



Influence of integrating hydrogen-based electrolyzer on fuel consumption and exhaust emissions in a modified fuel injection four-stroke motorcycle

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Abstract

The rapid growth of motorcycle usage has contributed significantly to increased fossil fuel consumption and urban air pollution, particularly through carbon monoxide (CO) and unburned hydrocarbon (HC) emissions. Enhancing combustion efficiency without extensive mechanical modification is therefore essential for reducing the environmental impact of existing motorcycle fleets. This study investigates the application of hydrogen-assisted combustion generated via a PWM-controlled wet-cell electrolyzer integrated into a fuel-injected four-stroke motorcycle. The electrolyzer system incorporates regulated electrical input, moisture separation, and controlled hydrogen-rich gas delivery to the intake manifold to ensure stable and safe operation. Experimental evaluations were conducted under real-road operating conditions by comparing baseline operation with hydrogen-assisted operation in terms of fuel consumption and exhaust emissions. The results demonstrate that controlled on-board hydrogen generation improves fuel utilization and reduces incomplete combustion products, as indicated by lower CO and HC emissions, while increased CO₂ concentrations suggest more complete oxidation during combustion. These improvements were achieved without major mechanical modifications to the engine, highlighting the practical feasibility of the proposed system. The findings extend current knowledge on hydrogen-assisted combustion by demonstrating its effectiveness in fuel-injected motorcycles under realistic driving conditions and provide a foundation for further optimization of on-board hydrogen generation and integrated control strategies.

Keywords

Hydrogen-assisted combustion, Wet-cell electrolyzer, PWM control, Fuel-injected motorcycle, Exhaust emissions

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Introduction

The rapid growth of motorcycle ownership, particularly in developing countries, has become a major concern in the transportation and environmental research community due to its contribution to increasing fossil fuel consumption and urban air pollution [1][2][3]. Motorcycles are widely adopted because of their affordability, fuel efficiency, and flexibility in dense traffic conditions; however, their large population size results in a significant cumulative impact on exhaust emissions. Pollutants such as carbon monoxide (CO) and unburned hydrocarbons (HC), which are primarily associated with incomplete combustion in spark-ignition engines, are recognized as key contributors to air quality degradation and public health risks. Therefore, reducing exhaust emissions and fuel consumption from motorcycles represents an important and relevant problem that must be addressed in the field of energy and automotive engineering.

Extensive efforts have been made to mitigate fuel consumption and exhaust emissions from internal combustion engines. Conventional approaches include improvements in engine design, optimization of fuel injection strategies, exhaust after-treatment systems, and the development of alternative fuels [4][5]. While these methods have demonstrated effectiveness, their implementation often requires substantial system complexity, high costs, or major modifications to existing vehicles. As a result, combustion enhancement techniques that can be applied to current vehicle fleets without extensive mechanical changes have gained increasing research attention.

Among combustion enhancement strategies, hydrogen-assisted combustion has been widely investigated due to the favourable combustion properties of hydrogen, such as its wide flammability limits, low ignition energy, and high flame propagation speed [6][7][8]. Previous studies have reported that small quantities of hydrogen added to gasoline-fuelled spark-ignition engines can enhance flame stability, improve thermal efficiency, and reduce incomplete combustion products, particularly CO and HC emissions [9][10][11]. These findings indicate that hydrogen can function effectively as a supplementary combustion enhancer rather than as a primary fuel.

Despite these promising results, existing studies on hydrogen enrichment exhibit several limitations. A considerable portion of the literature focuses on carburetted engines, stationary test engines, or laboratory-scale experiments conducted under steady-state operating conditions [9][10][11]. In addition, many on-board hydrogen generation systems reported in earlier studies employ simple electrolyzer configurations without adequate regulation of electrical input or hydrogen flow rate [12][13][14]. Such approaches may lead to unstable gas production, inefficient electrical energy utilization, and limited reproducibility, thereby restricting their applicability to modern fuel-injected vehicles.

