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Experimental Evaluation of Exhaust Emission Characteristics and Fuel Consumption of an F8A Engine with HHO Electrolyzer Addition

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Abstract

Growing vehicle use has increased interest in combustion additives that may reduce fuel use and exhaust emissions in conventional engines. This study evaluated an HHO-based electrolyzer system applied to a carburetted F8A engine without internal engine modification. An experimental comparison was conducted under standard operation without HHO and with an active electrolyzer at 800, 2000, 3000, and 4000 rpm. The measured parameters were CO, CO_2, HC, O_2, lambda, and fuel consumption. HHO addition reduced HC emissions by 14.2%, decreased O_2 by 18.5%, increased CO_2 by 10.9%, and shifted lambda from 1.197 to 1.124, indicating a movement toward more complete combustion. However, CO increased by 10.0%. Fuel consumption decreased by 7.0% at 800 rpm, 7.3% at 3000 rpm, and 9.8% at 4000 rpm, but increased by 4.5% at 2000 rpm. These findings indicate that HHO addition can modify the emission profile and fuel consumption of a carburetted F8A engine, although its benefits are engine-speed dependent.

Keywords
HHO electrolyzer; F8A engine; exhaust emission characteristics; fuel consumption; carburetted engine.

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INTRODUCTION

The increasing demand for petroleum-based fuels remains an important issue in Indonesia because the transportation sector still depends heavily on internal combustion engines. National oil production has shown a downward trend over the last decade, while the number of motor vehicles continues to increase. This condition creates two related challenges: higher fuel demand and greater exhaust emissions from vehicle operation [1], [2]. In gasoline engines, incomplete combustion can produce exhaust components such as carbon monoxide (CO), unburned hydrocarbons (HC), carbon dioxide (CO_2), oxygen residue (O_2), and air–fuel ratio indicators such as lambda. These parameters are commonly used to evaluate combustion quality and emission characteristics in automotive engines.

Several studies in automotive engineering have examined engine modification, fuel-system improvement, and additional combustion-support technologies as strategies to reduce fuel consumption and improve exhaust emission characteristics. Previous studies in AEEJ have shown that modification of ignition and engine components can change fuel consumption and exhaust emission behaviour in gasoline engines [3]. Other AEEJ studies have also reported that fuel-system conversion and supplementary systems, such as injection-system development and water injection, can influence exhaust emissions, specific fuel consumption, and engine temperature [4], [5]. These studies indicate that simple engine-support technologies remain relevant for conventional engines, especially in contexts where older carburetted vehicles are still used.

One technology that has received attention is the use of an electrolyzer to produce HHO gas, also known as oxyhydrogen. HHO gas is produced through water electrolysis, in which electrical energy is used to split water molecules into hydrogen and oxygen [6], [7]. In internal combustion engines, the generated gas can be introduced into the intake system as a combustion additive. Hydrogen has a high flame speed and low ignition energy, which may help accelerate flame propagation and improve the oxidation of the air–fuel mixture under certain operating conditions. However, the effect of HHO addition is not always uniform because combustion behavior depends on engine speed, fuel supply, air–fuel ratio, and the compatibility between HHO production and engine demand.

The electrolysis reaction used to generate hydrogen and oxygen from water can be expressed as follows:

$$2H_2O(l) \rightarrow 2H_2(g) + O_2(g) \quad (1)$$

In this reaction, liquid water is decomposed into hydrogen gas and oxygen gas through the application of direct electrical current. Figure 1 illustrates the general configuration of the HHO electrolyzer system, including the electrolyzer tube, electrode terminals, electrolyte solution, gas delivery pipe, water trap, and outlet line to the combustion chamber. This configuration is important because the generated HHO gas must pass through a safety and separation pathway before entering the intake system.

