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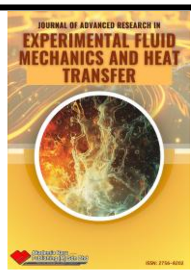

Effects of Oxyhydrogen (HHO) Gas Supplementation on Performance and Emissions of a 1.6L Spark Ignition (SI) Engine at Various Load Conditions

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ABSTRACT

This study investigates the effects of Oxyhydrogen (HHO) gas supplementation on the performance and emission characteristics of a 1.6L, 4-cylinder Multi-port Fuel Injection (MPI) spark ignition engine under varying load conditions. A dry-cell HHO generator utilizing potassium hydroxide (KOH) electrolyte at different molarities (0.3M, 0.5M, 0.7M, and 1.0M) was employed, with the generated gas supplied directly to the intake manifold just before the throttle body. The engine was tested in stock condition using only RON95 gasoline, while HHO testing was conducted in a dual-fuel configuration, combining RON95 gasoline with HHO gas. Performance and emissions were evaluated across engine speeds from 1500 to 3000 rpm at throttle valve positions of 25%, 50% and 75%. Brake power and torque were enhanced by up to 3.67% and 3.40%, respectively, with the most notable improvements occurring at 3000 rpm of engine speed. Brake-specific fuel consumption was reduced by up to 1.94%, although the highest molarity (1.0M) occasionally led to efficiency penalties. Emission measurements indicated significant reductions in CO and HC emissions, up to 11.90% and 22.98%, respectively, while monitoring CO_2, NO_x, O_2, and lambda/air-fuel ratio (AFR). The most favorable HHO concentration range was identified as 0.5–0.7M. These findings demonstrate that controlled HHO supplementation can effectively enhance fuel economy and emission performance in SI engines without major mechanical modifications, contributing to the advancement of more environmentally sustainable internal combustion technologies.

1. Introduction

Petrol engines continue to dominate the transportation sector owing to their reliability, performance, and extensive infrastructure. Nevertheless, they significantly contribute to environmental pollution by emitting harmful gases, including Carbon Monoxide (CO), unburned

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Hydrocarbons (HC), Nitrogen Oxides (NO_x), and Carbon Dioxide (CO_2) [1,2]. These emissions exacerbate climate change and present serious public health concerns. With growing global pressure to minimize ecological footprints and enhance energy sustainability, there is an urgent need for innovative solutions that boost fuel economy while reducing emissions.

A promising approach involves the integration of Oxyhydrogen (HHO) gas, which is a precise blend of hydrogen and oxygen, into petrol engines [3,4]. When injected into the combustion chamber, HHO can enhance combustion efficiency due to its rapid flame propagation and broad flammability range [5]. This leads to more thorough fuel oxidation, which may improve thermal efficiency, decrease fuel consumption, and lower harmful exhaust emissions [6].

However, the effectiveness of HHO supplementation depends on several critical factors, such as gas purity, stable on-demand production, and optimal delivery techniques into the engine's intake or combustion system [7-9]. These variables directly influence the degree to which HHO can enhance engine performance and reduce pollutant emissions.

Gad and El Soly [10] investigated the impact of HHO gas, produced via dry and wet electrolyzer configurations, on the combustion, emissions, and exergetic performance of a SI petrol engine. Their study compared HHO flow rates of $0.4\ \mathrm{L/min}$ (dry cell) and $0.6\ \mathrm{L/min}$ (wet cell) in a single-cylinder Honda GX-160CC engine under varying loads. Results indicated significant improvements in engine performance, with brake thermal efficiency increasing by 4% (dry cell) and 7.5% (wet cell), alongside reductions in Brake-Specific Fuel Consumption (BSFC) ($4.5\% - 8\%$). Emissions of CO, HC, and CO_2 decreased substantially (up to $35\%, 23\%$ and 37%, respectively) due to enhanced combustion efficiency from HHO's high flame velocity and oxygen enrichment. Exergy analysis revealed a $33\% - 36\%$ reduction in fuel exergy consumption and a $50\% - 55\%$ improvement in exergetic efficiency, underscoring superior energy utilization. While wet cells provided greater performance enhancements, dry cells were noted for their simplicity and corrosion resistance. The study concluded that HHO supplementation, particularly from dry cells, offers a viable method to improve engine efficiency and reduce emissions, addressing gaps in comparative HHO production techniques.

In another case, Leyko *et al.,* [11] examined the effect of minimal hydrogen enrichment on stabilizing lean combustion in a Spark-Ignition (SI) gasoline engine. Operating a 1.2L EURO 5MPI engine at an air-fuel ratio ($\lambda = 1.4$), the authors introduced hydrogen in small mass fractions ($0.15\% - 1.5\%$) via onboard HHO gas generated by an alkaline electrolyzer. Their results demonstrated that even 0.3% hydrogen addition significantly enhanced combustion stability, reducing cycle-to-cycle variability and improving flame propagation, particularly at low loads where lean operation is most unstable. While peak in-cylinder pressure remained largely unaffected at hydrogen fractions below 0.5%, the derivative of pressure rise increased, indicating faster combustion. The study proposed that a compact onboard hydrogen storage system ($10\mathrm{dm}^3 - 15\mathrm{dm}^3$) could feasibly mitigate lean-burn instability without major vehicle modifications. Notably, the findings contrast with prior assumptions that larger hydrogen quantities ($\sim 3\%$) are necessary for combustion improvement. The authors highlighted the potential of efficient electrolysis-based HHO generation as a practical solution to extend lean-burn operation, balancing performance gains with minimal infrastructure changes. This work advances understanding of hydrogen's role in lean SI engines and provides empirical support for its deployment at sub-stoichiometric concentrations.

Another relevant case study is by Kultsum *et al.,* [12] that evaluated the performance enhancement of a SI engine supplemented by a commercial HHO generator. Their experimental-numerical study employed a motorbike engine integrated with an electrolytic HHO system powered at $15\mathrm{V} - 30\mathrm{V}$. While higher voltage operation which is at $30\mathrm{V}$, yielded modest improvements (0.7% torque, 1.38% power increase), the enhancements remained statistically insignificant compared to baseline gasoline operation. The study revealed several critical limitations. Firstly, tap water electrolyte underperformed relative to theoretical Faraday predictions. Secondly, thermal efficiency gains were marginal ($\sim 20\%$ at $30V$), and lastly, system inefficiencies from electrical or mechanical losses constrained overall benefits. The authors identified key optimization pathways including electrolyte additives and automotive-grade power systems, while emphasizing the need for complementary emission studies to fully assess HHO's viability as a supplementary fuel. This work contributes empirical evidence on the practical challenges of implementing commercial HHO systems in small-scale SI engines.