On-board hydrogen generation through water electrolysis has emerged as a practical approach for supplying limited amounts of hydrogen for combustion enhancement, particularly in retrofit applications [12][13][14]. Wet-cell electrolyzers are attractive due

to their simple construction and low cost; however, their performance strongly depends on effective power management. Unregulated electrical supply can impose excessive load on the vehicle's electrical system and reduce overall efficiency. The integration of Pulse Width Modulation (PWM) control has therefore been proposed as a means to regulate voltage and current input, stabilize hydrogen production, and improve system reliability [15][16]. Nevertheless, the application of PWM-regulated wet-cell electrolyzers in small, fuel-injected motorcycle engines remains insufficiently explored.

Furthermore, modern fuel-injected motorcycles employ electronic control units (ECUs) that continuously adjust fuel delivery based on sensor feedback, resulting in combustion behaviour that differs fundamentally from that of carbureted engines [17][18]. Real-world motorcycle operation also involves transient engine speeds and loads that are not fully represented in conventional steady-state laboratory tests [19][20]. To the authors' knowledge, limited studies have reported the controlled integration of a PWM-regulated wet-cell electrolyzer applied to a fuel-injected motorcycle and evaluated under real-road operating conditions. This gap highlights the need for system-level experimental investigations that emphasize practical feasibility and emission performance under realistic driving scenarios.

Accordingly, the objective of the present study is to investigate the influence of integrating a PWM-controlled wet-cell hydrogen electrolyzer on fuel consumption and exhaust emissions in a modified fuel-injected four-stroke motorcycle. The proposed system incorporates regulated electrical power supply, moisture separation, and controlled hydrogen-rich gas delivery to the intake manifold. Comparative experiments were conducted under standard operating conditions, both with and without electrolyzer activation, using road testing and exhaust gas analysis. The results of this study are expected to provide insight into the practical potential of hydrogen-assisted combustion as a retrofit solution for improving fuel economy and reducing exhaust emissions in existing motorcycle fleets.

Method

This study employed an experimental research design to evaluate the effect of hydrogen-assisted combustion generated through on-board water electrolysis on fuel consumption and exhaust emissions of a fuel-injected four-stroke motorcycle. Comparative tests were conducted under two operating conditions, this comparative approach was selected to isolate the influence of hydrogen enrichment while maintaining identical engine, fuel, and operating conditions. The research design is shown in the pattern listed in Table 1.

Table 1. Research pattern

Group	Treatment	Experimental results	Description
R	X1	Y1	Without treatment (without using the electrolyzer tube).
R	X2	Y2	Treatment using the electrolyzer tube.

The experiments were carried out using a single-cylinder, four-stroke, spark-ignition motorcycle engine equipped with an electronic fuel injection (EFI) system, with specifications that can be seen in [Table 2](#).

Table 2. Specifications of the Test Vehicle: Motorcycle

Item	Specification
Type	Vega 2010, 4-Stroke SOHC
Engine	113.7 cc Gasoline
Bore x Stroke	50 mm x 57.9 mm
Transmission	4-speed manual transmission
Maximum torque	8.3 Nm/4,500 rpm
Fuel system	Fuel Injection Modification

Hydrogen was generated on-board using a wet-cell electrolyzer system supplied by the motorcycle's 12 V electrical system. The electrolyte solution consisted of 0.5 L of distilled water mixed with 5 g of sodium bicarbonate (NaHCO_3), which served as an electrolyte to enhance electrical conductivity. The electrolyzer electrodes were connected to a Pulse Width Modulation (PWM) controller, allowing regulation of the electrical input supplied to the system. During operation, the output voltage delivered to the electrolyzer was maintained at approximately 5.8 V to ensure stable gas production while limiting excessive electrical loading. A schematic representation of the electrolyzer installation and auxiliary components is shown in [Figure 1](#).

