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Research article

Influence of oxyhydrogen gas retrofit into two-stroke engine on emissions and exhaust gas temperature variations

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ABSTRACT

The generation of power and fuel sustainability that contributes to a cleaner output of exhaust gases is one of the most important objectives the world seeks. In this paper, oxyhydrogen gas is used to retrofit into a two-stroke engine. The water was electrolysed and generated a mixture of oxygen (O_2) and hydrogen (H_2) or known as oxyhydrogen (HHO) gas via an electrolytic dry cell generator. The HHO was retrofitted experimentally to investigate the engine emissions and exhaust gas temperature from a 1.5 kW gasoline engine. The engine was tested with different power ratings (84–720 W) to investigate the performance and emissions of the engine using gasoline followed by the addition of HHO. The emissions of CO and NOx were measured with different amounts of HHO added. The exhaust temperature was calculated as one of the variables to be considered in relation to pollution. The air-fuel ratios are varied from 12 to 20% in the experiment. The most appropriate air-fuel ratio needed to start the generator with the most environmentally friendly gas emission was analysed. The results showed that the addition of HHO to the engine is successful in reducing fuel consumption up to 8.9%. A higher percentage of HHO added also has improved the emissions and reduced exhaust gas temperature. In this study, the highest quantity of HHO added at 0.15% of the volume fraction reduced CO gas emission by up to 9.41%, NOx gas up to 4.31%, and exhaust gas temperature by up to 2.02%. Generally, adding oxyhydrogen gas has significantly reduced the emissions, and exhaust temperature and provided an eco-friendly environment.

1. Introduction

In recent years, the demand for energy supply is increasing compared to the supply capacity of common sources such as fossil fuels. Continuous extraction will cause a fossil fuel crisis due to depletion and a loss of emission control [1]. They will intensify air pollution, global warming and the degradation of health [2]. From vehicle engines to small-scale generators, these devices are the main catalysts that cause air pollution to the environment. Fossil fuels are classified as non-renewable and pollutants emitted by fossil energy systems, e.g. carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (CnHm), sulphur oxide (SOx), nitric oxide (NOx), radioactivity, heavy

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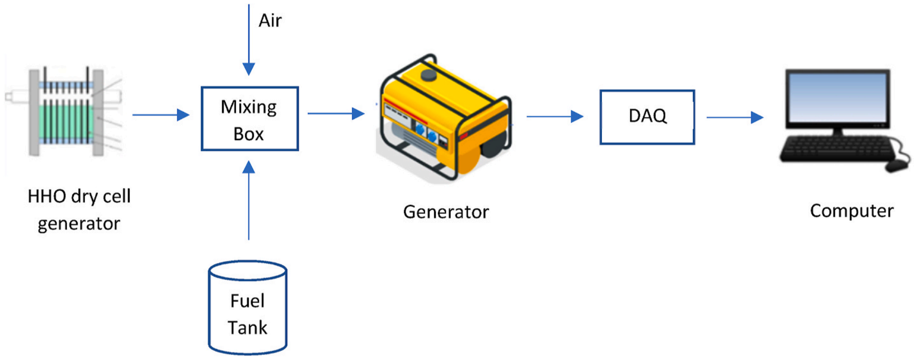
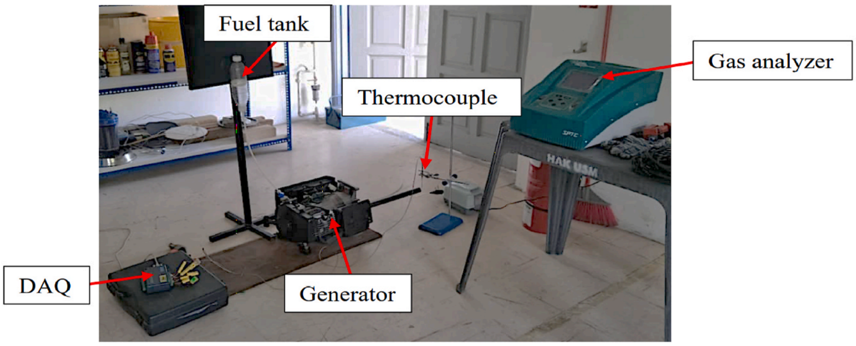


(a) Schematic of generator setup



(b) Experimental set-up

Fig. 1. (a–b) Schematic and photograph of experimental set-up.

metals, ash, and etcetera, are great and harmful. The gasoline generator operates by supplying air atmospheric pressure and converting gasoline fuel from liquid to vapour in the carburettor system [3]. The needle in the carburettor jet is crucial for controlling the amount of fuel flow into the carburettor. The stoichiometric air-fuel ratio of combustion in gasoline is between 14.7 and 15.1 [4]. Air-fuel ratio (A/F ratio) is the ratio of air mass to fuel mass used by the fuel system in the internal combustion engine. It plays an important role because it affects the fuel consumed by the engine and the emission of the exhaust gas [5]. The air-fuel (A/F) ratio must be between a certain range of minimum and maximum flammability limits to allow air and fuel to burn inside the engine. The stoichiometric fuel mixture occurs when the mixture of air to fuel is chemically perfectly balanced [6]. This process can be referred to as complete combustion. All oxygen in the air will be used by gasoline or hydrocarbons during combustion to produce water vapour (H_2O) and carbon dioxide (CO_2). The stoichiometric A/F ratio varies according to the chemical content of the fuel, therefore the quantity of oxygen required depends on the number of carbon and hydrogen atoms in the fuel. In low load conditions, the A/F ratio is most likely to fall close to the stoichiometric A/F ratio because it produces the lowest hydrocarbon (HC) and carbon monoxide emissions (CO). The A/F ratio differs from the stoichiometric ratio and can be either a lean mixture or a rich mixture [7].

Because of the low Well-to-Tank (WTT) emissions related with their production processes, alternative fuels, like synthetic fuels derived from green energy sources, have the potential to reduce Well-to-Wheel CO_2 emissions [8]. These fuels provide an additional level of CO_2 reduction since they combine the use of this emission as a raw material with renewable energy to produce a diverse spectrum of molecules that may be burned in traditional internal combustion engines [9]. Fuels such as methanol, synthetic gasoline, and e-Fischer Tropsch [10] can be obtained depending on the manufacturing method. Further processing of methanol can yield other fuels such as Oxymethylene Dimethyl Ethers [11]. Sustainable fuel can be used to replace and decrease the consumption of non-renewable fuel. Many parties are seeking alternative solutions to reduce fuel consumption and exhaust emissions from internal combustion engines. Methanol is one of the alternatives to fossil fuel [12]. In addition, biodiesel, alcohol and biodiesel from used cooking oils can be used as a sustainable and environmentally friendly alternative fuel [13]. Hydrogen is also considered to be energy carriers that can act as an additional source of fossil fuel [14,15]. It can also be used as a fuel entirely in an internal combustion engine due to its combustion advantage. The main aim of the supplementary source is not to completely substitute the gasoline, but to improve the performance of the engine by making less usage. In other words, it known as a hybrid fuel. Although hydrogen gas had many advantages, hydrogen could be hazardous because of its explosive properties [16,17].

A combination of atomic oxidation gas and hydrogen gas, which can be called an oxyhydrogen gas (HHO) is produced by the water electrolysis procedure with the atomic ratio of 2:1 [18]. Similar to hydrogen gas, HHO gas is still beneficial in combustion but it is less

Table 1
Specifications of generator.

Model	Europower Eg950 V
Frequency	50 Hz
Rated AC Output	650 W
Max AC Output	720 W
AC Output Voltage	230 W
Engine type	2-stroke, Air cooled, single cylinder
Displacement	63 cc
Max. Output	1.5 kW/2.0 HP

Table 2
Specifications of HHO dry cell.