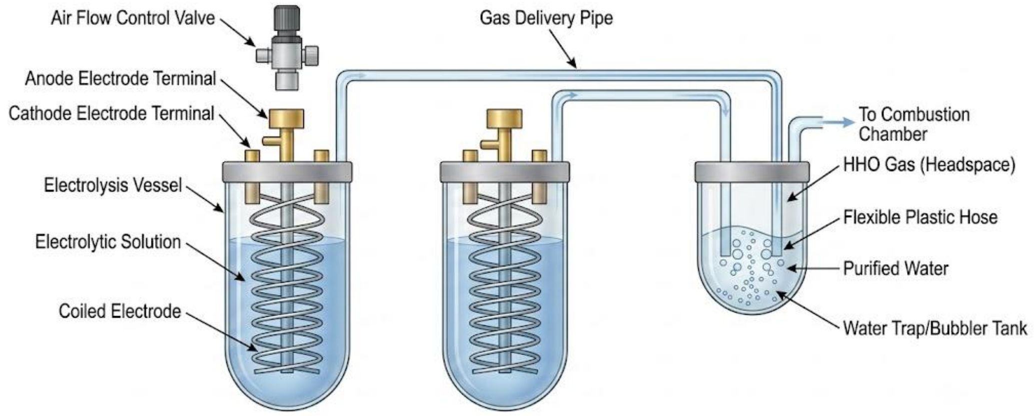

Figure 1. Schematic configuration of the HHO electrolyzer system and water trap.

Previous experimental studies have reported that HHO addition can affect engine performance, fuel consumption, and exhaust emission characteristics. Wahyudi et al. reported that electrolyzer installation on a modified four-stroke injection motorcycle reduced fuel consumption and changed exhaust gas composition at different engine speeds [6]. Gad and Abdel Razek found that HHO produced by dry and wet cell electrolyzers influenced diesel engine performance, emissions, and combustion characteristics [8]. Mohamed also reported that HHO assistance affected combustion, emissions, and performance in a gasoline/CNG bi-fuel engine [9]. Similar findings have been reported in spark-ignition and passenger-car applications using hydroxy gas or oxyhydrogen-enriched air [10], [11]. Sherman and Singh also reported that hydroxy-assisted gasoline fuel could influence fuel efficiency and emission behaviour in gasoline engine applications [12]. These studies suggest that HHO may support combustion improvement, but the results depend strongly on engine type, fuel system, operating speed, and electrolyzer configuration.

Despite these developments, previous studies have mostly focused on injection motorcycles, diesel engines, LPG engines, or modern fuel-controlled systems. Less attention has been given to the use of a simple HHO-based electrolyzer system on a conventional carburetted F8A engine. This gap is important because carburetted engines have different fuel–air mixing characteristics from electronically controlled injection systems. Therefore, the response of a carburetted F8A engine to HHO addition cannot be assumed to be identical to that of modern injection or diesel engines. A direct experimental evaluation is needed to determine how HHO addition changes fuel consumption and exhaust emission characteristics in this specific engine configuration.

The novelty of this study lies in the application of a simple electrolyzer-assisted HHO system to an F8A engine without internal engine modification. Unlike studies that focus on advanced electronic control systems or modified injection platforms, this study evaluates a carburetted engine configuration under standard and HHO-assisted conditions. This study aims to evaluate the exhaust emission characteristics and fuel consumption of an F8A engine with and without HHO electrolyzer addition at different engine speeds. The findings are expected to provide experimental evidence on the potential and limitations of HHO addition in conventional carburetted gasoline engines.

METHOD

This study employed an experimental method to evaluate exhaust emission characteristics and fuel consumption of an F8A engine with and without HHO electrolyzer addition. The experimental approach was used because the study compared two operating conditions, namely standard engine operation without HHO and engine operation with an active HHO electrolyzer system. Similar comparative experimental approaches have been used in previous HHO-assisted engine studies to examine changes in fuel consumption, exhaust emissions, and combustion-related indicators under different operating conditions [6], [8], [11], [13].

The object of this study was a Suzuki Jimny LJ80V equipped with an F8A gasoline engine and a conventional carburettor system. The F8A engine was selected because it represents a conventional gasoline engine configuration that does not use electronic fuel injection. Therefore, the study focused on comparing the observed response of this engine under standard operation and under HHO-assisted operation, without internal engine modification. The fuel type was not treated as an independent variable in this study; therefore, the comparison focused only on the presence or absence of HHO addition.