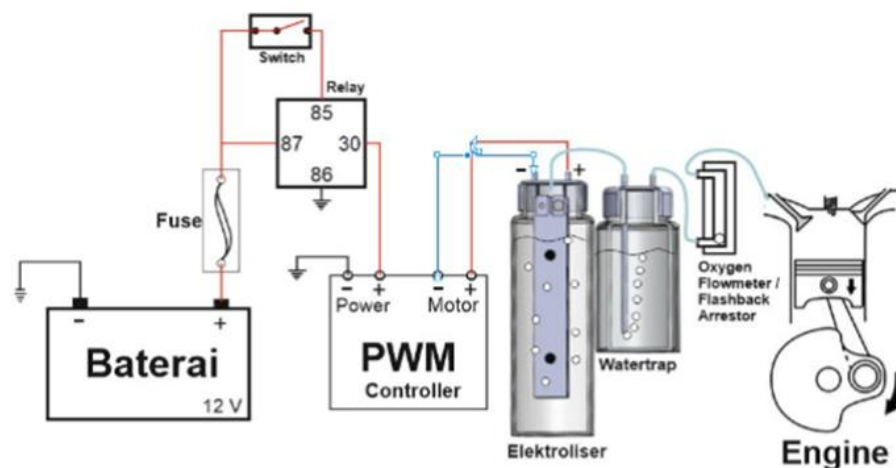


Figure 1. The installation scheme of an electrolyzer on a motorcycle.

To improve operational safety and gas quality, the electrolyzer outlet was connected to a water trap that functioned as a gas–liquid separator, removing water vapor from the hydrogen-rich gas stream. The gas then passed through an oxygen flowmeter equipped with a flashback arrester before being introduced into the intake manifold. This configuration ensured controlled gas flow and minimized the risk of backfire.

Electrical power for the electrolyzer system was supplied by the motorcycle battery through a fused circuit and relay system. The relay was activated via a switch to ensure that the electrolyzer operated only under designated test conditions. The PWM controller regulated the duty cycle of the electrical signal delivered to the electrolyzer, thereby controlling current draw and stabilizing hydrogen production. This approach

was adopted to reduce fluctuations in gas output and to prevent excessive load on the vehicle's charging system, which could otherwise influence engine performance and test results.

Experimental tests were conducted under real-road operating conditions to reflect practical motorcycle usage. For each test condition, the motorcycle was operated over a predefined route with similar traffic and road characteristics to minimize external variability. Prior to data collection, the engine was warmed to its normal operating temperature to ensure stable combustion conditions.

Fuel consumption measurements were obtained by recording fuel usage over a fixed travel distance for both baseline and hydrogen-assisted conditions. Each test was repeated multiple times to improve data reliability, and the average values were used for analysis. Exhaust emissions, including carbon monoxide (CO) and unburned hydrocarbons (HC), were measured using an exhaust gas analyser positioned at the tailpipe. The analyser was calibrated according to the manufacturer's specifications before testing to ensure measurement accuracy.

The exhaust gas analyser used in this study was capable of measuring CO and HC concentrations with standard accuracy suitable for automotive emission testing. The oxygen flowmeter provided qualitative control of the hydrogen-rich gas flow entering the intake system. Electrical parameters such as voltage and current supplied to the electrolyzer were monitored using a digital multimeter to verify stable operating conditions. Although minor measurement uncertainties are inherent in real-road testing, consistent procedures were applied across all test conditions to ensure comparability of results.

The collected data were analysed by comparing fuel consumption and emission levels between baseline and hydrogen-assisted operating conditions. Percentage changes in fuel consumption, CO emissions, and HC emissions were calculated to quantify the influence of hydrogen enrichment. The analysis focused on identifying trends and relative improvements rather than absolute performance limits, as the primary objective of the study was to assess the practical feasibility and emission-reduction potential of a PWM-controlled hydrogen-assisted combustion system in a fuel-injected motorcycle.

Results and discussion

This section presents the representative experimental findings obtained from the integration of a PWM-controlled wet-cell electrolyzer on a fuel-injected four-stroke motorcycle. The results are organized following the same chronological order as described in the Methodology section, beginning with hydrogen production characteristics, followed by fuel consumption performance, and finally exhaust emission behaviour.

After the electrolyzer system was designed and installed on the test motorcycle (Figure 2), preliminary measurements were conducted to evaluate the hydrogen-rich gas production rate under controlled electrical input conditions.