Expanding on earlier research into HHO-enhanced combustion, Sherman and Singh [13] present significant advancements through their HydroBoost technology implementation in a 3.5L Ford Escape engine. Unlike earlier studies that reported marginal improvements, which is $0.7\% - 8\%$ efficiency gains, this work demonstrates remarkable 11% to 72% BSFC reduction. Total Hydrocarbons (THC) emission decrease - the most substantial benefits documented in recent HHO literature. The study addresses key limitations identified in prior research by employing: (1) an optimized dry-cell electrolyzer with catalytic agents to minimize power losses, (2) Environmental Protection Agency (EPA) standardized test cycles (FTP-75/HWFET) for reliable performance evaluation, and (3) comprehensive emission monitoring using AVL i60 analyzers. Technology's success in maintaining stoichiometric combustion while achieving simultaneous reductions in all measured emissions ($HC\ 72\%, CH_4\ 69\%, NO_X\ 48\%, CO_2\ 24\%$) resolves the NO_X trade-off problem observed in lean-burn HHO applications [11]. Particularly noteworthy is the 24% total CO_2 reduction, which is a critical advancement given climate concerns, achieved through combined direct emission reduction and fuel efficiency gains. These results substantiate that optimized HHO systems can surpass the performance limitations reported in earlier small-scale implementations [12], while confirming the combustion enhancement mechanisms proposed by Gad and El Soly [10]. The work establishes HydroBoost as currently the most technologically mature HHO implementation, addressing 3 persistent challenges in the field, which are efficiency limitations, emission trade-offs, and system durability. Future research directions should focus on lifecycle analysis and large-scale vehicle fleet testing to validate these promising results under real-world operating conditions.

Another case analysis is by Gad *et al.,* [14], which investigated the effects of HHO gas supplementation on the performance and emissions of a SI engine using a dry cell electrolyzer system. The researchers conducted experiments on a Honda GX-160 single-cylinder engine operating at 3000 rpm under various load conditions. The electrolyzer, constructed with 26 plates of $316L$ stainless steel and using a 10% $NaOH$ catalyst solution at $12V$ and $25A$, produced HHO gas at a flow rate of $0.5L/min$. Results demonstrated significant improvements in engine performance, including an 8% increase in brake thermal efficiency, 9% reduction in BSFC, and 7.5% enhancement in volumetric efficiency compared to baseline gasoline operation. Emission measurements revealed substantial reductions of 18% for CO, 11% for CO_2, 15% for NO_x, and 9% for HC. Combustion analysis showed 1.5% increase in peak cylinder pressure and 4.5% higher heat release rate, indicating more complete and efficient combustion with HHO addition. The study attributes these improvements to the favorable combustion properties of HHO gas, including its high flame speed and low ignition energy requirements. These findings suggest that HHO supplementation from dry cell electrolyzers can effectively enhance engine performance and reduce emissions without requiring major engine modifications. The research provides valuable empirical data supporting the technical feasibility of HHO systems for improving the efficiency and environmental impact of SI engines.

Another documented analysis is by Kamarudin *et al.,* [15], which examined the effects of retrofitting a 2-stroke gasoline engine with HHO gas on emissions, fuel consumption, and exhaust gas temperature. Using a $1.5kW$ Europower $Eg950V$ generator modified with a dry cell electrolyzer (16 stainless steel plates, KOH electrolyte), the researchers tested HHO supplementation at varying power outputs, specifically $84W - 720W$ and air-fuel ratios which is $12 - 20$. Results showed that even small HHO additions ($0.05\% - 0.15\%$ by volume) improved engine performance, reducing fuel consumption by up to 8.9% and lowering emissions significantly, which are CO by 9.41%, NO_x by 4.31%, and HC by 5.19%. Exhaust gas temperature also decreased up to 2.02%, indicating enhanced combustion efficiency. The improvements were most effective at near-stoichiometric conditions, demonstrating HHO's potential as a retrofit solution for cleaner two-stroke engine operation. The authors suggest further investigation into higher HHO concentrations ($0.5\% - 1\%$) to optimize performance gains.

Another case analysis is by Padmanabhan *et al.,* [16] investigated a novel dual-additive approach combining hydroxy (HHO) gas and Ceric Dioxide (CeO_2) nanoparticles to enhance the sustainability of SI engines. Using a $22.95kW$ single-cylinder gasoline engine, the researchers tested 2 HHO flow rates ($0.15\ kg/h - 0.25\ kg/h$) and 2 nanoparticle concentrations ($25\ ppm - 50ppm$) under varying load conditions. Results demonstrated significant improvements, with brake thermal efficiency increasing by up to 18.1% and specific fuel consumption decreasing by 20.55%. The combined additives also substantially reduced emissions, achieving 23.6% lower HC and 15.74% lower CO levels compared to baseline gasoline operation. However, enhanced combustion led to a 22.79% increase in NO_x emissions due to higher combustion temperatures. Response Surface Methodology optimization identified $0.25\ kg/h$ HHO flow with $50\ ppm\ CeO_2$ as the most effective combination for performance and emissions reduction. While demonstrating promising results for sustainable engine operation, the study highlights the need for further research to address NO_x control and assess long-term nanoparticle effects on engine components. This work presents a viable pathway for improving gasoline engine efficiency while meeting environmental objectives through synergistic use of HHO gas and catalytic nanoparticles.