The main equipment used in this study consisted of an exhaust gas analyzer, a graduated measuring cylinder for fuel-consumption measurement, current and voltage measuring instruments, an HHO electrolyzer unit, connecting hoses, and a water trap. The electrolyzer system consisted of an electrolyzer tube, anode and cathode terminals, electrode wire, electrolyte solution, gas delivery pipe, plastic hose, and water-trap unit. The electrolyzer was connected to the engine intake manifold through a hose so that the generated HHO gas could enter the intake stream. The water trap was installed between the electrolyzer and the intake line to help reduce the possibility of liquid carryover into the engine. This configuration is consistent with HHO generator testing principles, in which oxyhydrogen gas is generated through electrolysis and directed into the intake system through a controlled delivery path [13], [14].

The research procedure followed the sequence shown in Figure 2. The procedure began with a literature study, followed by HHO generator fabrication, testing preparation, comparison of the without-HHO and with-HHO conditions, exhaust emission and fuel-consumption measurements, result analysis, and conclusion formulation. The flowchart was used to organize the experimental sequence and to ensure that both test conditions were evaluated using the same general procedure.

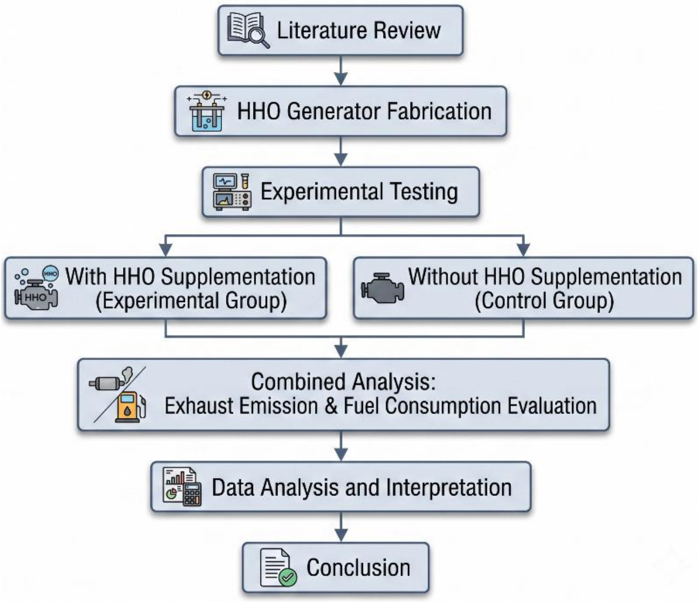

Figure 2. Research procedure for testing exhaust emissions and fuel consumption under standard and HHO-assisted engine conditions.

Testing was conducted under two operating conditions. The first condition was standard engine operation without HHO, which served as the control condition. The second condition used an active HHO electrolyzer system connected to the intake manifold. For each condition, the engine was operated at selected engine speeds. Fuel-consumption testing was conducted at 800, 2000, 3000, and 4000 rpm. Each engine-speed condition was tested five times to obtain repeated fuel-consumption data for comparison between the without-HHO and with-HHO conditions. Engine-speed-based testing was used because engine response to HHO addition may vary across operating speeds [15].

The exhaust emission parameters measured in this study were carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbon (HC), oxygen (O_2), and lambda. These parameters were measured using an exhaust gas analyzer under the without-HHO and with-HHO conditions. The emission data were analyzed descriptively by comparing the measured values between the two conditions. Because the manuscript reports emission values as comparative measurement results, the emission analysis was interpreted as a descriptive comparison of emission characteristics rather than as a statistically tested emission effect.

Fuel consumption was measured in millilitres using a graduated measuring cylinder. The measurement was conducted for both operating conditions at each selected engine speed. The same measurement basis was applied across the without-HHO and with-HHO conditions so that the average fuel-consumption values could be compared at each rpm. The fuel-consumption data were then analyzed using one-way analysis of variance (one-way ANOVA) separately for each engine speed. The analysis compared the mean fuel consumption between the without-HHO and with-HHO conditions at 800, 2000, 3000, and 4000 rpm. A significance level of 0.05 was used as the decision criterion. A p-value lower than 0.05 indicated a statistically significant difference in mean fuel consumption between the two test conditions at the corresponding engine speed. ANOVA has been widely applied in engine performance and emission-related studies to evaluate whether different operating conditions produce statistically meaningful differences in measured responses [16].