Figure 2. The application of the electrolyzer on a motorcycle

Table 3 summarizes the measured gas output obtained at an operating voltage of approximately 5.8 V. The electrolyzer produced an average gas flow rate of 1.91 ml s⁻¹, indicating stable and repeatable hydrogen generation under the selected operating conditions. This consistency confirms the effectiveness of PWM regulation in maintaining steady electrolysis performance throughout the experiments. Table 4 presents the measured fuel consumption values at engine speeds of 2000 rpm, 4000 rpm, and 6000 rpm.

Table 3. Results of measuring the production of HHO gas per second

Experiment	Voltage	Time (second)	Output Volume (ml)	Production (ml/s)
1	5.80	10	20	2
2	5.79	10	19	1.9
3	5.81	10	18.4	1.84
Average Flow Rate				1.91

Table 4. Results of fuel consumption experiments without treatment

No.	Engine Revolutions (RPM)	Time (second)	Experiment			Average fuel consumption (ml/s)
			I	II	Average	
1	2000	60	7.4	6.8	7.1	0.118
2	4000	60	7.2	8	7.6	0.126
3	6000	60	9.6	9	9.3	0.155

Fuel consumption tests were first conducted under baseline conditions without electrolyzer activation to establish a reference for comparison. Under baseline operation, fuel consumption increased with engine speed, reflecting higher fuel demand at elevated rotational speeds.

Subsequently, fuel consumption measurements were repeated with the electrolyzer activated, as summarized in Table 5.

Table 5. Results of fuel consumption experiments with treatment

No.	Engine Revolutions (RPM)	Time (second)	Experiment			Average fuel consumption (ml/s)
			I	II	Average	
1	2000	60	4.2	5.6	4.9	0.081
2	4000	60	7.2	6.6	6.9	0.115
3	6000	60	8.6	7.2	7.9	0.131

A reduction in fuel consumption was observed at all tested engine speeds when hydrogen enrichment was applied. To quantify this improvement, the average differences in fuel consumption between baseline and hydrogen-assisted conditions are presented in Table 6. These trends are illustrated in Figure 3, which shows consistently lower fuel consumption under hydrogen-assisted operation across all tested speeds.

Table 6. Calculation of the average change in fuel consumption

No.	Engine Revolutions (RPM)	Fuel Consumption (ml/s)		Fuel consumption difference (ml/s)
		Without Electrolyser	With Electrolyser	
1	2000	0.118	0.081	0.037
2	4000	0.126	0.115	0.011
3	6000	0.155	0.131	0.024

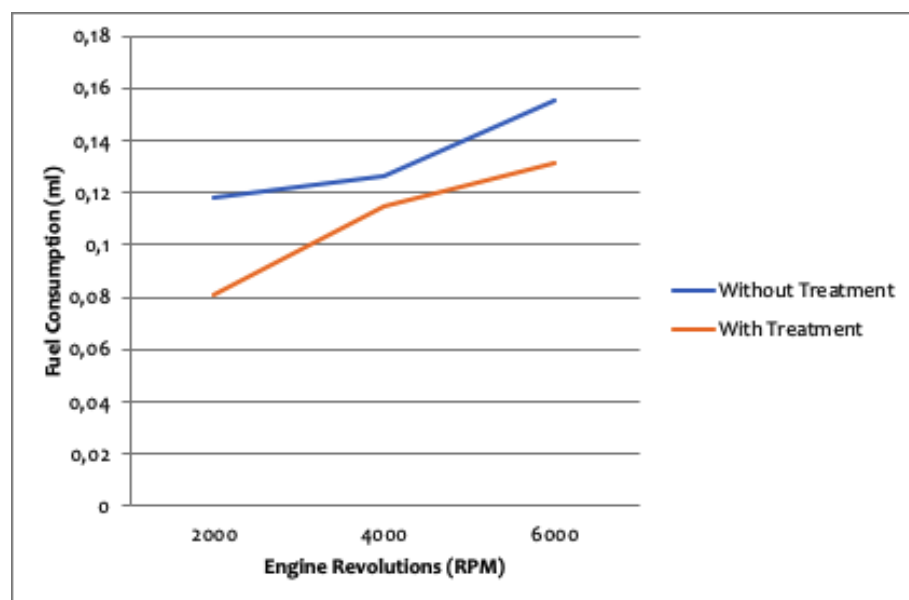


Figure 3. Graph of fuel consumption

The results indicate that the largest reduction in fuel consumption occurred at 2000 rpm, with a decrease of 0.037 ml/s, while reductions of 0.011 ml/s and 0.024 ml/s were observed at 4000 rpm and 6000 rpm, respectively.

