested engine was Honda G200 (197CC) and the measurements recorded at different speed. Gasoline engine hybrid with HHO gas resulted in increase of engine efficiency, reduction of NO and NOx about 50%, reduction of CO concentration about 20% and fuel consumption reduction between 20% to 30%. Al-Rousan [34] alone studied the same engine with two different sizes of HHO generators (B and C types). He defined the cell size as a ratio of cell surface area and piston area with optimum ratio 20:1, and the needed water volume is 1.5 times the engine capacity.

CI engines integrated with HHO gas was studied by Yilmaz et al. [35]; their results recorded an increase in torque by 19.1%, a reduction in CO and Hydrocarbons (HC) emissions percentage by 13.5% and 5% respectively and a reduction in specific fuel consumption by 14%. Karagöz [36] studied the diesel engine response to the introduction of different levels of hydrogen [0%, 40% and 75%] into intake manifold of engine. The tested diesel engine was single cylinder with volume 1163CC and compression ratio 14.7 at 1300rpm engine speed and full load. Increasing hydrogen percentage results in improvement of break thermal efficiency by 1.26% and 2.1%. The percentage of decrease carbon monoxide 25%, 60% and hydrocarbons 30%, 60% by using hydrogen as a secondary fuel were; also unusual decrease up to 70.7% of smoke emission was obtained at 75% hydrogen concentration.

After these reviews, this work aims to shed the light on HHO gas through the design and fabrication of different models of HHO gas dry generator. Also, enabling efficient, affordable and robust use of HHO gas generator for vehicle petrol engines (old and new).

2. EXPERIMENTAL SETUP AND PROCEDURES

2.1. HHO gas characteristics

HHO gas has the nature of implosion due to its atomic structure, when a pure gas burned consequently the vacuum is immediately formed causing this implosion. Flame temperature of HHO gas varied according to the receipting materials. Open air gas flame temperature about 135°C, applying the gas flame to the aluminum and brick causes temperature to reach up to 702°C and 1704°C respectively. HHO gas flame is awfully directional and the molecular structure of some materials can be changed by HHO gas influence. Auto-ignition of HHO gas occurs at about 570°C at STP. The theoretical energy level of HHO gas has about 60,000 Btu/lb. HHO gas is odorless, colorless and lighter than air; it does not need oxygen for burning meanwhile the gas internally contains the oxygen. Due to the wide range of flammability and high burning velocity (1000 times of petrol vapor) the HHO gas permits the use of lean air-fuel mixture with acceptable emissions and combustion efficiency. It has abnormal adsorption to gases, liquids and solids, making it to be used as an additive to other fuel to improve the environmental quality [37].

2.2. General design and constructional parameters of HHO generator

Generally, HHO dry generator is composed of metal plates, stainless steel is preferred due to its good electrical, thermal and physical properties, specifically stainless steel 316L is used in this study, with certain number and dimension determined according to the design and the application. Stainless steel is anti-corrosive metal with melting point 1375-1400°C.

The plates are connected to the electric DC power source such that, for one stack generator, one plate has positive charge (anode), one plate has negative charge (cathode) and the reminders are neutral. Numbers of neutral plates is determined according to the design in order to divide the source voltage equally between cells with reasonable value.

Every two successive plates formed a closed compartment with the aid of rubber gasket. The rubber gaskets ensure a good sealing of any plate to touch the neighbor plate and guarantee the water and gas existence inside the generator. Rubber has thickness tolerance under pressure force with final thickness 3mm is reasonable to satisfy a convenient current resistance and suitable space permitting the HHO gas to escape freely in the required direction.

The plates have down small holes for equalizing the water level in the cells and to permit the electrons to flow under voltage drop with small friction and heat generated. Also there are upper large holes permitting the gas to vent, these hole in uppermost to increase the surface area of contact with water and to speed up the gas out. If the plate design has a rectangular shape then the smaller edge length is oriented to be the path of HHO gas.

Generator has accessories: two acrylic end cover plates with thickness 12 mm one of them has inlet water hole and the other has outlet gas hole, bolts, washers, nuts, fittings, bubbler, connectors, non-return valve, hoses and tank. The tank ensures continuous feeding of electrolyte to the generator that guarantee cooling of the generator. A bubbler is a container partially filled with water and HHO gas is fed through its bottom, and obligatory rises through the water before continuing its passage. The bubbler is important to avoid backfires from reaching the electrolyzer and is required for drying and purification of HHO gas from water vapor before reaching to the power applications [38]. Non-return valve between the electrolyzer and bubbler is safety essential in the backfire case.

2.3. Operational parameters of HHO generator

According to the required amount of HHO gas and available electric power source the number of cells and stacks are determined; also the effective area of the plates is calculated. The number of cells and the electrolyte concentration has direct effect on cell voltage. The voltage of each cell can be calculated as the source voltage divided by the number of cells (from reviews; Faraday 1.24 V, Brown 1.48 V and Boyce 2-3 V for one cell) [38]. According to Boyce approximated 2 V value for each cell make the generator working conditions are appropriated without heating.

The gap between plates and the operation cell temperature must be taken into consideration when cell amperage was evaluated. Pure water in default has a high resistance to current flow so this resistance must be decrease by adding certain amount of electrolytes. The concentration of the electrolyte in water highly affect on the cell amperage determination. During the operation, if the electrolyte concentration slight increases due to heat generation consequently the current increases in response.

The quantity of HHO gas depends on the water efficiency to pass the current and the amount of current succeeded to travel through the plate surface area. Faraday highlight, each square inch of plate surface area can support 0.54 amps of current. Faraday's first law to calculate the theoretical maximum production of HHO gas [38];

$$V = \frac{RITt}{zFP}, \quad (1)$$

where: V is volume of gas (l), R is ideal gas constant = 0.0820577 l.atm/(mol.K), I is current (A), T is temperature (K), t is time (s), F is Faraday's constant = 96485 Coulombs/mol, P is ambient pressure (atm) and z is number of excess electrons (2 for H_2, 4 for O_2).