Dry cell model	L2KS
Current supply	Up to 20A
Production range	0–0.75 L/min

risky in internal combustion engine as an additional fuel than pure hydrogen [19,20]. HHO Gas was used to heat, cook in household, trimming and soldering for industrial and domestic applications [21,22]. HHO can be generated through electrolysis process by wet cells and dry cells [23–25]. Improved thermal transfer efficiency, optimized mixture combustion, and reduced gaseous emissions are all benefits of the ternary-fuel combination supply and lean-burn coupling technology [26]. Electrolysis kinetics were discussed in terms of chemical and thermodynamics. The addition of hydroxy gas increased engine thermal efficiency and output power. NOx, HC, CO, and CO_2 emissions are reduced by the addition of oxygen [27]. Sustainability analysis determines a system's ability to sustain itself. To be sustainable, demands from the present must be weighed against future considerations. Lowering thermodynamic losses may increase the value of the sustainability index. The maximum value of sustainability at full engine load while using only gasoline was 1.26. Exergy is reduced because irreversible processes increase the engine's energy loss [28–30]. Recent studies have also explored the use of fuel additives such as nanoparticles [31] and HHO [32,33]. These investigations into mixed combustion have resulted in improved engine efficiency and a more sustainable environment. In the present study, the influence of adding HHO by retrofit into a spark-ignition engine on the fuel consumption, exhaust gas temperature and emission are studied. This study is aimed to evaluate the mixture of HHO and gasoline on the engine fuel consumption, emissions and exhaust gas temperature.

2. Experimental set-up

The dry cell gas is premixed with air prior to fuelling the carburettor of a 2-horsepower (1.5 kW) generator as shown in Fig. 1(a and b). The specification of generator is shown in Table 1. The effect of adding HHO in a modified spark-ignition engine's fuel consumption and exhaust gas emission are studied. The HHO and air are mixed into the carburettor via a mixing box (Fig. 1(a)). The quantity of HHO supplied is adjustable and varied from stoichiometric to rich fuel mixture condition. Deionised water is used in the experiment. The device is tested with different voltage to identify the fuel consumption and emissions. Operating the generator at the best mixture of air-to-fuel (A/F) ratio according to how much fuel is consumed and how much it emits to help its longevity and performance. The generator powers are run in the ranges 84–720 W during the experiments (Fig. 1(b)).

A HHO dry cell generator, a power supply, a water tank, electrolyte, and polymer tubing were all needed for the HHO production. At initial stage, electrolyte with a concentration of 6 g/L KOH (which can also be substituted with NaOH) was poured into the water tank, which was then filled to the full line and tightly covered with the cover. The polymer tubing was then attached between the dry cell of the HHO generator and the water tank. Jumper wires were used to link the power supply to the HHO dry cell.

The HHO dry cell is made up of 16 stainless steel plates that are 100 mm × 100 mm in size. The dry cell's specifications are mentioned in Table 2.

In addition, the HHO output tubing was connected to the mixing box, and a flow metre was installed between the HHO gas outlet and the mixing box to track the HHO gas flow rate. The amount of HHO in the range of 0.025 L/min – 0.074 L/min. A thermocouple was mounted directly at the exhaust outlet to monitor the temperature of the gases, and the gas analyzer was set to gasoline to test the generator's emissions. The thermocouple was connected to a Data Acquisition System (DAQ), which enabled the computer to display the results numerically. A pitot tube is used to calculate the air flow speed entering the carburettor. The fuel tank serves as a source of gasoline for the generator. A thermocouple is connected to a DAQ computer to monitor temperature, and a gas analyzer is used to measure exhaust gas emissions at the discharge ducting. The readings of fuel consumption, emission and exhaust temperature were repeated 3 times during the experiment and the average readings were used in the present study. The digital gas flow sensor by vogtlin was used in the experiment to measure the fuel consumption. The flow meter can be measured the lowest flowrate up to 0.0001 L/min.

3. Results and discussion

The operating range of air-fuel (A/F) ratio for the generator, according to the experiment, is A/F ratio 12 to A/F ratio 20. The

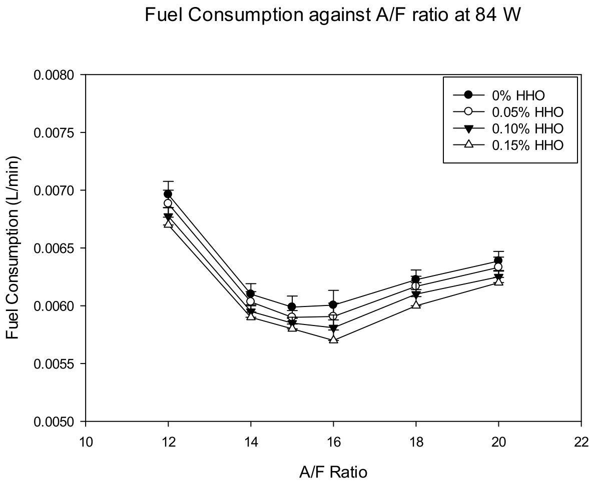


Fig. 2. Fuel consumption at 84 W.

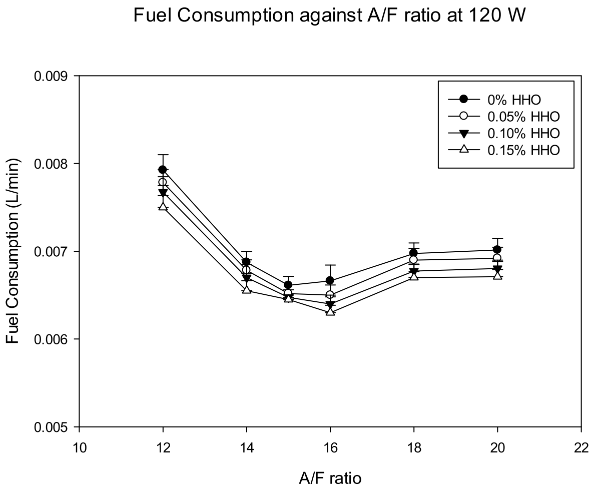


Fig. 3. Fuel consumption at 120 W.

investigation includes the study on fuel consumption as well as hazardous gas emissions such as CO, NOx and exhaust temperature. The average values of fuel consumption, gas emission and temperature are plotted together with error bars. The calculated errors for fuel consumption, CO and NOx are 3.17–41.02%, 0.31–6.15 and 0.37–16.6% respectively. As far as the authors aware, there is no previous studies before used a dry cell for HHO gas production and coupled with a generator via mixing chamber. Thus, this experimental set-up provided novelty for the present study.

3.1. Fuel consumption

According to the findings, when the generator is running, the fuel consumption rises in tandem with the power output to the electrical appliances. The electrical load and fuel consumption have a proportional relationship. Engine fuel efficiency will decrease at high power consumption levels. Furthermore, the fuel consumption varies depending on the engine's A/F ratio. For all power outputs, it can be said that the best set-up of fuel consumption is about the A/F ratio of 15. The fuel consumption difference between the rich mixture (A/F ratio = 12) and the lean mixture (A/F ratio = 20) is negligible at lower power outputs such as 84 W, 120 W, 240 W, 600 W, and the highest power output is 720 W where the fuel consumption of the mixture is rich. In a rich mixture, the generator will run at a lower speed, resulting in higher fuel consumption than in a lean mixture, which will run at a higher speed.

The generator runs cooler with slightly less air and produces more power for rich mixtures, while the generator runs hotter with less fuel and produces less power for lean mixtures. The same power output is analysed in this study, so the rich and lean mixtures would use more fuel than the stoichiometric mixture, which burns the fuel at the most effective rate. The amount of gasoline and air mixture into the engine is found to be just sufficient to carry out the combustion. At this stage, the engine is operating at stoichiometric condition.