A study by Truong *et al.,* [17] examined the impact of HHO-enriched air on the performance and emissions of a simulated biogas-fueled SI engine. Using a modified 4-cylinder engine and simulated biogas ($55\%\ CH_4, 35\%\ CO_2$), the researchers introduced 0.1% HHO gas by volume to the air intake while measuring performance parameters and emissions. Experimental results combined with AVL Boost simulations showed significant improvements, with combustion duration decreased from $44.5°$ to $40°$ crank angle, peak cylinder pressure increased from $42.12\ bar$ to $45.73\ bar$, and maximum rate of heat release rose from $34.52\ J/deg$ to $41.68\ J/deg$. The HHO addition recovered 7.68% of the biogas engine's power deficit compared to gasoline, reduced brake-specific energy consumption by 4.5%, and improved idle stability, where coefficient of variation of speed decreased from 1.58% to 0.47%. Emissions analysis revealed substantial reductions in CO with 20.2% and HC with $14.2\% - 18.6\%$, though NO_x increased by $9.4\% - 33.4\%$ due to higher combustion temperatures. The study demonstrates HHO's potential to enhance biogas engine performance while highlighting the need for NO_x mitigation strategies in future applications. The combined experimental-simulation approach provides valuable insights for optimizing HHO-assisted biogas combustion in stationary engine systems.

This paper aims to examine the influence of varying operating conditions such as electrolyte concentration and applied voltage. Gaining a clearer understanding of these parameters is essential to establish reliable HHO generation suitable for engine applications. In addition, this paper evaluates the effects of HHO gas enrichment on petrol engine performance, particularly in terms of fuel consumption and exhaust emissions. The analysis focuses on how the introduction of HHO gas under different driving conditions influences overall engine efficiency and emission characteristics.

2. Methodology
2.1 Experimental Setup

This study investigated engine performance and exhaust emissions, where the experiment utilized a 1.6L, in-line, 4-cylinder SI S4PH engine model equipped with a Multi-port Fuel Injection (MPI) system. The engine's technical specifications are detailed in Table 1. The stock Electronic Control Unit (ECU) wiring harness was adapted with minor modifications to integrate a dry-cell HHO generator into the system. This generator utilizes potassium hydroxide (KOH) as the electrolyte for electrolysis. 4 HHO gas injection nozzles were installed on the air intake manifold, positioned proximally to the inlet valves. The original gasoline injectors remained fully functional. The gasoline fuel used in this study is RON95 and purchased only from one brand to make sure the constant additive composition of the fuel.

Table 1
Technical specifications of S4PH engine [18]

Type model	S4PH
Total displacement (L)	1.6L
Number of cylinders	4
Orientation	East-West
Valve train	DOHC 16 V
Compression ratio	10.0: 1
Bore x stroke (mm)	76 x 88
Power (kW)	82 @ 6000RPM
Torque (Nm)	148@ 4000RPM
Fuel / system	Petrol / multi point port injection

Engine performance, specifically brake power and brake torque, was quantified using a Dynapack $4022\ 650\text{kW}$ chassis dynamometer. Exhaust emissions, including Carbon Monoxide(CO) and Hydrocarbons (HC), were measured using a QGA6000 gas analyzer with a tailpipe probe with a repeatability value of 2%. Gasoline fuel consumption was determined using an Ono Sokki FZ-2100 Coriolis mass flow meter. A Bosch KTS 570 V1.2 scan tool facilitated real-time monitoring of engine parameters and system integrity. This integration of high-precision sensors and real-time data acquisition tools reflects the increasing alignment of experimental engine testing with Internet of Things (IoT)-based monitoring systems, which are becoming central to modern automotive research and diagnostics [19]. To maintain the accuracy of the data, all equipments are calibrated by authorized bodies. All experimental conditions were replicated three times to ensure data reliability. The ambient conditions were maintained constant throughout the experiments, with a temperature of 29 °C, atmospheric pressure of 1010 mbar, and relative humidity of approximately 70%.

2.2 Experimental Procedures

The engine's performance and exhaust emissions were evaluated across various engine speeds, specifically 1500, 2000, 2500 and 3000 rpm. The gear used for the experiment is gear 4 because of the 1:1 ratio from the engine to the wheel. Based on the combination of engine speed and gear ratio, the maximum attainable vehicle speed was 86 km/h, which is marginally below the national speed limit of 90 km/h applicable to Malaysian state and federal roads. Figure 1 illustrates the schematic diagram of the engine test setup. A steady-state testing methodology was employed to acquire data. The engine was operated at incremental speeds of 500 rpm, with Throttle Valve Positions (TVP) controlled at $25\%, 50\%, 75\%\ and\ 100\%$ for each speed increment. Prior to data acquisition, the engine was warmed up for a duration of approximately 10 minutes until the exhaust tailpipe exhibited water droplet formation, signifying the attainment of stable combustion conditions. The stock condition was tested using only RON95 gasoline sourced from a single brand to ensure consistency in fuel additive composition. For the HHO test condition, the HHO gas was introduced into the intake system near the throttle body to promote effective mixing with the incoming air. During each test, engine speed and (TVP) were maintained in a stable state for a minimum duration of 10 seconds to ensure data consistency. Each test condition was conducted over a period of 5 minutes to allow for reliable measurement and repeatability. Each test condition was replicated thrice to mitigate experimental error and ensure data reliability.

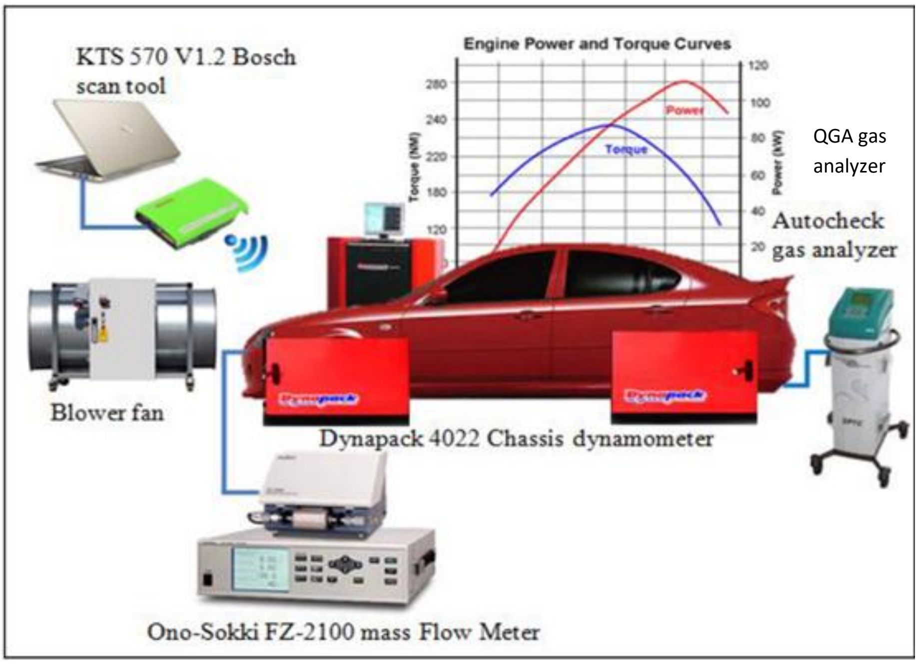

Fig. 1. Schematic diagram of the engine test setup [20]