2.4. Experimental work on HHO generators

The design of HHO generators varies according to the application, required energy from the output HHO gas, and available electrical power. Every design has limited operational conditions and performance according to the efficiency of the electrolysis process. Number of plates, plates metal, plates dimensions, type of electrolyte and its concentration and distance between plates; all these design parameters professionally affects the efficiency, durability and the productivity of HHO gas generators. The operational parameters, pressure, temperature, amperage and voltage, must be taken into consideration. Before installation of the generator in any application its performance must be investigated individually. In this study, different generators are designed, fabricated and tested; 5, 7, 9 plates single stack generators, 13 plates two stacks (2 negative and 1 positive plates) generator and 19 plates 3 stacks (2 negative and 2 positives plates) also 7 plates single stack generator was tested with different electrolyte concentrations (sodium hydroxide, NaOH), as shown in fig. 1. All these models were fabricated generally without targeted application but to investigate the behavior of HHO generators and to evaluate their performance to obtain the finger print of any generator. In each case the amount of HHO gas, amperage and temperature were measured. Experimental measurements required; voltmeter, K-type thermocouple, clamp meter, graduated cylinder, bottle and stopwatch. The amount of produced HHO gas is measured manually using water displacement from bottle in the graduated cylinder and stopwatch.

a)
b) c)
d) e)

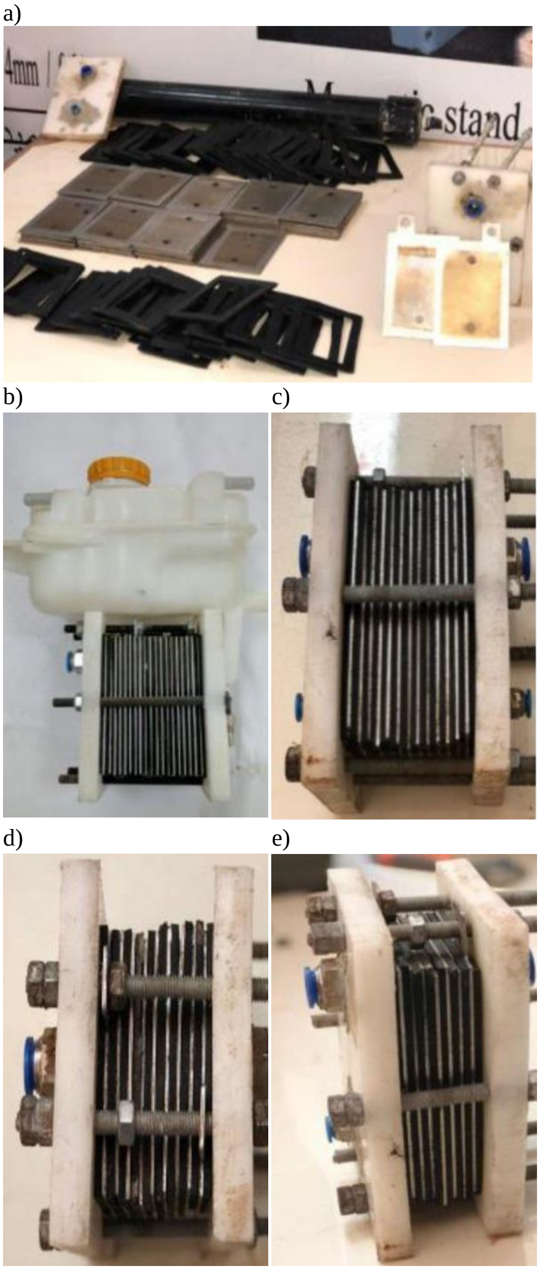


Fig. 1. Photograph of different HHO generators and construction materials: a) Materials required for generators construction; b) 19 plates, 3stacks (6cells); c) 13 plates, 2 stacks (6 cells); d) 9 plates, 1 stack (8cells); e) 7 plates, 1 stack (6 cells)

The plates are fabricated from stainless steel 316L with dimension 140×100×1 mm. According to the design and available power the number of active plates, neutral plates, and number of stacks are determined. The thickness of the used rubber gasket is 4mm between each two mean plates and between the extreme plates and the acrylic cover. This thickness with tightening the cell by nails and nuts wasdecreased to 3 mm. 12 V battery was used as a power source. According to Bob Boyce 2 V average for each cell is a good electrical pressure value for durable working conditions. Experimental test of 7 plates (6 cells) generator with different electrolyte molarity is performed firstly to choose the most suitable electrolyte concentration of the remaining experiments. From the experimental results electrolyte molarity 0.125 shows good efficiency so it is applied to all generators. The average working time of each experiment is approximately one hour. The experimental results are shown in Table 1. The experimental set-up and showed results turns out the reader for actually figuring out the pros and cons of the adopted systems.

From the experimental measurements shown in Table 1, at fixed cell voltage and plate area, the amperage is controlled by Sodium Hydroxide (electrolyte) concentration.

It can be observed, a directly proportion relationship between the electrolyte temperature and the cell amperage, which is considered generator obstacle. The increased current through the cell causes the generator become hotter which is a closed loop results in bad efficiency [38]. The electrolyte heating causes the increase of the electrolyte concentration with time as the amount of NaOH is constant while the amount of the water reduces due to evaporation. This problem can be solved by reducing the concentration of NaOH in water at starting such that after certain working time the electrolyte temperature reached its maximum value and the designed current is reached. This solution is simple but the amount of HHO gas at starting is very low till reached the required operating conditions, also the determined electrolyte concentration is evaluated by trials.