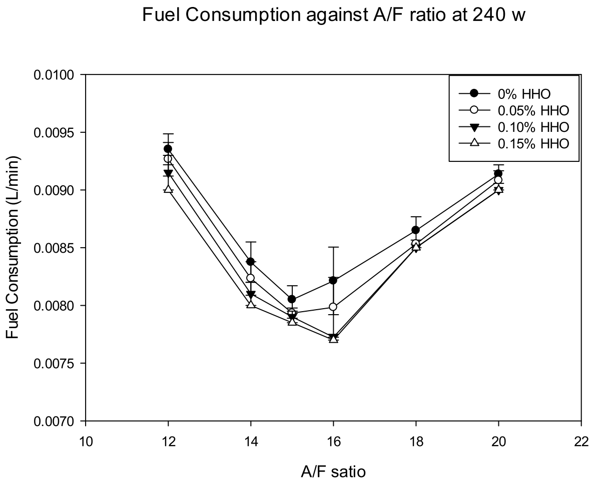


Fig. 4. Fuel consumption at 240 W.

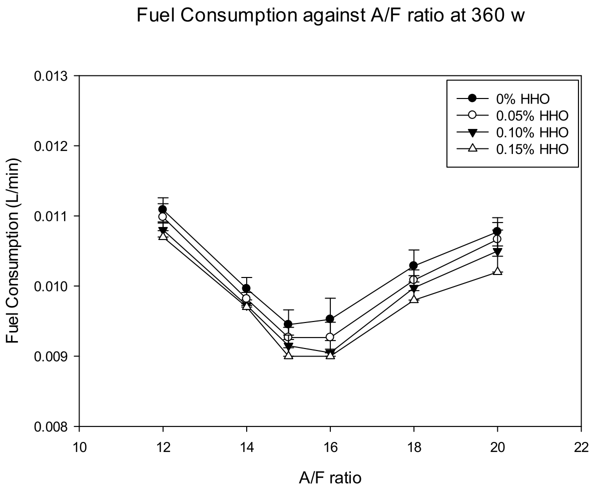


Fig. 5. Fuel consumption at 360 W.

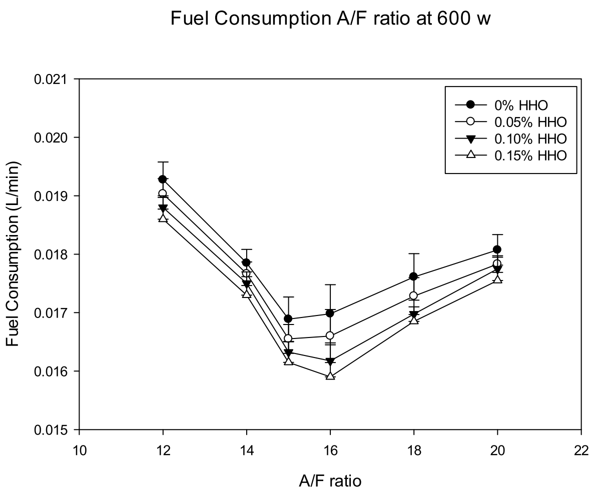


Fig. 6. Fuel consumption at 600 W.

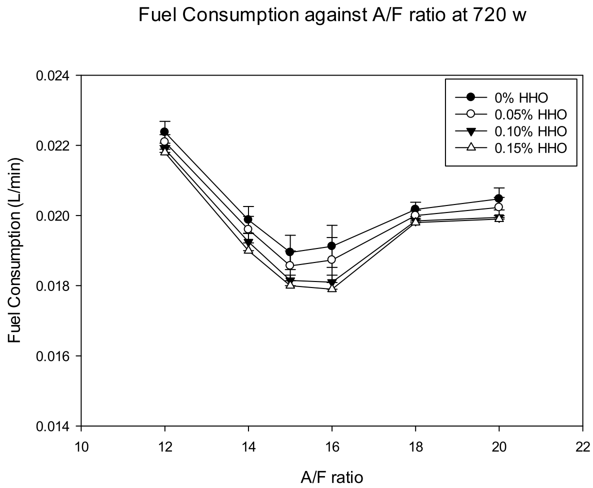


Fig. 7. Fuel consumption at 720 W.

Fig. 2 through 7 show the maximum and minimum points of fuel consumption at rich, lean, and stoichiometric mixtures have been investigated. At a power output of 84 W and a pure gasoline operation (0% HHO addition), the maximum fuel consumption is 0.0072 L/min at an A/F ratio of 12 and the minimum fuel consumption is 0.0062 L/min at an A/F ratio of 15. Fuel consumption dropped between rich and stoichiometric mixture at 0.0066 L/min at the highest point of A/F ratio at 20. At a power output of 720 W, the maximum fuel consumption was 0.0273 L/min at an A/F ratio of 12 and the minimum fuel consumption was 0.0211 L/min at an A/F ratio of 15. Fuel consumption dropped between the minimum and maximum fuel consumption at 0.025 L/min when using a lean mixture with an A/F ratio of 20 as shown in Fig. 2.

The addition of 0.05% HHO and the addition of 0% HHO have the same relationship between power output and the A/F ratio (Fig. 3). The consumption of fuel is increasing with increasing power consumption. The rich mixture consumes the most fuel, followed by the lean and stoichiometric mixtures. The maximum fuel consumption at 84 W is 0.0071 L/min at A/F ratio 12, while the minimum fuel consumption is 0.0062 L/min at A/F ratio 15. The maximum fuel consumption at 720 W is 0.0231 L/min at both A/F ratios 12 and 20, and the minimum fuel consumption at A/F ratio 15 is 0.0188 L/min (Fig. 7).

Fuel consumption at 0.10% HHO addition showed a similar relationship between power output and fuel consumption, as well as the A/F ratio, as it did at 0% and 0.05% HHO addition. When a higher power output is used, the fuel consumption would increase. Furthermore, at an A/F ratio of 15, which approaches stoichiometric mixture, fuel consumption tends to be lower. The highest rate of fuel consumption at 84 W is 0.0071 L/min at A/F ratio 12, while the lowest rate is 0.0059 L/min at A/F ratio 15 (Fig. 2). The highest rate of fuel consumption at 720 W is 0.0218 L/min at both A/F ratios 12 and 20, while the lowest rate is 0.0179 L/min at A/F ratio 15 (Fig. 7).

The gasoline with 0.15% HHO addition has the same relationship as 0%, 0.05%, and 0.1% HHO addition in terms of power generation, fuel usage, and A/F ratio. At the lowest power output of 84 W, the minimum fuel consumption at A/F ratio 16 is 0.0058 L/min, and the maximum fuel consumption at A/F ratio 12 is 0.0067 L/min (Fig. 2). The minimum fuel consumption at A/F ratio 16 is 0.0174 L/min, while the maximum fuel consumption at A/F ratio 12 and 20 is 0.0207 L/min (Fig. 7). For this 84 W power output, as compared to operating on pure gasoline, 0.05% HHO addition reduced fuel consumption by 2.094% on average, 0.01% HHO addition reduced 4.84% on average, and 0.015% HHO addition reduced fuel consumption by 7.44% on average.