2.3 HHO Generator Setup

The HHO generator employed in this study utilized a dry cell configuration, which was selected for its improved thermal management and compact design. The generator consisted of a plate stack composed of 10 neutral plates, 2 anode plates, and 1 cathode plate, arranged in a symmetrical configuration to ensure balanced current distribution and efficient gas production [3,4]. All plates were fabricated from 316-grade stainless steel, selected for its corrosion resistance and electrochemical stability under alkaline electrolysis conditions. Each plate had a thickness of 1.15 mm and was separated using Ethylene Propylene Diene Monomer (EPDM) rubber gaskets, which provided chemical resistance and reliable sealing. The total active surface area available for electrolysis on each plate was 253.735 cm^2. The inter-plate gap was maintained at 3 mm, allowing adequate electrolyte flow and gas bubble release during electrolysis. Figure 2 illustrates the configuration of the HHO generator employed in the experimental setup.

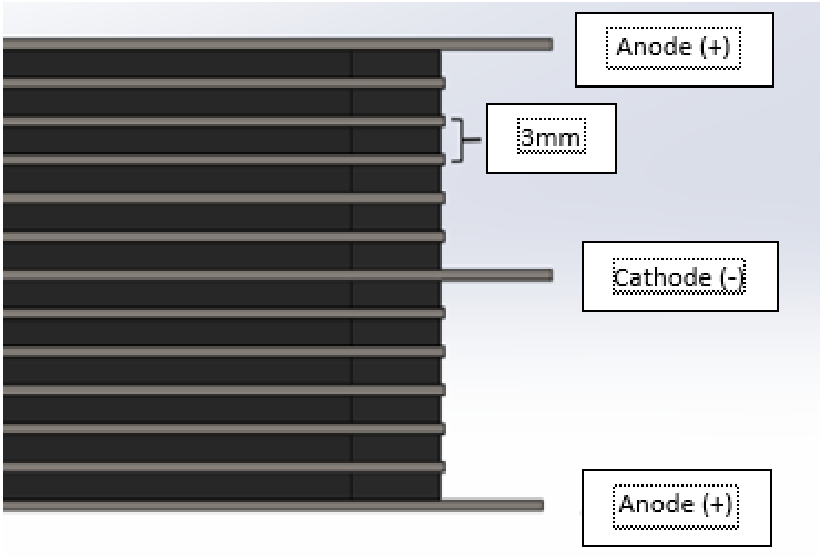

Fig. 2. Inter-plates configuration

The electrolyte used was Potassium Hydroxide (KOH) dissolved in distilled water, with test concentrations of 0.3M, 0.5M, 0.7M, and 1.0M. This molarities was chosen to evaluate the effect of electrolyte concentration on gas production rates and corresponding engine performance. The electrolyte was stored in an integrated reservoir tank with a capacity of 2 liters, ensuring sufficient fluid volume during extended testing. To mitigate the risk of flame flashback and maintain system safety, the setup included a bubbler unit positioned between the HHO generator and the engine intake. The complete configuration of the HHO generator utilized in this study is illustrated in Figure 3, which provides a detailed representation of the system components and their arrangement.

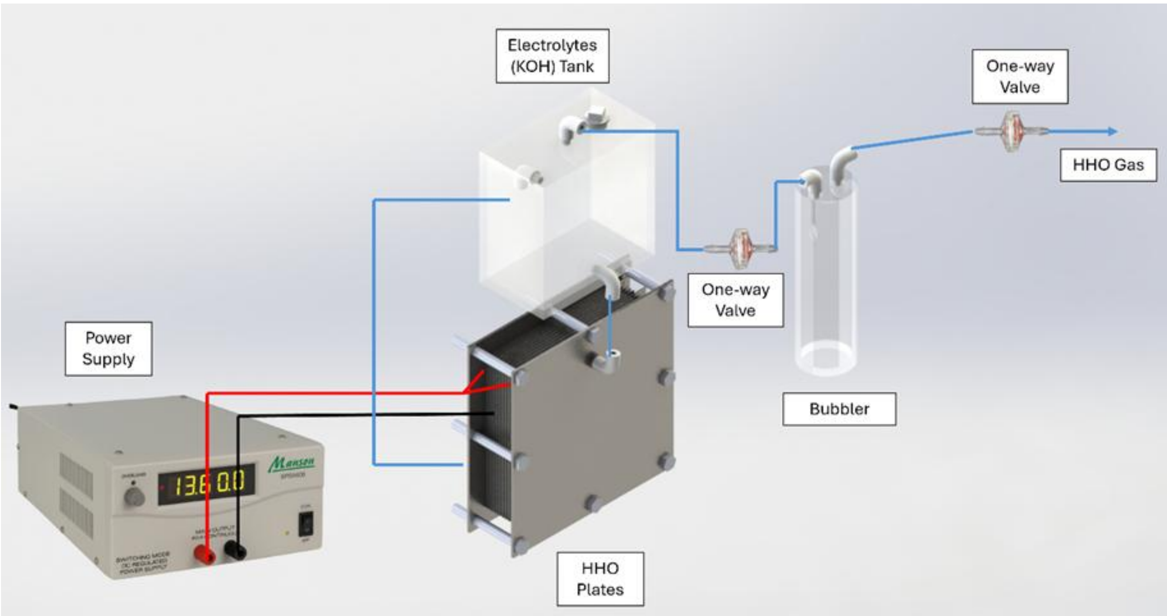

Fig. 3. HHO generator setup for the experiment

Additionally, one-way check valves were installed on both the line from the electrolyte tank to the bubbler and from the bubbler to the engine's air intake system, ensuring unidirectional gas flow and preventing back-pressure damage. Power for the electrolysis process was supplied by a regulated Direct Current (DC) power source operating within the range of 13.5 to 14.5 volts. The current draw was continuously monitored via the integrated ammeter on the power supply, with a maximum of 40 Ampere, allowing for the evaluation of electrical consumption relative to electrolyte molarity and operational stability. The HHO gas generated was delivered into the engine's intake manifold for performance and emissions testing under various operating conditions.