Table 1 shows, from point of view of gas productivity to used power ratio, 13 plates two stacks with 0.125 electrolyte molarity had been preferred. The generator with 5 plates has abnormal behavior due to the cell voltage has 3 V which is very large value compared to the standard cell voltage that results in high temperature and amperage. The ambient temperature is considered a main factor in determining the resistance of the water so it was measured in all tests.

Tab. 1. Performance of different HHO generators and effect if molarity variations

Item	Voltage (V)	Current (A)	Power(W)	Gas production (ml/min)	MMW (ml/min/W)	Molarity (M)	Temp. (°C)
5 plates	12	4.2-4.4	50.4-52.8	194-203	3.84	0.125	34-39
7 plates	12	3.7-3.9	44.4-46.8	179-189	4.03	0.125	30-35
9 plates	12	3.6-3.8	43.2-45.6	213-246	4.9-5.3	0.125	30-37
13 plates, 2 stack	12	4.8-5.1	57.6-61.2	469-513	8.1-8.3	0.125	31-38
19 plates, 3 stack	12	5.6-5.9	67.2-70.8	551-585	8.19-8.26	0.125	31-41
7 plates generator at different molarity	12	3.7-3.9	44.4-46.8	179-189	4.03	0.125	30-35
	12	3.8-4.2	45.6-50.4	180-199	3.9-3.95	0.25	30-41
	12	4.3-5.1	51.6-61.2	205-245	3.97-4	0.5	31-48

The plate area must be optimized such that the grater area means the grater produced gas due to the enlargement in the probabilities of bubbles escaping from the plates but the greater current is required that causing high power requirement and heating the electrolyte. It is suggested that the face area of the plates between 2 to 4 in 2 per ampere of current [38]. The electrolyte heating is a bad effect as it drives a water vapor mixes with the gas and is fed to the engine, diluting gas concentration and lowering the waited power from the hybrid engine with HHO gas. In the electrolysis process the liquid water transforms to HHO gaseous state through a phenomenon neither evaporation nor separation and with less energy.

2.5. HHO gas generator corrosion

Distilled water has high current flow resistance, so if it used alone as a working fluid in the electrolysis process no gas will be produced. However, catalyst materials (electrolytes) must be added to the distilled water to increase its conductivity. The additive catalyst materials must be carefully chosen to avoid any undesirable effects. Salts, as one of the proposed additive to water, enhance the electrolysis rate but results in corrosion and chlorine gas. The corrosion is clearly shown if a tap water was used instead of distilled one, and its effect is tremendous if the materials of generator plates can be corroded or with low grade. Fig. 2 shows the cell corrosion after working 28 hours under potential voltage 110 V (to accelerate the corrosion effect), tap water with salt as a catalyst and low grade stainless steel plates. Many substances can be used as a catalyst of the water in the electrolysis process but large numbers of them have disagreeable influences.

a) b) c)

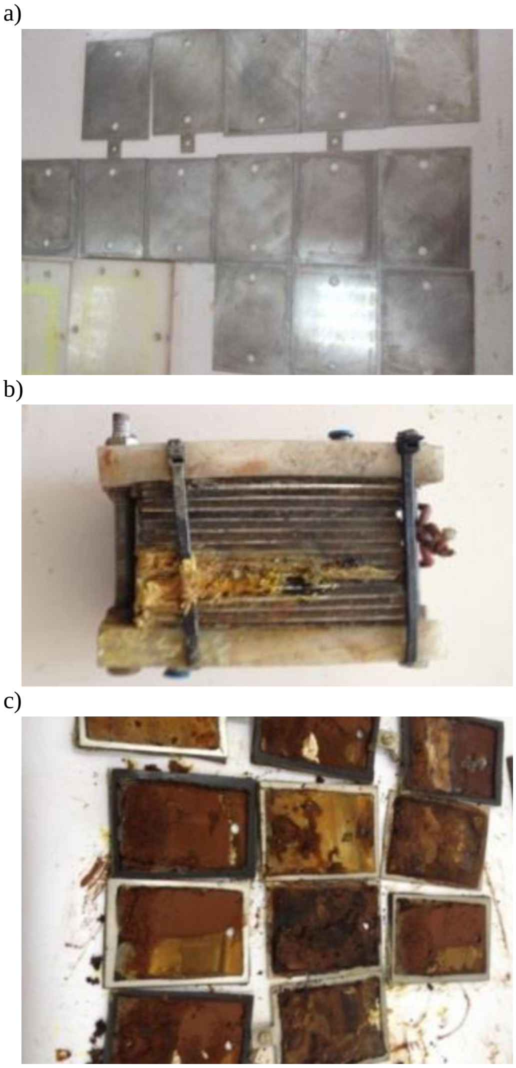


Fig. 2. Photos of generator corrosion: a) Plates before corrosion; b) Generator after corrosion; c) Plates after corrosion

Sodium hydroxide, NaOH or lye, and potassium hydroxide, KOH, are the best additives choices as catalysts. The percentage of the catalyst is a main factor in evaluating the cell current. There is a boundary to this concentration percentage, the gas production increases with catalyst concentration until the limit 28% (weight). Subsequently any increase in the concentration produces a reduction in gas production. Every time of experimental preparations, start with water, add the catalyst slowly, stirring and let the mixture to cool between the additions [39].

2.6. HHO gas quantifications

The exhaust gases from the experimental tests were analyzed in mass spectrometer. HHO gas is a combustible gas composed of a mixture of hydrogen and oxygen gases with volumetric ratio (stoichiometric) 66.66% hydrogen to 33.33% oxygen (2/3:1/3). HHO gas has abnormal behavior since it is not composed of only hydrogen and oxygen but has additional heavier species. Experimentally, HHO specific weight is 12.3 g/mol but numerically it has 11.3 g/mol with 8.8% difference in specific weight corresponds to 60.79% hydrogen (H_2, 2 atomic mass unit (amu)) to 30.93% oxygen (O_2, 32 atomic mass unit (amu)) and other heavier, high reactive and stable species resulted from bonding of 5.87% hydrogen and 2.94% oxygen [40].