At 120 W power output, 0.05% HHO gas addition has reduced fuel consumption by 3.54%, 0.10% HHO addition has reduced fuel consumption by 6.04%, and 0.15% HHO addition has reduced fuel consumption by 9.2% (Fig. 3). For 240 W power output, with 0.05% HHO gas was applied, the fuel consumption is decreased by 3.442%. When 0.10% HHO gas is added, fuel consumption is reduced by 6.71%, while fuel consumption is reduced by 8.2% when 0.15% HHO gas is added (Fig. 4). However, for a 360 W power output, the fuel consumption is decreased by 3.72% when 0.05% HHO gas is added, 6.83% when 0.10% HHO gas was added, and 9.76% when 0.15% HHO gas was added (Fig. 5).

At 600 W power output, adding 0.05% HHO gas reduced fuel consumption by 3.803%, adding 0.10% HHO gas reduced fuel consumption by 6.979%, and adding 0.15% HHO gas reduced fuel consumption by 9.49% (Fig. 6). At 720 W power production, adding 0.05% HHO gas reduced fuel consumption by 2.76%, adding 6.84% HHO gas reduced fuel consumption by 6.84%, and adding 0.15% HHO gas reduced fuel consumption by 9.33% (Fig. 7).

3.2. Emissions

In this study, the emissions of CO, NOx and HC were measured and analysed since they are classified as harmful gases. The CO is a toxic gas and the most harmful to the human. Similar to the NOx gas is created when one nitrogen atom reacts with one or more oxygen atoms could cause the acid rains. However, HC emission caused by unburned fuel during combustion. Therefore, the focus of this study

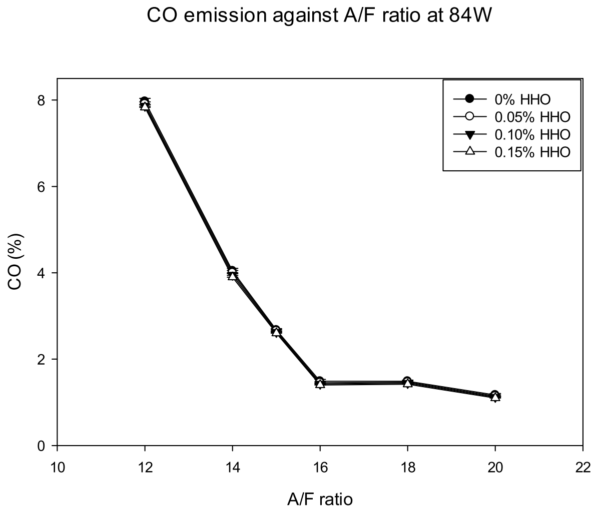


Fig. 8. CO emission at 84 W.

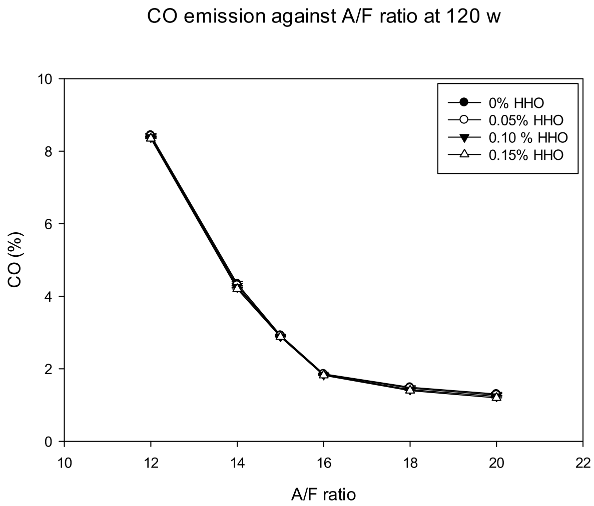


Fig. 9. CO emission at 120 W.

is to reduce and limit these toxic gas emissions formation before its exhausted to the environment.

3.2.1. CO emissions

Fig. 8 is shown the CO emission of engine power output of 84 W, with 0.05–0.15% addition of HHO gas has reduced CO gas emissions by 3.56%, 0.10% addition of HHO gas reduced CO gas emissions by 6.28%, and 0.15% addition of HHO gas reduced CO gas emissions by 9.26%. Whereas, Fig. 9 is shown the results for 120 W power output, with 0.05% HHO gas added reduced 3.67% CO emission, 0.10% HHO gas added reduced 6.58% CO emission, and 0.15% HHO gas added reduced 9.36% CO emission. For 240 W power output (Fig. 10) when 0.05% HHO gas added, the emission reduced to 3.64% of CO emission, with 0.10% HHO gas added 6.46% CO reduced, and with 0.15% HHO gas added reduced CO reduced 9.29%. Further increase in power output to 360 W as shown in Fig. 11, for 0.05% HHO gas added has reduced 3.63% CO emission, 0.10% HHO gas added reduced to 6.38% and 0.15% of HHO gas added reduced to 9.49% of CO emission.

Fig. 12 shows the results for 600 W power output, for HHO gas added with 0.05% has reduced 3.52% CO emission, 0.10% HHO gas added reduced 6.57% and with 0.15% of HHO gas added reduced up to 9.68%. Whereas for a 720 W power output, 0.05% of HHO gas added reduced 3.52% CO emission, 0.10% HHO gas added reduced 6.38% of CO emission and 0.15% of HHO gas added 9.33% of CO emission (Fig. 13).

The results obtained (Figs. 8–13) also illustrate that when gasoline undergoes incomplete combustion, the CO gas is formed. The CO gas is produced due to an excess of fuel in the cylinder. The CO emissions rise in lockstep with the increase in power output. With the numerous power appliances attached, more fuel is burned as the power output rises. On the other hand, as the A/F ratio rises, CO

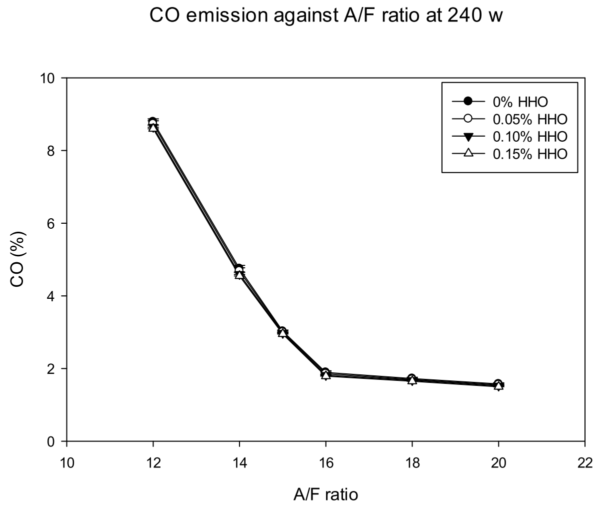


Fig. 10. CO emission at 240 W.

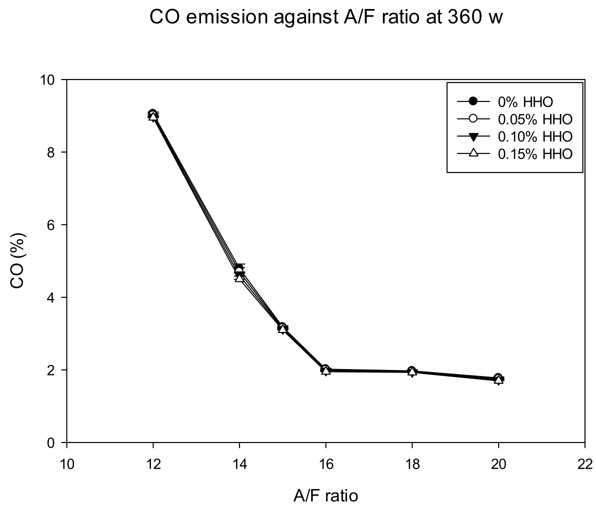


Fig. 11. CO emission at 360 W.

emissions gradually decrease. When there is incomplete combustion, CO is generated. The percentage of CO in a rich mixture (A/F ratio A/F stoichiometric) is higher since there is more fuel in the engine, resulting in incomplete combustion. Since there is less fuel available for combustion in a lean mixture (A/F ratio > A/F stoichiometric), the percentage of CO decreases dramatically. Total combustion occurs in the engine. The air-to-fuel ratio is greater than the stoichiometric requirement, causing most of the fuel to burn completely. The engine design can cause the fuel to burn incompletely, resulting in a low percentage of CO gas being released. When comparing rich and stoichiometric A/F ratios, CO emission is significantly lower at stoichiometric A/F ratio. This may be because of the engine's nature, which allows the fuel to burn incompletely.