3. Results and Discussion
3.1 Brake Power

In this experiment, brake power, which represents the usable power output measured at the engine’s crankshaft and is a key indicator of overall engine performance, was evaluated under various load and speed conditions, as illustrated in Figure 4 below.

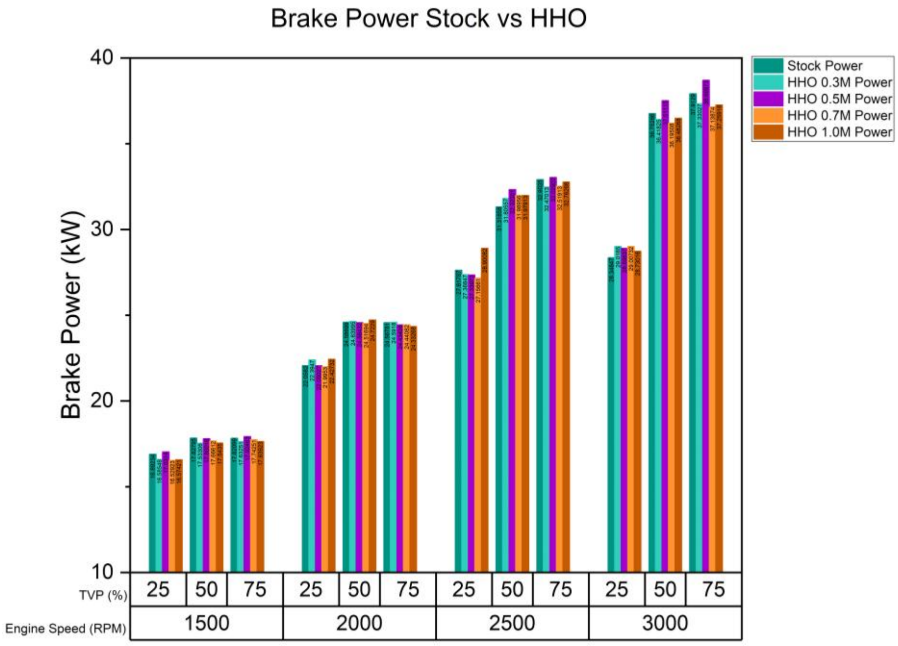

Fig. 4. Comparison graph of brake power stock and HHO

The supplementation of HHO gas demonstrated notable effects on brake power across varying engine speeds and Throttle Valve Positions (TVP). At 1500 rpm, the addition of HHO gas led to modest improvements in brake power, with increases up to 0.83% across all TVP levels. These findings are consistent with previous studies highlighting hydrogen's ability to enhance combustion efficiency even at lower engine speeds. As the engine speed increased to 2000 rpm, brake power gains became slightly more pronounced, achieving an enhancement of up to 1.49% with 0.3M HHO enrichment. However, a slight decline in performance was observed at higher molarity levels, emphasizing the critical role of maintaining an optimal air-fuel ratio for effective combustion.

At 2500 rpm, the impact of HHO supplementation became more evident, with brake power improvements reaching up to 3.67% at 50% TVP. This suggests that hydrogen's contribution to combustion phasing becomes increasingly beneficial under moderate load conditions. The most significant enhancements were observed at 3000 rpm, where the amount of brake power increased by approximately 2.07% to 2.36%. These results indicate that the benefits of HHO enrichment are maximized at higher engine speeds and loads [4], where the favourable combustion characteristics of hydrogen such as low ignition energy, high flame speed, and a wide flammability range are more effectively utilized due to elevated airflow rates and intensified combustion chamber conditions [20].

Overall, the results affirm the potential of HHO gas to substantially enhance engine output, particularly under high-speed and high-load operating conditions [21].

The experimental results clearly demonstrate that the addition of HHO gas contributes to improvements in brake power across a broad range of engine speeds and load conditions. Notably, the magnitude of these enhancements was more pronounced at higher engine speeds and under moderate to high load conditions, where combustion dynamics are more demanding. Conversely, at lower engine speeds or under light load, the observed improvements were smaller and, in some cases, inconsistent. These findings underscore that the advantages of hydrogen supplementation are most effectively realized in operating regimes that require accelerated combustion and enhanced thermal efficiency [22]. The inherent properties of hydrogen, such as its high flame speed and low ignition energy, appear to play a critical role in optimizing combustion under these more challenging conditions [23].

3.2 Brake Torque

This study also examined brake torque, following the analysis of brake power. Brake torque, defined as the rotational force produced by the engine at the crankshaft, plays a critical role in determining the engine's capacity to deliver brake power. The two parameters are mechanically related by the Eq. (1):

$$\text{Brake Power}=\frac{2\pi\times\text{Torque}\times\text{Engine Speed}}{60} \quad (1)$$

indicating that any increase in torque at a constant engine speed will result in a proportional increase in brake power. This interdependence reinforces the performance improvements observed, as torque enhancements under HHO enrichment directly contributed to the gains in brake power. The results are presented in Figure 5 below.

The addition of HHO gas yielded varying degrees of improvement in brake torque across different engine speeds and TVP. At the lower operating range of 1500 rpm, torque enhancements were relatively modest, with a maximum gain of 0.83%. As engine speed increased to 2000 rpm, more substantial torque gains emerged, with improvements reaching 3.40% at 50% TVP and 1.15% at 75% TVP, highlighting hydrogen's ability to support more efficient combustion under moderate loading.

Progressing into mid-speed operation at 2500 rpm, the trend of improvement continued, with torque increasing by 3.16% at 50% TVP and 0.39% at 75% TVP. At peak engine speeds of 3000 rpm, although results were more varied, a torque enhancement of up to 2.07% was still achieved at higher loads. Collectively, these results affirm that HHO supplementation contributes positively to torque output, particularly under moderate to high load conditions where combustion phasing has a more pronounced influence on performance. The observed improvements are largely attributed to hydrogen's favourable combustion characteristics, which enhance the indicated mean effective pressure (IMEP) and overall torque generation [24].