2.7. Experimental work on hybrid internal combustion engines and HHO gas

The unconventional added fuel for the traditional internal combustion engines fuels speaks to lessening fuel utilization and toxin outflows emission created by these engines. This part of study aims to boost engines performance and to scale back fuel consumption by combination the traditional gasoline engines with HHO gas at the engine intake. This application of HHO gas is considered one of the most important applications.

The experiments are performed on two engines; Dayune 150CC as old engine and Mitsubishi Lancer 1.3GL as new one, the engines detailed specifications are shown in Table 2. In order to show the effect of HHO gas, the performance of engines with and without HHO generators are evaluated and compared under constant load conditions with engines speed variation from 1100 rpm to 2500 rpm for 150CC and from 1250 rpm to 2500 rpm for 1300CC. Bob Boyce prescribed the optimum amount of oxy-hydrogen varied between 0.25 and 0.5 liter per minute for each 1000CC of engine [38]. So, the tested engines capacity required 0.0375-0.075 l/min and 0.325-0.65 l/min of HHO gas for 150CC and 1300CC gasoline engines respectively. From investigations and several trials, Bob Boyce prescription of the optimum amount of oxy-hydrogen required for each engine is valid for large engines volume and not applicable to small engines. So, the required generators are 9 plates (140*100*1 mm) one stack for 150cc and 13 plates two stacks each stack 7 cells for 1300CC (140*100*1 mm).

After the generators have been installed with engines, the average cell efficiency was recorded at different engine speed and electrolyte concentrations. The cell efficiency depends on the cell productivity of HHO gas with certain calorific value as cell output energy and the time of induced electrical power as cell input energy. Fig. 3 shows the effect of 1300CC tested engine speed (1500 and 2000 rpm) and catalyst concentration (5, 10 and 20 g/L) variations on average cell efficiency. Catalyst concentration 5 g/L of NaOH gives higher efficiency at different engine speeds.

Tab. 2. Engines specifications

	Dayun engine	Mitsubishi Lancer engine
Engine type	Single cylinder, 4- stroke, air-cooled	4 cylinders, 4 – stroke, water-cooled
Start type	Electric & kick	Electric
Engine displacement (cc)	150CC	1298CC
Ignition system	CDI	Naturally aspirated petrol 4G13
Bore	0.062 m	0.071 m
Stroke	0.0495 m	0.082 m
Clearance volume	2.23168×10^{-5} m^3	9.5:1 compression ratio
No. of gears	5	5 speed manual gearbox
Cylinder Arrangement	Single cylinder	straight
Maximum power	8.5 kW @ 7500 rpm	55kW @ 6000 rpm
Maximum torque	11.5 Nm @ 6000 rpm	108 Nm @ 3000 rpm
Fuel tank capacity	13L with 20W50 fuel type	50L, EFi fuel system

The installation of the generators with engines have certain precautions such as, chose the place that exposed to air cooling and away from heat engine and rotating parts as shown in fig. 4. HHO gas directed to engine through pipe fixed at the air intake manifold. Safety precaution requires connection of flash back arrestor in the way of HHO gas from the generator to the air manifold of engine to separate the engine and generator in case of flash back. The two engines are controlled by 12V battery and according to the voltage distribution principle each compartment of 150CC and 1300CC HHO generators has 1.5 V and 1.71 V respectively. According to Bob Boyce the average voltage of any compartment must be around 2 V for optimum and durable operation. During the engines operation the battery alternator changes the voltage by range from 13.5 to 14 V. By this way, the compartment voltage becomes 1.71 V and 1.96 V respectively which are reasonable.

HHO gas generator can work with old vehicle engines operated by carburetor and with modern vehicle engines operated with computer (ECU). The performance of old vehicle engine enhanced immediately with HHO gas incorporation with simple modification which is the changing of the jet to a smaller diameter. Whenever, in modern vehicles the system needs a lot of modifications to reasonably work with HHO gas. Due to the combustion advantages of HHO gas, it causes the improvement of gasoline burning in the engine cylinder results in increase in engine performance. The vehicle computer is guessing the same amount of oxygen in the exhaust gases and increases the fuel rate to reach its normal stabilized operation conditions. By this way HHO gas has no improvement to the engine performance waiting the adjustment of the vehicle computer. So, vehicle ECU is connected to oxygen sensors to control the fuel consumption. The range of the oxygen sensor 0.2-1 V (low value means the mixture is too lean) depending on the amount of oxygen in the exhaust gases is transmitted to ECU to adapt the fuel rate. So, after HHO installation, the voltage output from the oxygen sensor must be changed.

There are some additional accessories must be incorporated with ECU and oxygen sensors to ensure the effect operation of HHO gas as shown in fig. 5. Mass air flow sensor (measure the amount of air in the intake and send the signal to ECU to introduce fuel according to the corresponding air to fuel mixture ratio), Manifold Absolute Pressure sensor (measure the vacuum pressure in the intake and send the signal instantaneously to ECU according to this value), these sensors help the engine to operate properly and must be adapted in case of HHO gas to reduce the fuel consumption, influence ignition timing and increase the engine performance. In some cases, researchers preferred using Electronic Fuel Injection Enhancer (EFIE) to emphasize the engine modifications and to ensure the reduction of fuel consumption with HHO gas but it increase the system complications. As shown in fig. 5, ECU has a great control function to save the consumed fuel and to increase the mileage with HHO gas. The data of these sensors are recorded during the experiments to show the state of fuel consumption and the effect of HHO gas.