3.2.2. NO_x emission

Fig. 14 through 19 show that gas NOx is measured in parts per million as similar to CO (ppm). NOx is formed when nitrogen and oxygen react at a high temperature, which occurs most commonly during combustion. The main components of ambient air are nitrogen and oxygen, and during combustion, some nitrogen can react with oxygen to form a NOx. A high level of NOx is not desirable because it has a variety of harmful effects on the environment. According to this research, increase in NOx emissions as power production increased. When the generator load increases, so does the combustion temperature, which leads to an increase in NOx emissions. It emits the most NOx at a slightly lean A/F ratio of about 15–16, according to the relationship between NOx emission and A/F ratio. This is because the amount of oxygen and nitrogen content is most preferable to react under the high combustion temperature at lean A/F ratio range. The amount of oxygen required to react with nitrogen in a rich mixture (A/F ratio A/F stoichiometric) is less due to air is limited. Thus, less fuel to heat up the engine in a lean combination caused drop in temperature.

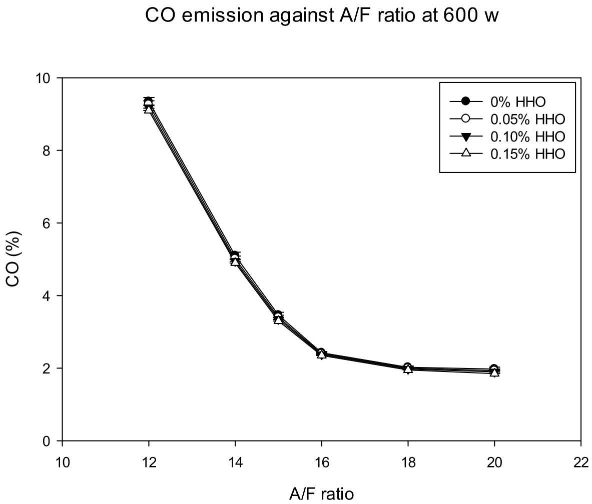


Fig. 12. CO emission at 600 W.

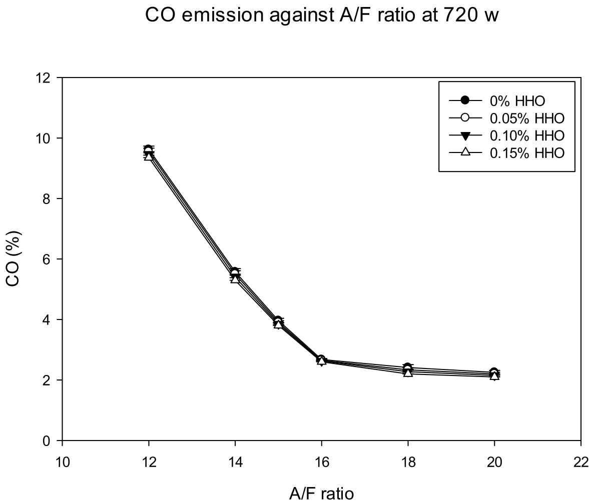


Fig. 13. CO emission at 720 W.

Fig. 14 is shown the results for engine power output of 84 W, with 0–0.15% addition of HHO gas has reduced NO_X gas emissions by 4.45%, 0.05% HHO gas added reduced 1.26% NOx emission, 0.10% addition of HHO gas reduced NO_X gas emissions by 6.28%, and 0.15% addition of HHO gas reduced NO_X gas emissions by 9.26%. Whereas, Fig. 15 is shown the results for 120 W power output, with 0.05% HHO gas added reduced 1.34% of NO_X emission, 0.10% HHO gas added reduced 3.03%, and 0.15% HHO gas added reduced to 4.81% of NO_X emission. For 240 W power output (Fig. 16) when 0.05% HHO gas added, the emission reduced to 1.39% of NO_X emission, with 0.10% HHO gas added 2.86% NO_X reduced, and with 0.15% HHO gas added reduced NO_X by 4.25%. Further increase in power output to 360 W as shown in Fig. 17, for 0.05% HHO gas added has reduced 1.34% in NO_X emission, 0.10% HHO gas added reduced to 2.75% and 0.15% of HHO gas added reduced to 4.34% of NO_X emission.

Fig. 18 shows the results for 600 W power output, for HHO gas added with 0.05% has reduced 1.32% NO_X emission, 0.10% HHO gas added reduced 2.42% and with 0.15% of HHO gas added reduced up to 4.17%. Whereas for a 720 W power output, 0.05% of HHO gas added reduced 1.35% NO_X emission, 0.10% HHO gas added reduced 2.51% of NO_X emission and 0.15% of HHO gas added 4.11% of NO_X emission (Fig. 19).

3.2.3. HC emissions

Figs. 20–25 illustrate the levels of hydrocarbon (HC) emissions from unburned fuel during combustion. Typically, when the rated power output is high, the fuel is consumed in generating power for electrical appliances, leading to lower HC gas emissions. However, combustion at a stoichiometric A/F (in the range of 14–16) ratio results in the least amount of HC emissions. Fig. 20 shows that for a power output of 84 W, the addition of 0.05% HHO reduced HC emissions by 0.93%, 0.10% HHO reduced emissions by 2.21%, and

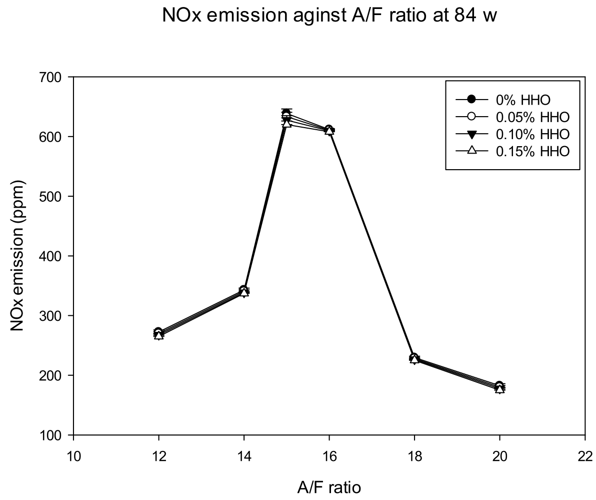


Fig. 14. NOx emission at 84 W.

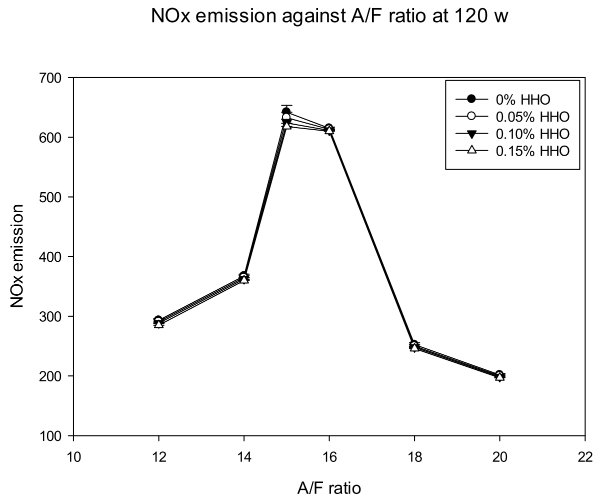


Fig. 15. NOx emission at 120 W.