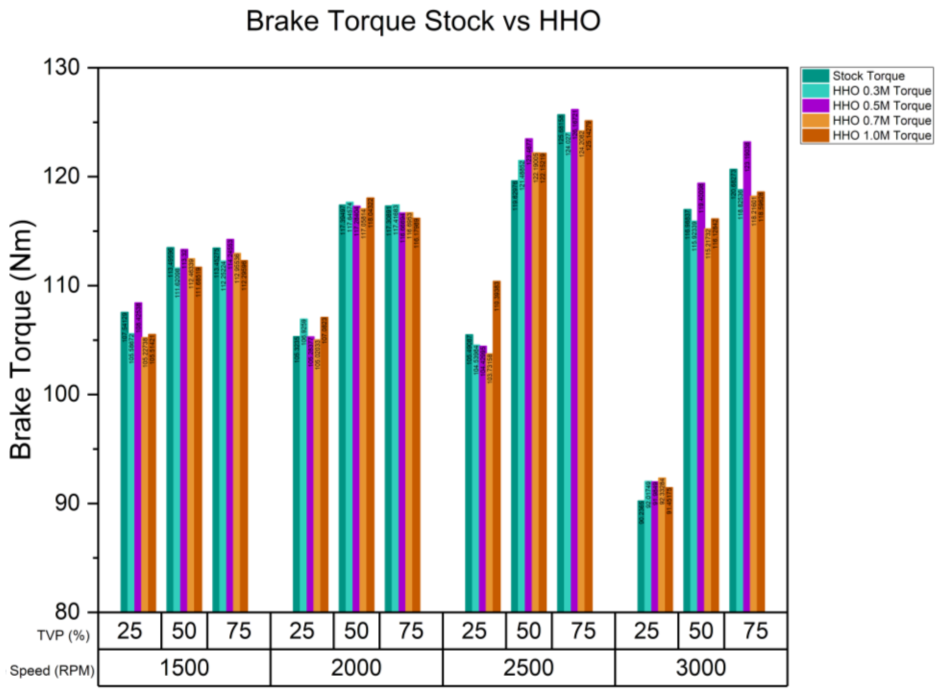

Fig. 5. Comparison graph of brake torque stock and HHO

The observed improvements in brake torque with HHO gas enrichment can be attributed to the inherent combustion characteristics of hydrogen, including its wider flammability limits, higher flame propagation speed, and lower ignition energy requirements. These properties contribute to more rapid and complete combustion, thereby enhancing torque output, particularly under demanding engine conditions [21,11].

Determining the optimal molarity of HHO gas is critical for maximizing engine performance. Experimental findings indicate that moderate concentrations, particularly 0.5M and 0.7M, consistently yielded superior results compared to both lower (0.3M) and higher (1.0M) molarity levels. Excessive enrichment with HHO, especially at higher concentrations, may disrupt the air-fuel balance, leading to combustion instability or reduced volumetric efficiency [23,24]. These findings are comparable to results reported by Badrulhisam *et al.,* [25], where lower-volume alcohol blends improved brake power and emissions, while higher ratios caused degradation in performance. These poor effects are most evident under low-speed and low-load operating conditions, where the engine is more sensitive to fluctuations in mixture composition and combustion dynamics [26].

3.3 Brake-Specific Fuel Consumption (BSFC)

Brake-Specific Fuel Consumption (BSFC), a crucial metric indicating the fuel efficiency of the engine by measuring the amount of fuel consumed per unit of brake power output, was analysed and is graphically represented in Figure 6.

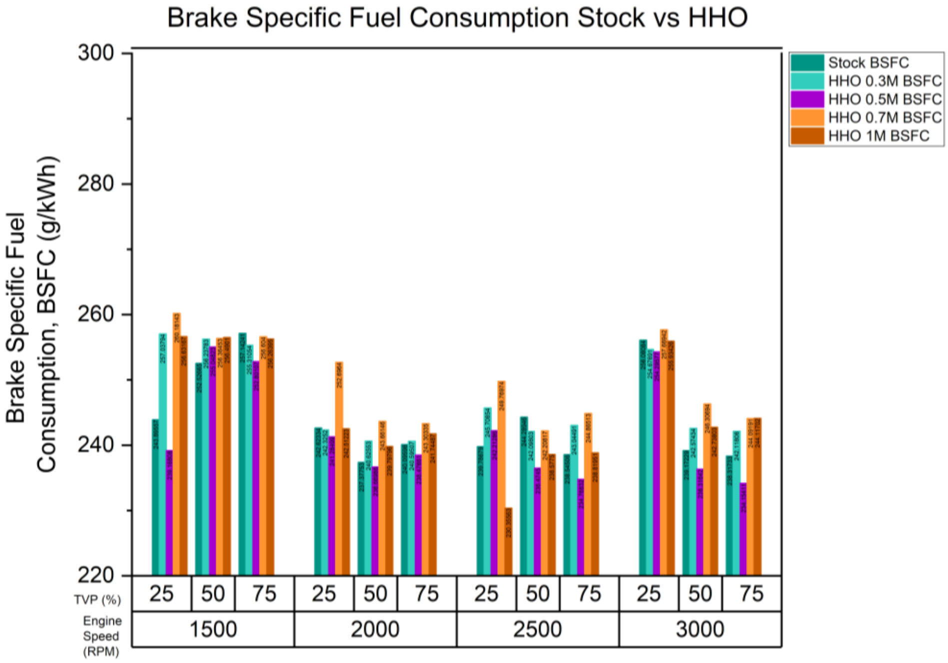

Fig. 6. Comparison graph of brake-specific fuel consumption stock and HHO

On the low-speed operating range of 1500 rpm, the application of HHO at a moderate concentration of 0.5M resulted in a slight improvement in BSFC, reducing it by 1.94%. Conversely, enrichment with 1.0M HHO led to a 5.23% increase in BSFC, suggesting that excessive hydrogen dosing may induce over-enrichment and compromise combustion efficiency. As the engine speed transitioned to 2000 rpm, a marginal BSFC reduction of 0.30% was observed with 0.5M HHO, while higher concentrations continued to exhibit diminishing returns, slightly worsening fuel economy.