This study did not examine variations in electrolyte concentration, electrical input, or HHO production rate as independent variables. Therefore, the interpretation of the results was limited to the comparison between the standard engine condition and the HHO-assisted condition at the tested engine speeds. The emission results were interpreted descriptively, while the statistical analysis was limited to fuel-consumption data.

RESULTS AND DISCUSSION

Exhaust Emission Characteristics

The exhaust emission test was conducted on a Suzuki Jimny LJ80V equipped with an F8A engine to compare emission characteristics under two operating conditions: standard operation without HHO and operation with an active HHO electrolyzer system. The measured parameters were carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbon (HC), oxygen (O_2), and lambda. The emission test results are presented in Table 1.

Table 1. Exhaust emission characteristics of the F8A engine without and with HHO addition

Parameter	Without HHO	With HHO	Absolute Change	Relative Change	Direction
CO (% vol)	2.09	2.3	0.21	10.00%	Increased
CO_2 (% vol)	9.2	10.2	1	10.90%	Increased
HC (ppm vol)	871	747	-124	-14.20%	Decreased
O_2 (% vol)	5.41	4.41	-1	-18.50%	Decreased
Lambda	1.197	1.124	-0.073	-6.10%	Decreased

As shown in Table 1, HHO addition produced different responses across the measured exhaust parameters. HC decreased from 871 ppm vol to 747 ppm vol, representing a 14.2% reduction. O_2 also decreased from 5.41% vol to 4.41% vol, while lambda shifted from 1.197 to 1.124. In contrast, CO increased from 2.09% vol to 2.30%, and CO_2 increased from 9.20% vol to 10.20%. These results show that HHO addition changed the emission profile of the F8A engine, with reductions in HC and O_2 but increases in CO and CO_2. The relative changes in the measured emission parameters are illustrated in Figure 3.

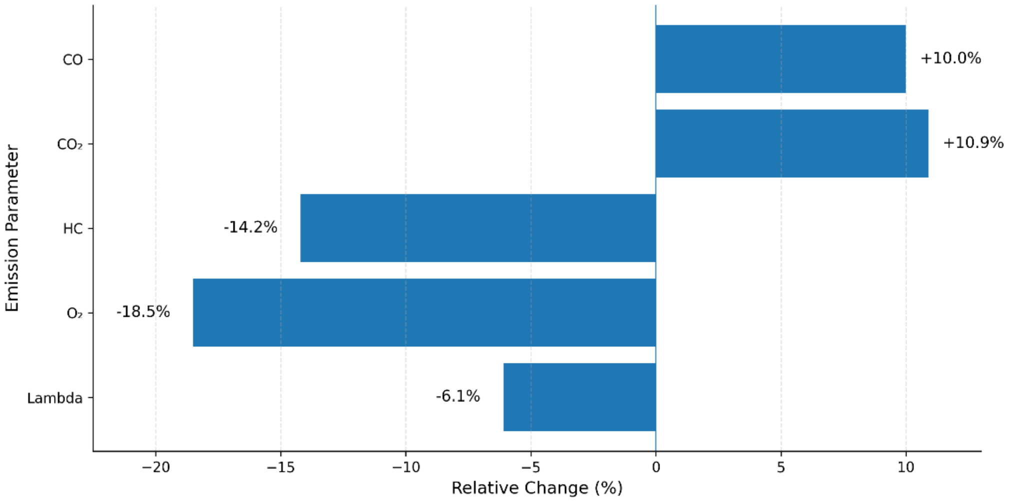

Figure 3. Relative change in exhaust emission parameters after HHO addition.

Fuel Consumption and ANOVA Results

Fuel consumption was tested under two operating conditions: without the electrolyzer system and with HHO addition. The tests were conducted at four engine speeds: 800, 2000, 3000, and 4000 rpm. Each engine-speed condition was tested five times for both operating conditions. The fuel-consumption data were analyzed using one-way ANOVA to compare the mean fuel consumption between the without-HHO and with-HHO conditions at each engine speed. The summary of fuel consumption and ANOVA results is presented in Table 2.