0.15% HHO reduced emissions by 5.19%. Meanwhile, Fig. 21 presents the results for a power output of 120 W, indicating that 0.05% HHO gas addition reduced HC emissions by 1.16%, 0.10% HHO gas addition reduced emissions by 2.18%, and 0.15% HHO gas addition reduced emissions by 4.17%.

For a power output of 240 W (Fig. 22), the addition of 0.05% HHO gas resulted in a 1.54% reduction in HC emissions, 0.10% HHO gas addition reduced emissions by 2.13%, and 0.15% HHO gas addition reduced emissions by 4.15%. With a further increase in power output to 360 W, as depicted in Figs. 23 and 0.05% HHO gas addition reduced HC emissions by 1.32%, 0.10% HHO gas addition reduced emissions by 2.34%, and 0.15% HHO gas addition reduced emissions by 4.45%. The results for 600 W power output are illustrated in Fig. 24, showing that 0.05% HHO gas addition reduced HC emissions by 1.42%, 0.10% HHO gas addition reduced emissions by 2.78%, and 0.15% HHO gas addition reduced emissions by 4.97%. Similarly, for 720 W power output, as indicated in Figs. 25 and 0.05% HHO gas addition reduced HC emissions by 1.42%, 0.10% HHO gas addition reduced emissions by 2.77%, and 0.15% HHO gas addition reduced emissions by 4.97%.

3.3. *Exhaust gas temperature*

In the most cases, the exhaust temperature (EGT) would be about 300 °C. However, since the exhaust pipe was extended from the muffler to fit in the gas analyzer, the temperature of the exhaust is in the range of 160 °C – 164 °C. The heat was passed through the air as well as the 10 cm mild steel exhaust pipe surface. Furthermore, the inversely proportional relationship between exhaust temperature and air fuel ratio is shown in Fig. 26. The temperature of the exhaust increases as the power output increases. The exhaust temperature has reduced due to a decrease in the amount of fuel available to burn (lean condition), caused decrease in the combustion temperature

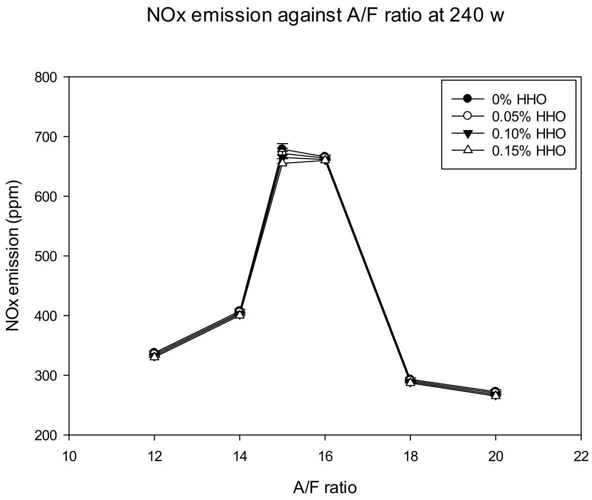


Fig. 16. NOx emission at 240 W.

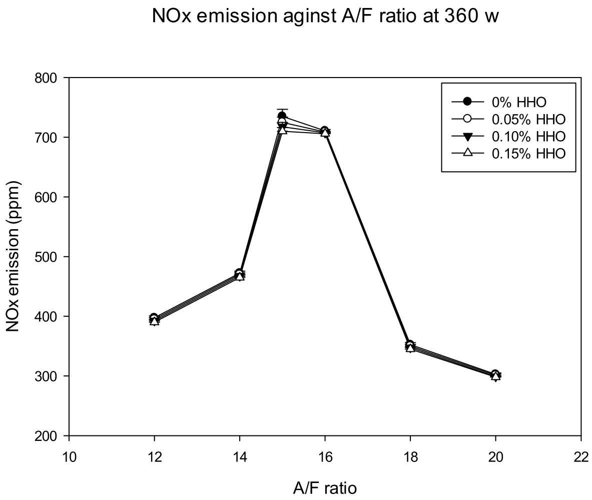


Fig. 17. NOx emission at 360 W.

and exhaust temperature.

Fig. 26 is shown the EGT at various air-fuel ratio, HHO percentage and power output. The results illustrate that the maximum and minimum temperatures obtained are 163.67 °C and 162.3 °C respectively for the gasoline without HHO. However, after adding 0.05% the EGT has reduced up to 1.41% compared to the generator without HHO. When the HHO increases to 0.15%, the EGT has reduced to 1.8%. It is shown by adding the HHO has reduced the combustion temperature with lower temperature before the gas discharges to the environment.

4. Conclusion

In this study, the evaluation of oxyhydrogen gas at different percentage addition and air-fuel ratio on the fuel consumption, exhaust gas temperature and emission were carried out. The engine also tested at different running power and the percentage improvement on engine performance and emissions of CO and NOx was compared and analysed. The main conclusions are found for as follows:

1. The addition of HHO gas has significantly reduced fuel consumption up to 8.9%. On average, 0.05% HHO gas addition lowers fuel consumption by 3.23%.
2. The results demonstrated that by adding HHO gas, CO emissions has reduced by 9.41%. On average, 0.05% of HHO gas addition reduced CO emissions by 3.59%.
3. By adding HHO gas also reduced NOx gas emissions up to 4.31%. On average, 0.05% of HHO gas supplements reduced 1.34% of the emissions of NOx gas.

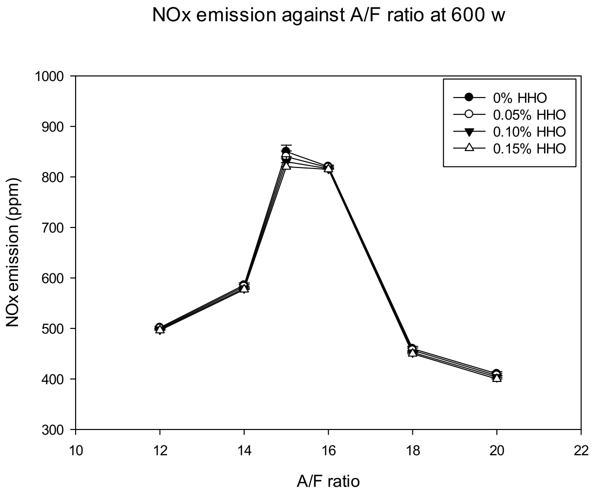


Fig. 18. NOx emission at 600 W.

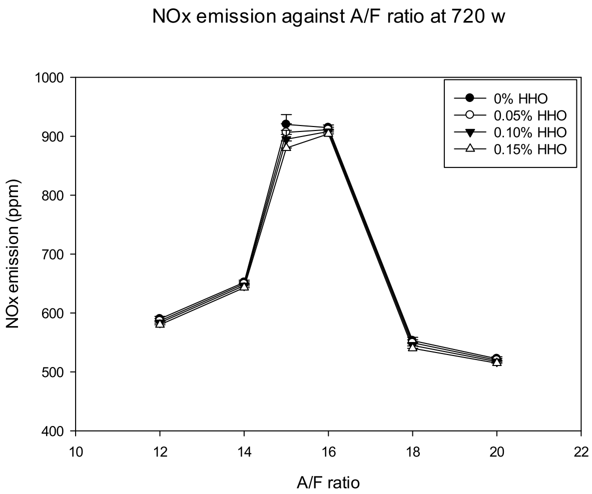


Fig. 19. NOx emission at 720 W.