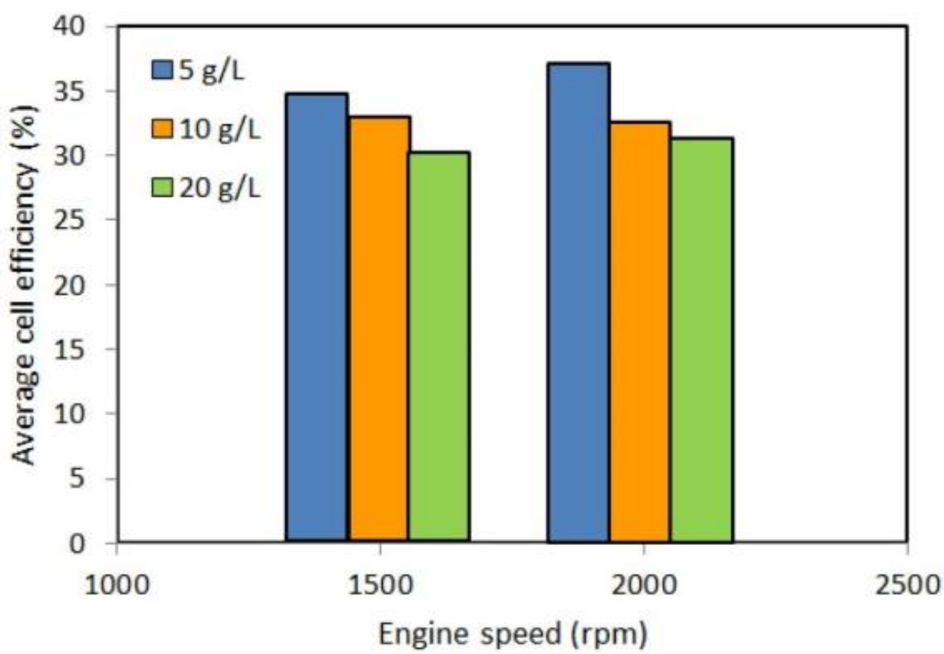


Fig. 3. Average cell efficiencies with using different NaOH concentrations at different engine speeds

Fig. 4. Photograph of the experimental setup of different engines with HHO generators: a) Dayun engine 150CC; b) Dayun 150CC; c) Dayun 150CC; d) Suzuki 1000CC; e) Daewoo Nubira 1600CC; f) Mitsubishi Lancer 1300CC

In all tests, the engine performance was recorded with and without HHO gas and compared. Code reader diagnostic scanner tool, tachometer (for engine speed measurement), K-type thermocouple (for exhaust gas temperature measurement), voltmeter, clamp meter and flow meter are equipment used in experimental work. In all experimental tests, for both engine cases, the ambient and engine temperatures are normal, the engines were at idle states and the code reader diagnostic scanner tool reading had no problem code.

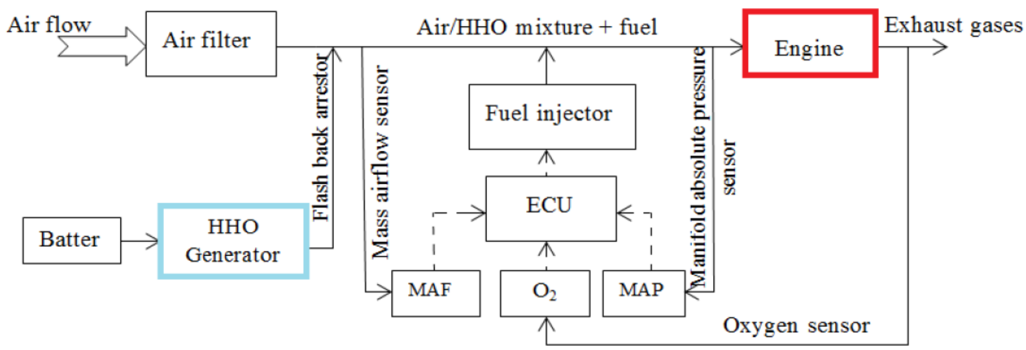


Fig. 5. Schematic drawing of modern gasoline engine with HHO generator.

3. RESULTS AND DISCUSSIONS OF ENGINES PERFORMANCE WITH HHO GAS

3.1. Engine performance

Fig. 6 shows the motor brake power efficiency at constant load and different engine speeds. Since HHO gas has calorific value higher than gasoline, the measurements recorded a growth of the engine brake efficiency with HHO gas generator 17.9% for 150CC and 22.4% for 1300CC. This enhancement resulting from the heat energy liberated from HHO burning, simplified the break of bonds of gasoline molecules, resulted in high combustion efficiency. This complete, efficient and smooth combustion in addition to the piston can safely complete its stroke closer to top dead center (TDC) were the main reasons for this engine break efficiency development with HHO gas. The resulted high power from complete combustion turned into obvious mechanical torque. At high engine speeds, for two engine cases, there are small differences of brake efficiency due to the saturation state of HHO generators has been reached, threshold gas productivity, as the amperage increased the HHO gas productivity amount still constant.

Since thermal efficiency depends on the brake efficiency and the heat input also it's an indication of combustion efficiency. Fig. 7 shows the enhancement of thermal efficiency was clear for engines with HHO gas. The recorded enhancements in thermal efficiencies were 15.7% for 150CC and 19.1% for 1300CC. This development indicates complete combustion and reduction of heat input due to the great energy content of the HHO/air/fuel mixture. Also, shorter combustion time and high flame speed results from HHO gas addition to the gasoline engines results in high thermal efficiency and a reasonable amount of combustion energy was transferred to useful power. One of the supreme advantages of HHO gas, it increases the octane rating of any fuel added with it and so enhances the characteristics of the low grade fuel and delays its ignition to approach TDC in safe similar to the high octane fuel.