Table 2. Summary of fuel consumption and ANOVA results at different engine speeds

Engine Speed (rpm)	Mean Without HHO (ml)	Mean With HHO (ml)	Absolute Change (ml)	Relative Change (%)	F-value	p-value
800	15.7	14.6	-1.1	-7	121	0.00000415
2000	24.06	25.15	1.09	4.5	102.422	0.00000776
3000	36.56	33.9	-2.66	-7.3	299.814	0.000000126
4000	39.78	35.9	-3.88	-9.8	1045.444	9.12E-10

As presented in Table 2, fuel consumption showed an engine-speed-dependent pattern. With HHO addition, the mean fuel consumption decreased at 800 rpm, 3000 rpm, and 4000 rpm. The reduction was 1.10 mL, or 7.0%, at 800 rpm; 2.66 mL, or 7.3%, at 3000 rpm; and 3.88 mL, or 9.8%, at 4000 rpm. The largest decrease occurred at 4000 rpm. However, at 2000 rpm, fuel consumption increased by 1.09 ml, or 4.5%, from 24.06 ml to 25.15 ml. This indicates that the direction of fuel-consumption change was not uniform across all tested engine speeds.

The ANOVA results showed p-values lower than 0.05 at all tested engine speeds. Therefore, the mean fuel consumption differed statistically between the without-HHO and with-HHO conditions at 800, 2000, 3000, and 4000 rpm. However, the direction of the difference varied across engine speeds: HHO addition was associated with lower fuel consumption at 800, 3000, and 4000 rpm, but higher fuel consumption at 2000 rpm. The comparison of mean fuel consumption between the two operating conditions is presented in Figure 4.

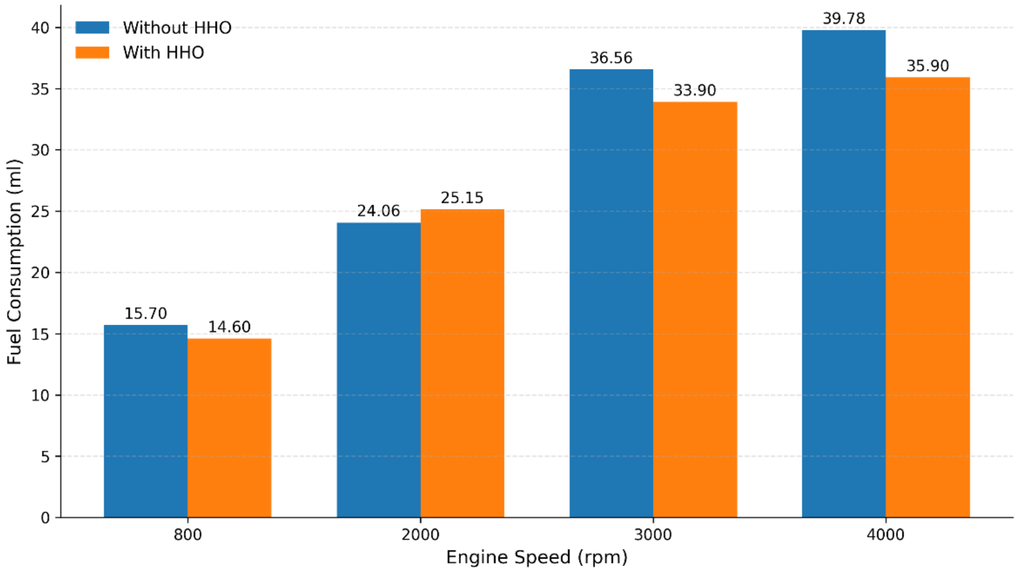

Figure 4. Fuel consumption of the F8A engine without and with HHO addition at different engine speeds.

Discussion

The results indicate that HHO electrolyzer addition changed both the exhaust emission profile and the fuel-consumption pattern of the F8A engine, but the direction of change was not uniform across all measured parameters. Based on Table 1 and Figure 3, HC decreased by 14.2%, O_2 decreased by 18.5%, and lambda shifted from 1.197 to 1.124. These changes suggest that the air–fuel mixture moved closer to the stoichiometric region and that less unburned hydrocarbon remained in the exhaust gas. However, CO increased by 10.0%, and CO_2 increased by 10.9%. Therefore, the emission findings should not be interpreted as a general reduction in all exhaust gas components. A more proportional interpretation is that HHO addition reduced HC and modified the combustion-related emission characteristics of the F8A engine.