Exhaust gas emission measurements were conducted to evaluate the influence of hydrogen-assisted combustion on carbon monoxide (CO), carbon dioxide (CO₂), and unburned hydrocarbons (HC). Tables 7 and 8 present the emission results obtained without and with electrolyzer activation, respectively, at engine speeds of 2000 rpm, 4000 rpm, and 6000 rpm.

Table 7. Results of exhaust gas emission experiments without treatment.

No.	Engine Revolutions (RPM)	CO (%)			CO ₂ (%)			HC (ppm)		
		I	II	Average	I	II	Average	I	II	Average
1.	2000	6.14	6.78	6.46	8.1	7.9	8	176	243	209.5
2.	4000	5.01	5.09	5.05	9.4	9.2	9.3	115	116	115.5
3.	6000	4.44	4.45	4.44	9.9	9.8	9.85	208	240	224

Table 8. Results of exhaust gas emission experiments without treatment.

No.	Engine Revolutions (RPM)	CO (%)			CO ₂ (%)			HC (ppm)		
		I	II	Average	I	II	Average	I	II	Average
1.	2000	2.76	4.04	3.4	10.2	9.7	9.95	92	138	115
2.	4000	0.25	0.86	0.55	12.7	12.5	12.6	151	45	98
3.	6000	2.32	2.87	2.59	11.6	11.5	11.55	165	252	208.5

Based on these data, the average changes in exhaust emissions are summarized in [Table 9](#). The results show a clear reduction in CO and HC emissions across all operating conditions when hydrogen enrichment was applied. Conversely, CO₂ concentrations increased under hydrogen-assisted operation, suggesting a shift toward more complete combustion.

Table 9. Calculation of the average change in exhaust gas emission

No	Engine Revolutions (RPM)	CO (%)			CO ₂ (%)			HC (ppm)		
		Without Treatment	With Treatment	Difference	Without Treatment	With Treatment	Difference	Without Treatment	With Treatment	Difference
1	2000	6.46	3.4	3.06	8	9.95	-1.95	209.5	115	94.5
2	4000	5.05	0.55	4.5	9.3	12.6	-3.3	115.5	98	17.5
3	6000	4.44	2.59	1.85	9.85	11.55	-1.7	224	208.5	15.5

The emission trends are further illustrated in [Figure 4](#), which presents comparative graphical representations of CO, CO₂, and HC emissions for both test conditions.

The experimental results demonstrate that the integration of a PWM-controlled wet-cell electrolyzer has a measurable influence on fuel consumption and exhaust emissions in a fuel-injected four-stroke motorcycle. The observed reductions in fuel consumption under hydrogen-assisted operation indicate an improvement in combustion efficiency, particularly at lower engine speeds. The more pronounced fuel savings at 2000 rpm suggest that hydrogen enrichment is especially effective under conditions where flame propagation and mixture preparation play a dominant role in combustion stability.

The reduction in CO emissions observed across all engine speeds can be attributed to enhanced oxidation of carbon-containing species during combustion. Hydrogen, with its high flame speed and low ignition energy, promotes faster and more uniform flame development, reducing the likelihood of incomplete combustion that leads to CO formation. Similarly, the decrease in HC emissions indicates improved oxidation of unburned fuel fragments, further supporting the role of hydrogen as a combustion enhancer.