Under mid-speed conditions at 2500 rpm, BSFC improvements became more pronounced, particularly at 75% TVP, where reductions reached up to 1.58%. During high-speed operation at 3000 rpm, the trend was mixed: a 1.19% decrease in BSFC was achieved with 0.5M HHO, whereas the 1.0M concentration again resulted in an adverse 2.41% increase. These findings underscore the critical importance of optimizing HHO concentration to achieve maximum fuel efficiency. While hydrogen's high diffusivity, low ignition energy, and rapid flame speed enhance combustion, overuse can lead to adverse effects such as cooling losses or air-fuel ratio imbalances that degrade performance. Thus, careful calibration of HHO dosing is essential to maintain the balance between combustion enhancement and engine efficiency [27].

The incorporation of HHO gas into the engine's air intake stream was found to enhance combustion efficiency under specific operating conditions, as indicated by modest yet consistent reductions in BSFC at selected engine speeds and load levels. These improvements are primarily attributed to the advantageous combustion properties of hydrogen, which include its exceptionally low ignition energy, high flame propagation speed, and broad flammability range. Collectively, these characteristics facilitate more complete and rapid combustion, thereby improving thermal efficiency and reducing fuel consumption when appropriately dosed within the air-fuel mixture [25,11].

However, the inconsistent trends observed at higher HHO molarity levels (0.7M and 1.0M) indicate that excessive hydrogen-oxygen enrichment may disrupt combustion stability or displace the optimal air-fuel ratio, particularly under low or partial load conditions. Such over-enrichment can lead to suboptimal ignition timing, increased combustion variability, or reduced volumetric efficiency, ultimately offsetting the potential benefits of hydrogen-assisted combustion [11]. This is consistent with the findings of Yusri *et al.,* [28], who reported that increased alcohol blending ratios led to reduced thermal efficiency and greater cyclic variation in diesel engines due to lower calorific value and extended ignition delay. Moreover, the importance of controlling the hydrogen addition rate, highlighting that while small additions enhance thermal efficiency, excessive additions can lead to combustion anomalies, increased wall heat losses, and reduced volumetric efficiency [29].

3.4 Carbon Monoxide (CO) Emission

As shown in Figure 7, CO emission, which is a byproduct of incomplete combustion was assessed to evaluate the combustion quality and environmental impact of the engine under different HHO enrichment levels.

The introduction of HHO gas into the intake system consistently contributed to reductions in CO emissions across a majority of operating conditions, highlighting its potential for cleaner combustion. Under low-speed and light-load conditions (1500 rpm, 25% TVP), CO emissions decreased from 0.34% under stock conditions to 0.31% with 1.0M HHO enrichment, reflecting an 8.82% reduction. Similar trends were observed at higher loads, at 50% TVP, emissions declined from 0.30% to 0.29% (3.33%), while at 75% TVP, a drop from 0.31% to 0.29% corresponded to a 6.45% reduction.

In the light-to-moderate speed range around 2000 rpm under 25% TVP, a slight increase in CO emissions was recorded from 0.33% in stock conditions, indicating that HHO's effectiveness may diminish under very light loads. A marginal rise was also observed at 2500 rpm and 75% TVP, where CO levels increased from 0.37% to 0.38% (2.70%), possibly due to combustion instability under high load conditions. In contrast, high-speed operation at 3000 rpm demonstrated substantial emission benefits, at 75% TVP, CO levels dropped from 0.42% to 0.37%, an 11.90% reduction, while emissions remained stable at 0.40% at 50% TVP.

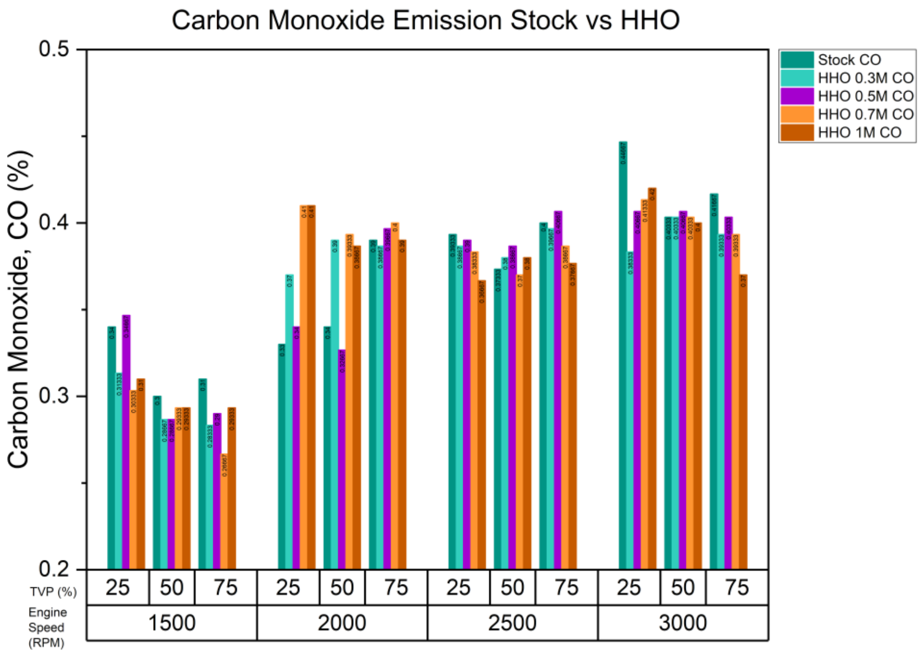

Fig. 7. Comparison graph of Carbon Monoxide (CO) emission stock and HHO

These findings affirm the emission-reducing potential of HHO supplementation, particularly at higher engine speeds [4]. The consistent decline in CO levels can be attributed to the favourable combustion properties of hydrogen, namely its high laminar flame speed, low ignition energy threshold, and broad flammability limits, which collectively enable more rapid and complete oxidation of the fuel-air mixture [30]. The findings suggest that small additions of hydrogen improve oxidation efficiency, lowering partial oxidation products like CO, especially under low-to-moderate load and speed conditions. Notably, at some points, for example at 2500 rpm with 25% TVP, slight increases in CO emissions were observed, likely due to non-optimized air–fuel mixing or combustion phasing, phenomena [31]. These results underline the critical need for precise control strategies when integrating HHO systems to maximize their benefits across a full operating map.