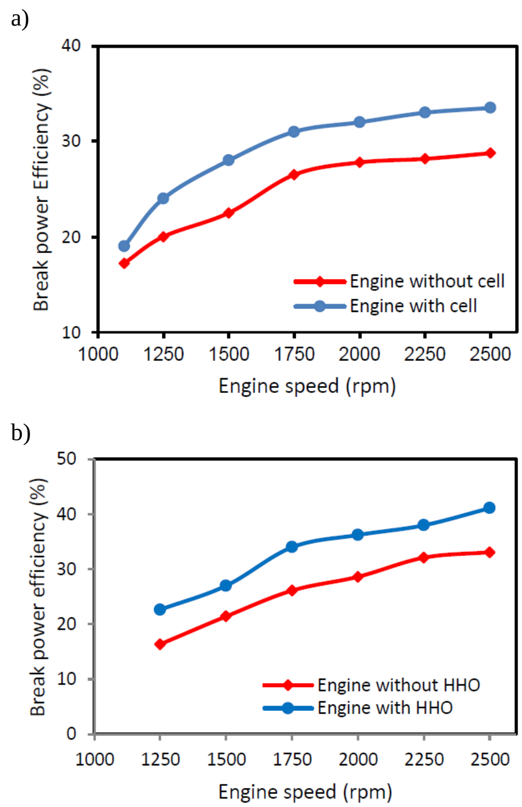


Fig. 6. Break power efficiency (%) versus engine speed (rpm) with and without HHO: a) Engine 150CC; b) Engine 1300CC

Fig. 8 shows the fuel consumption at different engine speeds with a reduction in the consumed fuel amount with addition of HHO gas to the engines. HHO gas helps the engine to reach the required power and mileage with smaller fuel amount. The reduction in fuel is approximately 14.8% for 150CC and 16.3% for 1300CC. Fig. 9 shows, as the engine speed increases the specific fuel consumption decreases while for engines with HHO gas this decrease is obvious. The values of specific fuel consumption for engines with HHO gas are lower than for the same engine without HHO gas at the same engine speed.

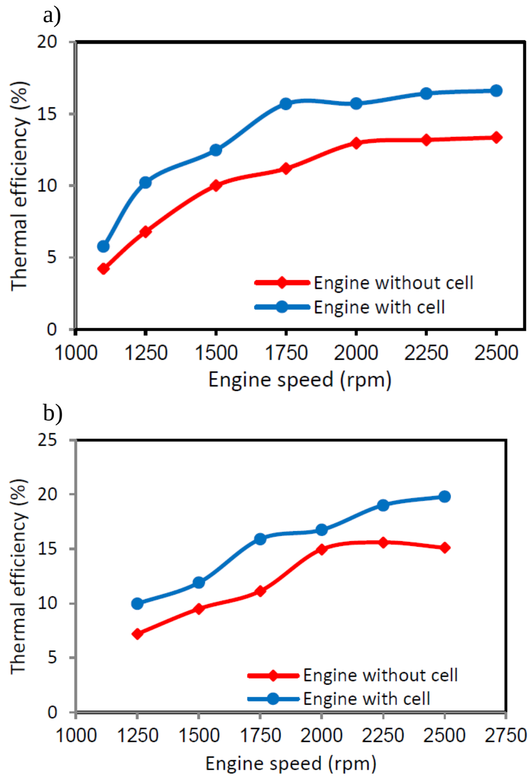


Fig. 7. Thermal efficiency (%) versus engine speed (rpm) with and without HHO: a) Engine 150CC; b) Engine 1300CC

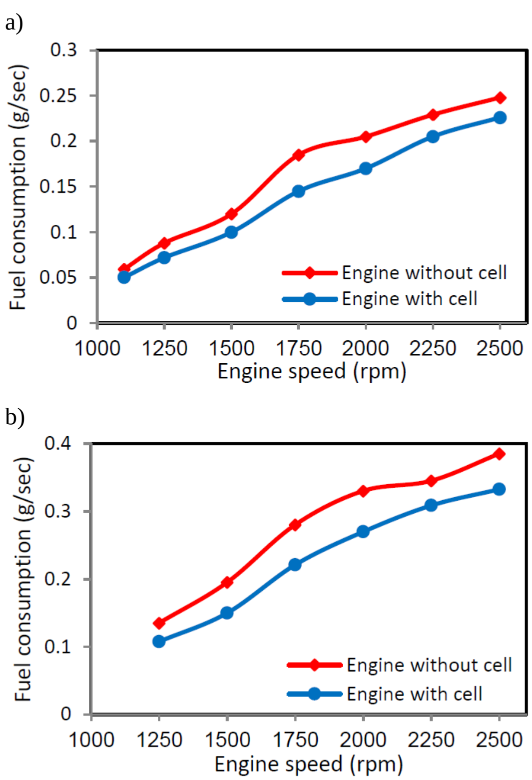


Fig. 8. Fuel consumption (g/sec) versus engine speed (rEngine 1300CCpm) with and without HHO a) Engine 150CC; b) Engine 1300CC