The reduction in HC can be linked to the combustion-supporting characteristics of HHO gas. Hydrogen has a high flame speed and low ignition energy, while the oxygen contained in HHO may support oxidation during combustion. In the present study, the decrease in HC and O_2, together with the lambda shift toward 1, indicates that HHO addition may have helped more of the air–fuel mixture participates in the combustion process. This interpretation is in line with previous studies reporting that HHO addition can influence combustion behaviour and reduce unburned hydrocarbon emissions under specific engine operating conditions [6], [9], [14]. Gad and El Soly also showed that oxyhydrogen generated from different electrolyzer configurations affected combustion, emissions, and exergy behaviour in a petrol engine, indicating that the engine response to HHO is closely related to how the gas is generated and delivered into the intake system [17].

The increase in CO from 2.09% to 2.30% requires careful interpretation. Although HC decreased, the higher CO value suggests that carbon monoxide oxidation into carbon dioxide may not have been fully completed under the tested condition. This may occur when local mixture distribution, residence time, flame development, or oxygen availability is not fully balanced during combustion. Zhao et al. reported that HHO addition in a spark-ignition engine can change combustion and emission characteristics depending on fuel-injection configuration and air–fuel mixture behaviour [18]. Another study on brown gas addition in a gasoline direct-injection engine also showed that the effect of HHO depends on lambda, EGR condition, and operating strategy [19]. Therefore, the CO increase in the present study should be treated as part of a mixed emission response rather than being overlooked or generalized as an overall emission improvement.

The increase in CO_2 from 9.20% to 10.20% may indicate that a greater portion of carbon in the fuel was oxidized after HHO addition. This interpretation is supported by the simultaneous decrease in HC and O_2. However, CO_2 is also a greenhouse gas, so the increase in CO_2 should not be framed as an environmental benefit by itself. Hassan et al. reported that hydroxygen-blended gasoline engine performance and emission outcomes were influenced by catalyst configuration and operating condition, showing that HHO-related emission responses are highly system-dependent [20]. In the present study, the CO_2 increase can be interpreted as a possible indicator of more complete oxidation, but not as direct evidence of reduced environmental impact.

The fuel-consumption results in Table 2 and Figure 4 show an engine-speed-dependent response. Fuel consumption decreased by 7.0% at 800 rpm, 7.3% at 3000 rpm, and 9.8% at 4000 rpm. These reductions suggest that, at these operating points, HHO addition was associated with lower fuel use. The largest decrease occurred at 4000 rpm, where combustion duration becomes shorter and faster flame development may provide a greater practical advantage. Yilmaz reported that a modified HHO system could influence the performance and emission characteristics of a spark-ignition engine, particularly when HHO delivery and engine operating parameters were adjusted as part of the experimental configuration [21]. This supports the view that HHO can be beneficial under certain operating conditions, but its benefit cannot be assumed to be identical across all engine speeds.

The fuel-consumption reductions at 800, 3000, and 4000 rpm are comparable with recent HHO studies on spark-ignition engines. Kunaraj and Mathavan reported that HHO integration in a small four-stroke spark-ignition engine reduced fuel consumption and emissions under selected test conditions [22]. Jumali et al. also found that controlled HHO supplementation in a 1.6 L spark-ignition engine reduced brake-specific fuel consumption within certain operating ranges, although the outcome was influenced by HHO concentration and engine load [23]. These studies strengthen the interpretation that HHO can contribute to lower fuel consumption, but only when the supplied gas and engine operating condition are compatible.

The increase in fuel consumption at 2000 rpm is an important finding because it shows that HHO addition did not consistently reduce fuel use across the tested engine speeds. At this engine speed, fuel consumption increased by 4.5%, from 24.06 ml to 25.15 ml. This result suggests that the HHO supply condition used in this study may not have matched the combustion requirement of the engine at medium speed. Estrella-Guayasamín et al. reported that the fuel-consumption response to HHO addition depends on HHO flow rate, electrolyte concentration, and current input, and that different HHO flow levels can produce different fuel-saving responses during road testing [24]. Because the present study did not measure HHO flow rate or vary the electrical input as independent variables, the increase at 2000 rpm should be interpreted cautiously as an observed operating-point response, not as proof of an optimal or non-optimal HHO setting.