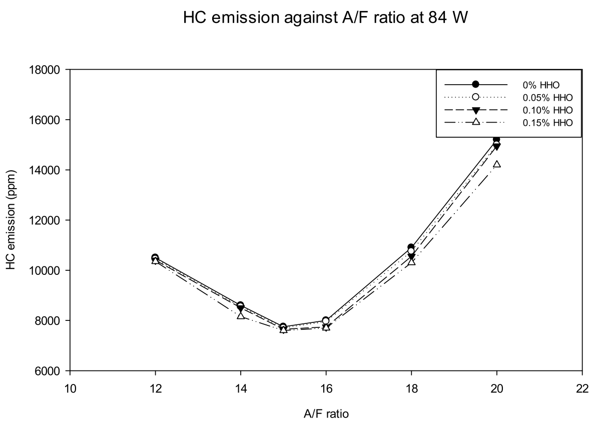


Fig. 20. HC emission at 84 W.

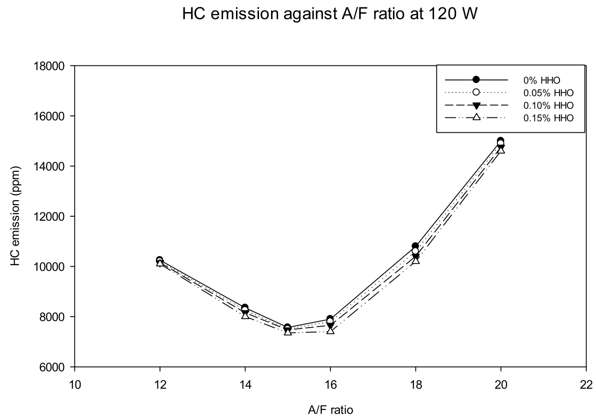


Fig. 21. HC emission at 120 W.

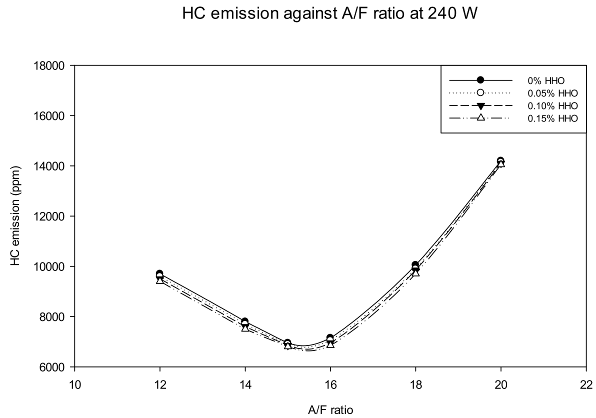


Fig. 22. HC emission at 240 W.

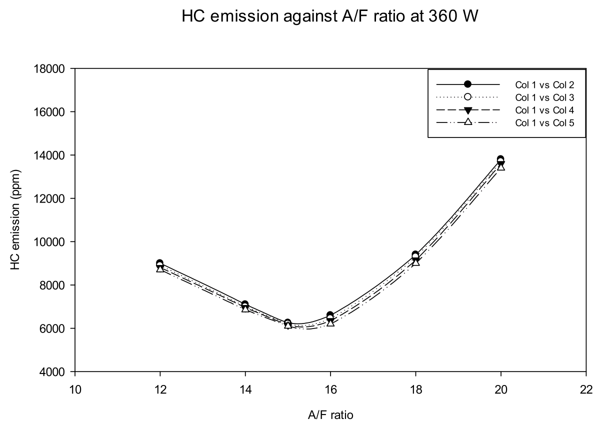


Fig. 23. HC emission at 360 W.

4. The EGT is reduced almost linearly with air-fuel ratio. The EGT is reduced up to 1.8%. In average, EGT was reduced to 1.41% for 0.05% of the HHO gas supply.

The outcome from these results illustrated that the fuel consumption, emissions and exhaust gas temperature are significantly improved engine performance. This work also demonstrated by adding oxyhydrogen gas has significantly reduced the emissions, exhaust temperature and provided eco-friendly environment. More study required especially for higher HHO percentage (0.5–1%) on

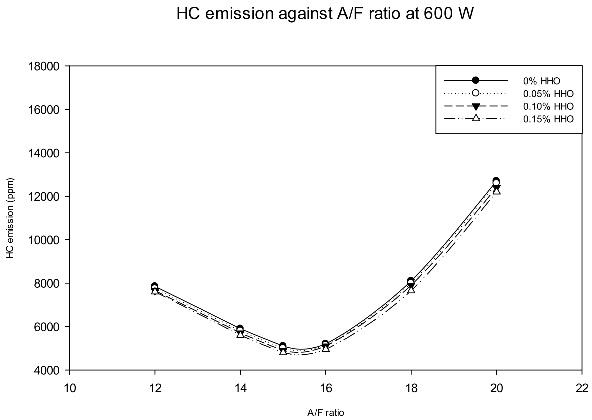


Fig. 24. HC emission at 600 W.

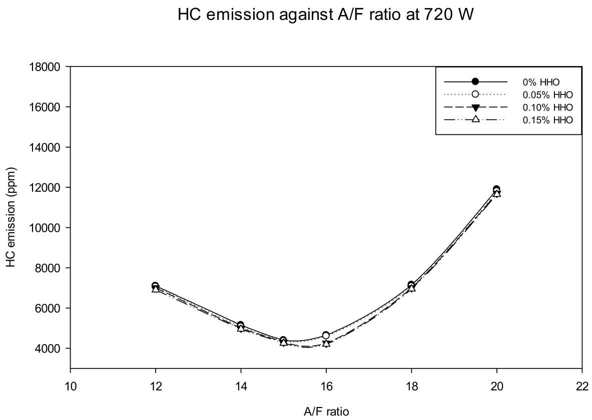


Fig. 25. HC emission at 720 W.

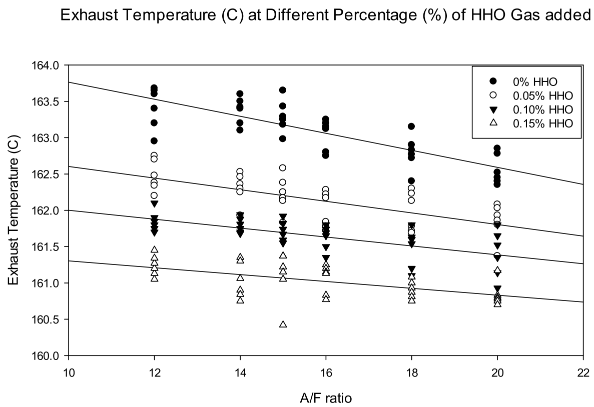


Fig. 26. Exhaust temperature versus air/fuel ratio.

the engine performance be studied in the future to ensure further improvement on the engine performance and emissions.