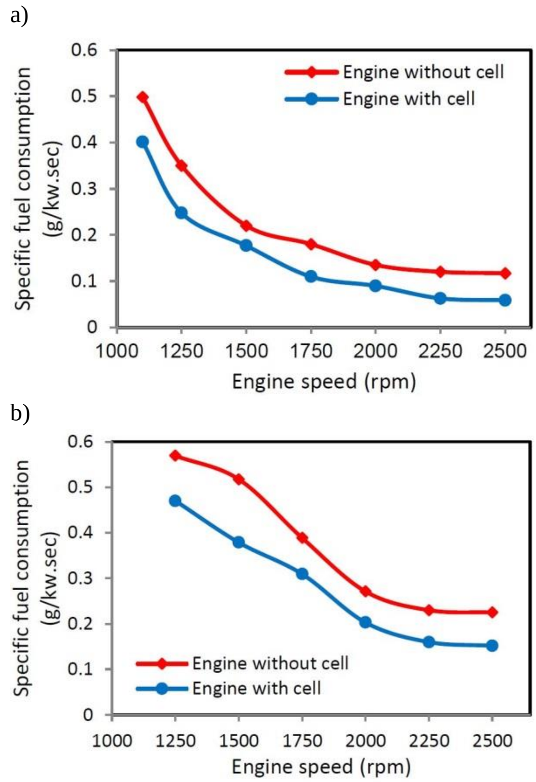


Fig. 9. Specific fuel consumption (g/kw.sec) versus engine speed (rpm) with and without HHO: a) Engine 150CC; b) Engine 1300CC

In all tests, the temperature of the engines exhaust gases increases as the engines speeds increase nevertheless for engines with HHO gas the temperature is lower than the conventional engine. Fig. 10 records the exhaust gas temperature and explains the reduction in case of engines with HHO gas. In each cases, as the engine speed increases the exhaust gas temperature increases but with lesser amounts in case of HHO gas utilization due to the enhancement in the combustion with the formation of H_2O as a combustion result that helps in decreasing the exhaust gas temperature. Also the presence of HHO reduces the consumption amount of the fuel, lean mixture phenomenon, causing a drop in the temperature.

With the same previous steps, many real tests and trials with different HHO generators, measurements and different engines performance evaluation are performed experimentally on different internal combustion engines. All experimental results are recorded and adapted to increase the engines performance. The results were promising and depend on the engine year model and driver behavior as shown in Table 3.

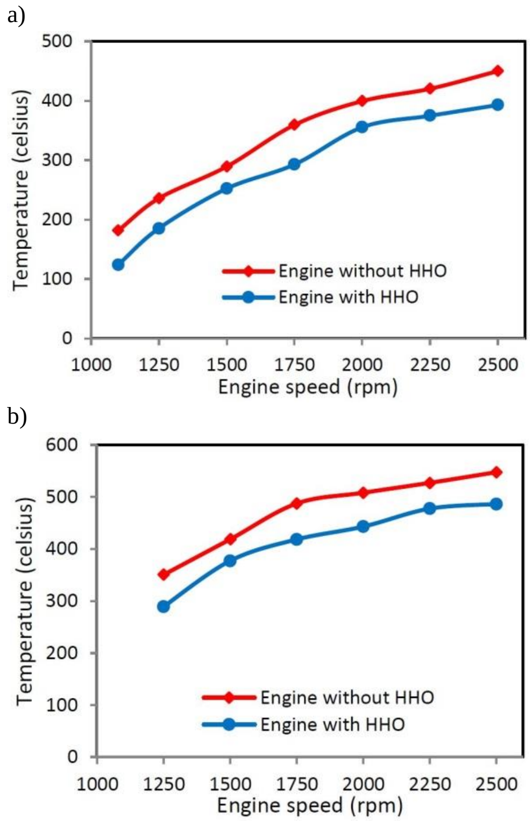


Fig. 10. Exhaust gas temperature (°C) versus engine speed (rpm) with and without HHO: a) Engine 150CC; b) Engine 1300CC

Tab. 3. Reduction percentage of fuel consumption of different engines.

Engine model	Engine size (CC)	Year model	Saving fuel consumption (%)
Renault Duster	1800	2001	27
Jeep Sheroky	3700	2011	30
Daewoo Nubira	1600	1998	21
Chevrolet Lanos	1500	2003	18
Suzuki (carburetor)	1000	2013	20
generator	500kw	-	18

3.2. Engine gas emissions

The exhaust gases are analyzed using gas analyzer for engines without and with HHO gas. The results indicate a reduction in gas emissions for engines with HHO gas. HORIBA automotive emission analyzer MX-002 (MEXA-324J) is an emission gas analyzer device used to measure the concentrations of CO and HC in the engine exhaust gases. The gas analyzer readings are shown in Table 4. That records CO and HC readings for 150CC and 1300CC engines with and without HHO gas.

As carbon monoxide emission was affected by the engine combustion efficiency and the Air/fuel ratio. So, the utilization of HHO gas with interior oxygen content enriches the engine combustion process and decreases the percentage of CO in the exhaust gases as shown in fig. 11. The reduction in CO percentage for 150CC and 1300CC using HHO gas with engines are 33% and 24.5% respectively.

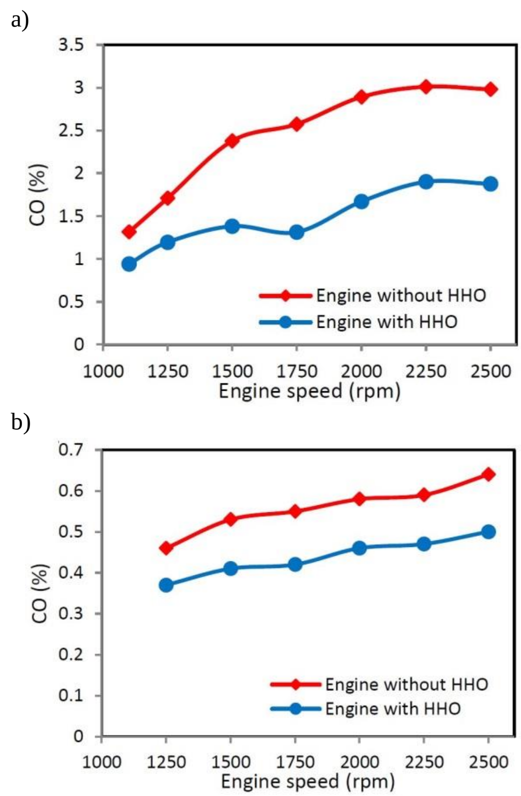


Fig. 11. carbon monoxide concentration (%) versus engine speed (rpm) with and without HHO: a) Engine 150CC; b) Engine 1300CC

Tab. 4. Gas analyzer readings of CO and HC emission gases.