The ANOVA results summarized in Table 2 show statistically significant differences in mean fuel consumption between the without-HHO and with-HHO conditions at all tested engine speeds. However, statistical significance only indicates that the mean values differed between the two conditions; it does not automatically indicate that the change was beneficial. At 800, 3000, and 4000 rpm, the significant difference was associated with lower fuel consumption under HHO addition. At 2000 rpm, however, the significant difference was associated with higher fuel consumption. This distinction is important because the practical interpretation of statistical results must consider both the significance value and the direction of the measured change. Reviews on hydrogen use in internal combustion engines also emphasize that hydrogen-related combustion benefits depend on engine configuration, mixture preparation, control strategy, and operating condition [25].

Compared with previous studies, the present research provides a narrower but practically relevant contribution. Many recent HHO studies have focused on diesel engines, modern injection engines, electronically controlled combustion systems, or engines with controlled electrolyte concentration, HHO flow rate, and fuel-blend strategy [8], [11], [13], [15], [18], [23], [24]. In contrast, this study applied a simple HHO electrolyzer system to a carburetted F8A engine without internal engine modification. Fayez et al. examined HHO-LPG dual-fuel additives for gasoline engines and reported that combined gaseous-fuel strategies could change both performance and emission characteristics, but such systems involve a more complex fuel configuration than the simple HHO-assisted setup evaluated in the present study [26]. Therefore, the contribution of this study lies in documenting how a conventional carburetted F8A engine responds to HHO addition in terms of emission characteristics and fuel consumption at different engine speeds.

Overall, the findings suggest that HHO electrolyzer addition has potential to reduce HC emissions and lower fuel consumption at selected engine speeds in the F8A engine. Nevertheless, the results also show important limitations. CO and CO_2 increased, fuel consumption increased at 2000 rpm, and emission parameters were analyzed descriptively rather than statistically. Therefore, the electrolyzer system should not be described as uniformly reducing emissions or fuel consumption. A more balanced implication is that HHO addition can modify combustion-related emission characteristics and fuel-consumption behavior, but its benefit depends on the compatibility between HHO supply and engine operating condition. Future research should measure HHO flow rate, electrical input, electrolyte concentration, engine load, torque, power, exhaust temperature, and long-term engine component response to clarify the operating conditions under which HHO addition becomes beneficial for conventional carburetted gasoline engines.

CONCLUSION

This study evaluated the use of an HHO-based electrolyzer system on a carburetted F8A engine by comparing exhaust emission characteristics and fuel consumption under without-HHO and with-HHO conditions. The results showed that HHO addition reduced HC emissions from 871 ppm to 747 ppm, representing a 14.2% decrease. O_2 also decreased by 18.5%, while lambda shifted from 1.197 to 1.124, indicating that the air–fuel mixture moved closer to the stoichiometric region. However, CO increased from 2.09% to 2.30%, and CO_2 increased by 10.9%. Therefore, the emission results should be interpreted as changes in emission characteristics rather than as a uniform reduction in all exhaust components.

In terms of fuel consumption, the HHO system reduced fuel use by 7.0% at 800 rpm, 7.3% at 3000 rpm, and 9.8% at 4000 rpm. However, fuel consumption increased by 4.5% at 2000 rpm, showing that the response of the F8A engine to HHO addition was dependent on engine speed. The ANOVA results indicated statistically significant differences in mean fuel consumption between the without-HHO and with-HHO conditions at all tested engine speeds. Overall, the findings suggest that HHO electrolyzer addition has potential to support HC reduction and fuel-consumption improvement at selected engine speeds, but its benefits were not uniform across all measured parameters. Further studies should examine HHO flow rate, electrical input, electrolyte concentration, engine load, power, torque, thermal efficiency, and long-term engine component response to clarify the operating conditions under which HHO addition is most beneficial for conventional carburetted gasoline engines.

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