3.5 Hydrocarbon (HC) Emission

The variation in Hydrocarbon (HC) emissions, which reflect the amount of unburned fuel released into the exhaust due to incomplete combustion, is presented in Figure 8 and serves as an indicator of combustion efficiency.

The supplementation of HHO gas resulted in a consistent and substantial reduction in HC emissions across all tested engine conditions. Under low-speed, light-load conditions (1500 rpm, 25% TVP), HC levels decreased from 168 ppm in the baseline configuration to 151 ppm with 1.0M HHO enrichment, marking a 10.12% reduction. As the load increased to 75% TVP under the same speed range, emissions further declined from 162 ppm to 148 ppm, representing an 8.64% decrease. During light-load, moderate-speed operation (2000 rpm, 25% TVP), HC emissions dropped modestly from 146 ppm to 142 ppm, reflecting a 2.74% improvement. More noticeable reductions were recorded under mid-speed, moderate-to-high load conditions.

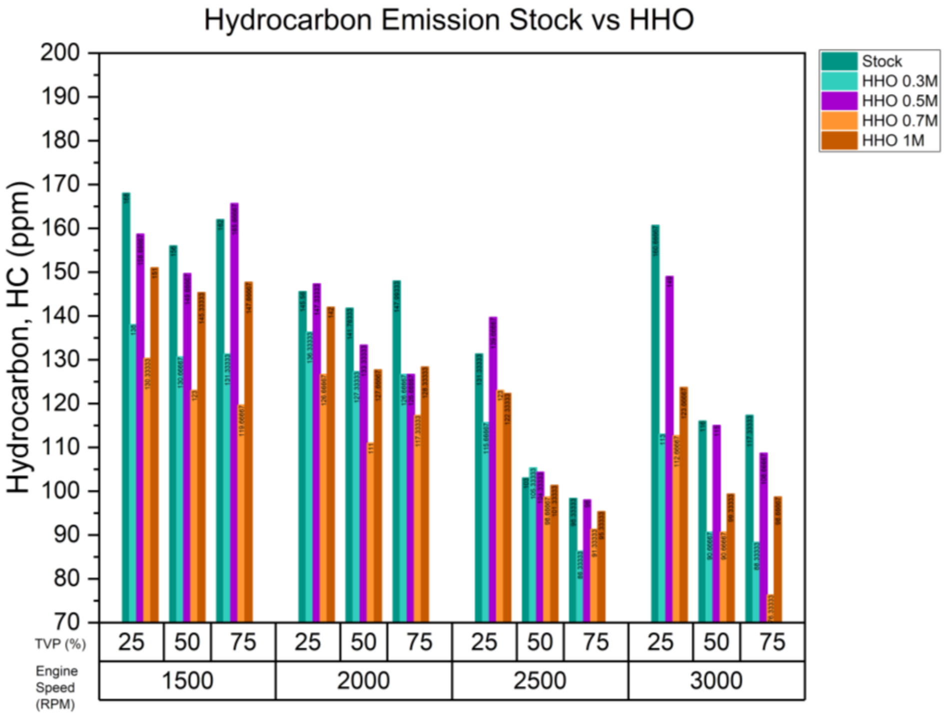

Fig. 8. Comparison graph of Hydrocarbon (HC) emission stock and HHO

At 2500 rpm and 50% TVP, HC levels decreased from 103 ppm to 101 ppm (1.94%), while at 75% TVP, the drop was more significant, from 98 ppm to 91 ppm, yielding a 7.14% reduction. The most pronounced benefits were observed under high-speed operation. At 3000 rpm and 75% TVP, HC emissions decreased from 117 ppm to 99 ppm, a 15.38% reduction, while under light load (25% TVP), emissions dropped dramatically from 161 ppm to 124 ppm, representing the highest overall decrease of 22.98%. This trend indicates that HHO gas enrichment becomes increasingly effective at reducing HC emissions under conditions involving higher engine speeds and greater throttle openings. These operating regimes are characterized by more dynamic combustion environments that allow the enhanced flame speed, broader flammability range, and low ignition energy of hydrogen to be more fully exploited, resulting in more complete fuel oxidation and a corresponding reduction in unburned hydrocarbons [32].

The substantial reductions in HC emissions following HHO gas addition are primarily attributed to hydrogen's superior combustion properties notably its lower minimum ignition energy, higher flame speed, and wider flammability limits [33]. These properties reduce the amount of unburned hydrocarbons by promoting faster and more complete combustion. Moreover, hydrogen addition effectively reduces cyclic variations, which are a major contributor to incomplete combustion and HC emissions, particularly under lean-burn or partial load conditions [11]. Interestingly, the reductions were generally more significant at higher speeds (2500–3000 rpm), suggesting that the benefits of HHO enrichment are amplified under more demanding combustion conditions where mixture homogenization and flame propagation are critical [34].

4. Conclusion

This comprehensive investigation into HHO gas supplementation in a 1.6L spark ignition engine has produced several significant findings that address critical gaps in the existing literature [3,4]. The study establishes a clear relationship between HHO enrichment parameters, engine operating conditions, and resultant performance and emission characteristics. The findings can be summarized as follows:

i. The effect of HHO on engine performance:
   a. 0.56 - 3.67%, with optimal gains at 2500-3000 rpm
   b. Brake torque is enhanced by 0.39-3.40%, particularly at 50-75% throttle valve positions
   c. BSFC reduced by up to 1.94% with moderate HHO concentrations (0.5-0.7M)
   d. Excessive HHO enrichment (1.0M) negatively impacted fuel economy by up to 5.23%

ii. The effect of HHO on exhaust emissions:
   a. CO emissions decreased by up to 11.90%
   b. HC emissions reduced by up to 22.98%
   c. Most significant reductions observed at higher engine speeds

iii. The optimal parameter observations of HHO:
   a. Most effective HHO concentration range: 0.5-0.7M
   b. Most beneficial operating conditions: moderate-to-high speeds and loads
   c. Performance benefits diminish at very low speeds/loads and with excessive HHO

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