Emission	150CC engine			1300CC engine		
	without HHO	with HHO	Reduction percent %	without HHO	with HHO	Reduction percent %
CO	2.45%	1.64%	33%	0.57%	0.43%	24.5%
HC	985 ppm	674 ppm	27.4%	180 ppm	142 ppm	21%

The diatomic and magnecular bonds in HHO gas atomic structure with high start response without propagation delay of ignition owing to reaction surface travel time ensures complete and efficient fuel burning and results in the reduction of emission percentages.

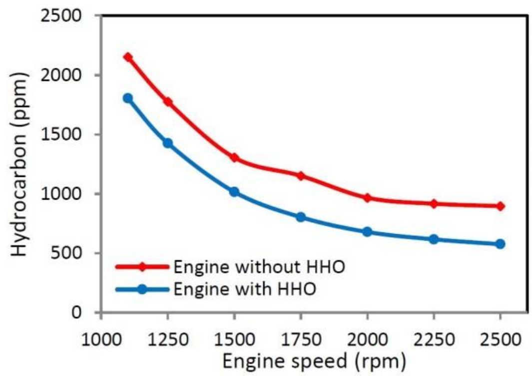
The unburned fuel, means hydrocarbons (HC), emitted with emission gases due to the incomplete burning. Fig. 12 shows HC is decreased as the engine speed is increased. HC percentage for engines blending HHO gas with air and fuel mixture was lower than the conventional engines. HC is decreased due to the increase of the fuel oxidation; as oxygen is already exist with sensible percentage in HHO gas, which results in fewer quenching distance, wide-ranging flammability and high combustion efficiency. The reduction in HC percentage for 150CC and 1300CC with using HHO gas are 27.4% and 21% respectively. By comparison with earlier works [29 & 30] have the same engine volume but different models, and approximately at the same test conditions, the present work for 150CC shows greater reduction in fuel consumption and gas emissions but for 1300CC lower reduction in fuel consumption and higher reduction in gas emission.

3.3. Experimental error and uncertainty analysis

The accuracy of the measured data must be analyzed to validate the results. After devices calibration, the measured errors decrease to small values and acceptable range. The uncertainty analysis can be calculated and depends on the error of direct measured data [29, 41]. Engine power uncertainty (UEP) depends on engine speed and engine load errors (UES and UEL) however HHO cell power uncertainty (UCP) depends on voltage and amperage errors (UV and UI) at maximum and minimum operating conditions as shown in Table 5.

$$U_p = \sqrt{\left(\frac{\partial P}{\partial x} \times U_x\right)^2 + \left(\frac{\partial P}{\partial y} \times U_{yx}\right)^2} \qquad (2)$$

a)



b)

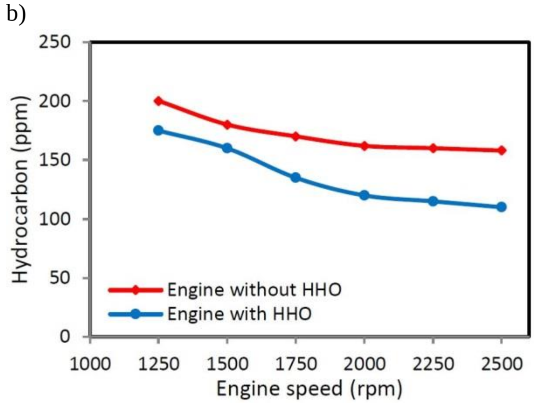


Fig. 12. Hydrocarbons concentration (ppm) versus engine speed (rpm) with and without HHO a) Engine 150CC; b) Engine 1300CC

Tab. 5. Uncertainty analysis.

Item	Engine speed (rpm)	Engine speed error (UES)	Engine load (N)	Engine load error (UEL)	Engine power uncertainty (UEP)
Maximum engine conditions	2500	±50	100	±1	±0.41
Minimum engine conditions	1100	±50	20	±1	±0.12
Item	Cell current (A)	Cell current error (UI)	Cell voltage (V)	Cell voltage error (UV)	Cell power uncertainty (UCP)
Maximum HHO cell conditions	11	±0.02	14.1	±0.01	±0.178
Minimum HHO cell conditions	4	±0.02	12	±0.01	±0.126

4. CONCLUSIONS

Oxy-hydrogen gas can be generated from dry cell by electrolysis process of water with NaOH as a catalyst. HHO gas has several advantages and several applications. Decreasing the fuel consumption and the environmental pollution are considered the main factors of using HHO gas especially in recent years since the fossil fuel is sever depleted and the environment is highly polluted. Many types of HHO dry generators were designed, fabricated, and tested. HHO gas has different applications in transportation, desalination, cooking, welding and cutting. Vehicles were considered a promising application of HHO gas, so two engines are tested 150CC and 1300CC (old and new engines). Results showed reduction 14.8% and 16.3% in fuel consumption, 33% and 24.5% reduction in CO, 27.4% and 21% reduction in HC and obviousreduction in the exhaust gases temperature for 150CC and 1300CC engines respectively. Also, 17.9% and 22.4% increase in brake power and 15.7% and 19.1% increase in thermal efficiency were recorded for 150CC and 1300CC respectively.

Multi-media content: This link shows the videos of all studied experimental tests: https://youtu.be/9VrXVaomFgM

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Biographical notes is not available.