CRediT authorship contribution statement

R. Kamarudin: Writing – original draft. **Y.Z. Ang:** Formal analysis. **N.S. Topare:** Funding acquisition. **M.N. Ismail:** Resources. **K. F. Mustafa:** Methodology. **P. Gunnasegaran:** Project administration, Funding acquisition. **M.Z. Abdullah:** Supervision, Funding acquisition. **N.M. Mazlan:** Data curation. **I.A. Badruddin:** Validation. **A.S.A. Zedan:** Visualization. **R.U. Baig:** Writing – review &

editing. **S.M. Sultan:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:PREM GUNNASEGARAN reports financial support was provided by UNIVERSITI TENAGA NASIONAL. NIRAJ S TOPARE reports financial support was provided by Dr Vishwanath Karad MIT World Peace University. MOHD ZULKIFLY ABDULLAH reports financial support was provided by Universiti Sains Malaysia. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] V. Smil, Energy Transitions: Global and National Perspectives, Praeger, California, 2017.
[2] F. Caiazzo, A. Ashok, I.A. Waitz, S.H. Yim, S.R. Barrett, Air pollution and early deaths in the United States. Part I: Quantifying the impact of major sectors in 2005, Atmos. Environ. 79 (2013) 198–208.
[3] B. Aqif, H. Bugis, B, Effect of Splash Method in Vapor Carburetor to Fuel Consumption with Fuel Variation, AIP Conference, Surakarta, 2019.
[4] M. Zimmerman, The Essential Guide to Motorcycle Maintenance, Quarto Publishing Group USA Inc, Minneapolis, 2016.
[5] A. Abdel-Rehim, A. Ahmed, A.A. Ahmed, Does Magnetic fuel treatment affect engine's performance, in: SAE 2014 World Congress & Exhibition, United States, 2014.
[6] Q.A. Acton, Advances in Carbon Research and Application, Scholarly Editions, Atlanta, 2013.
[7] L. Carley, AAlCar, 2019. www.aa.l.car.com. (Accessed 30 June 2020).
[8] J. Benajes, A. Garcia, J. Monsalve-Serrano, S.R. Lago, Fuel consumption and engine-out emissions estimations of a light-duty engine running in dual-mode RCCI/CDC with different fuels and driving cycles, Energy 157 (2018) 19–30.
[9] A. Garcia, J. Monsalve-Serrano, S. Martinez-Boggio, V. Rucket Roso, N. Duarte Souza Alvarenga Santos, "Potential of bio-ethanol in different advanced combustion modes for hybrid passenger vehicles,", Renew. Energy 150 (2020) 58–77.
[10] J. Benajes, A. Garcia, J. Monsalve-Serrano, S. Martinez-Boggio, Optimization of the parallel and mild hybrid vehicle platforms operating under conventional and advanced combustion modes, Energy Convers. Manag. 190 (2019) 73–90.
[11] J. Benajes, A. Garcia, J. Monsalve-Serrano, R. Sari, Clean and efficient duel-fuel combustion using OMEx as high reactivity fuel: comparison to diesel-gasoline calibration, Energy Convers. Manag. 216 (2020) 112953.
[12] R. Niculescu, A. Clenci, V. lorga-Siman, Review on the use of diesel-biodiesel-alcohol blends in compression ignition engines, Energies 12 (7) (2019) 1194.
[13] H. Chen, J. He, Y. Chen, H. Hua, Performance of a common rail diesel engine using biodiesel of waste cooking oil and gasoline blend, J. Energy Inst. 91 (6) (2018) 856–866.
[14] M.A. Rosen, S. Koohi-Fayegh, The prospects for hydrogen as an energy carrier: an overview of hydrogen energy and hydrogen energy systems, Energy, Ecology and Environment 1 (2016) 10–29.
[15] E. Kahraman, S.C. Ozcanli, B. Ozerdem, An experimental study on performance and emission characteristics of a hydrogen fuelled spark ignition engine, Int. J. Hydrogen Energy 32 (12) (2007) 2066–2072.
[16] R. H, S. K, M. S, M. M. R. A. and A. N, Hydrogen mixture with gasoline for conventional motorcycles and effect of mass flow rate, brake thermal efficiency and emissions, Int. J. Automot. Mech. Eng. 12 (3) (2016) 3681–3695.
[17] A.C. Yilmaz, E. Uludamar, K. Aydin, Effect of hydoxy (HHO) gas addition on performance and exhaust emissions in compression ignition engines, Int. J. Hydrogen Energy 35 (20) (2010) 11366–11372.
[18] V. Krishna, Emissions control and performance evaluation of spark ignition engine with oxy-hydrogen blending, International Journal of Heat and Technology 36 (1) (2018) 118–124.
[19] A. Sakhrieh, A. Al-Hares, F. Faqes, Baqain Al, N. Alrafie, " optimization of oxyhydrogen gas flow rate as a supplementary fuel in compression ignition combustion engines,", International Journal of Heat and Technology 35 (1) (2017) 116–122.
[20] S. Wang, C. Ji, J. Zhang, B. Zhang, Improving the performance of a gasoline engine with the addition of hydrogen-oxygen mixtures, Int. J. Hydrogen Energy 36 (17) (2011) 11164–11173.
[21] T. N, M.M. K. D, Enabling efficient use of oxy-hydrogen gas (HHO) in selected engineering applicatios; transportation and sustainable power generation, J. Clean. Prod. 237 (2019) 117798.
[22] M.A. Usmani, S. Khan, B.H. Khan, S. Ahmed, "Use of oxy hydrogen gas in stationary devices: a review, International Journal of Advance Research, Ideas and Innovations in Technology 4 (5) (2018) 307–310.
[23] S. Shah, Z. Ali, J. Larik, A. Kaimkhani, Comparative study of dry cell and wet cell for the HHO gas generation as a supplement fuel for I.C. engine, in: International Conference on Computing, Mathematics and Engineering Technologies, iCoMET), 2018, 2018.
[24] P. Pawar, P. Baheti, S. Darade, P. Menghani, Performance analysis of gasoline engine by addition of HHO gas as a secondary fuel, International Conference on Ideas, Impact and Innovation in Mechanical Engineering 5 (6) (2017) 2321–8169.
[25] M.M. EL-Kassaby, Y.A. Eldrainy, M.E. Khidr, K.I. Khidr, Effect of hydoxy (HHO) gas addition on gasoline engine performance and emissions, Alex. Eng. J. 55 (1) (2016) 243–251.
[26] Z. Zhao, Y. Huang, Z. Shang, X. Yu, P. Sun, L. Ren, T. Sang, M. Li, Z. Li, Experimental study on combustion and emission of ternary-fuel combined supply SI engine with oxyhydrogen/butanol/gasoline at different excess air ratios, Case Studies in Thermal Engineering Journal 49 (2023).
[27] B. Subrammanian, S. Ismail, Production and use of HHO gas in IC engines, Int. J. Hydrogen Energy 43 (14) (2018) 7140–7154.
[28] A.A. Al-Rousan, S.A. Musmar, Effect of anodes-cathodes inter-distances of HHO fuel cell on gasoline engine performance operating by a blend of HHO, Int. J. Hydrogen Energy 43 (41) (2018) 19213–19221.
[29] A.K. El Soly, M.A. El Kady, A.E. Farrag, M.S. Gad, " Comparative esperimental investigation of oxyhydrogen (HHO) production rate using ry and wet cells, Int. J. Hydrogen Energy 46 (24) (2021), 126390-12639.
[30] V.G. Bui, V.N. Tran, A.T. Hoang, T.T.M. Bui, A.V. Vo, A Simulation Study on a Port-Injection SI Engine Fueled with Hydroxy-Enriched Biogas," *Energy Sources, Part A Recovery*, Utilization and Environmental Effects, 2020.

[31] S. Ozer, F. Haciyusufoglu, E. Vural, Experimental investigation of the effect of the use nanpparticle additional biodiesel on fuel consumption and exhaust emissions in tractor using a coated engine, Therm. Sci. 27 (48) (2023) 3189–3197.
[32] U. Demir, S. Celebi, S. Ozer, Experimental investigation of the effect of fuel oil, graphene and HHO gas addition to diesel fuel on engine performance and exhaust emissions in a diesel engine, Int. J. Hydrogen Energy 52 (2023) 1434–1446.
[33] S. Ozer, E. Vural, The effect of the addition of H_2, H_2+HHO and H_2+HHO+O_2 from the intake manifold on exhaust emissions in a diesel generator using diesel/toluene/diethyl ether as pilot fuel, Int. J. Hydrogen Energy 52 (2024) 1247–1260.