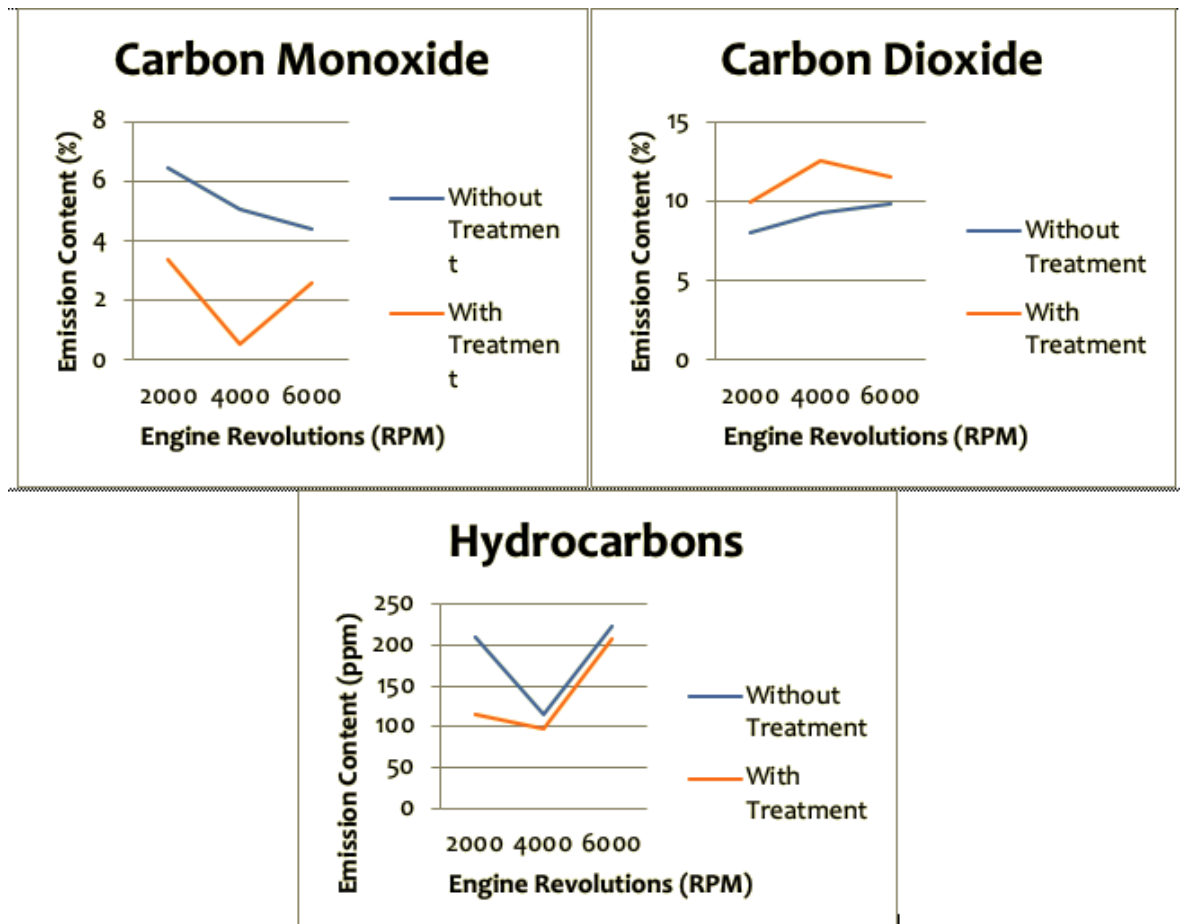


Figure 4. Graph of exhaust gas emissions

The increase in CO₂ concentration observed with electrolyzer activation provides additional evidence of more complete combustion. Higher CO₂ levels are generally associated with more efficient conversion of carbon in the fuel into fully oxidized products, provided that exhaust system integrity is maintained. In the present study, the concurrent decrease in CO and HC alongside an increase in CO₂ suggests that the combustion process shifted toward a more ideal oxidation pathway rather than being influenced by exhaust leakage or dilution effects.

Compared with baseline operation, the results obtained in this study are consistent with the fundamental principles of hydrogen-assisted combustion reported in previous investigations, while extending their applicability to fuel-injected motorcycles operating under real-road conditions. The use of PWM regulation played a critical role in stabilizing hydrogen production and minimizing electrical system interference, which may explain the consistent performance improvements observed across repeated tests.

Although the results demonstrate clear benefits, the magnitude of improvement varies with engine speed, indicating that the interaction between hydrogen enrichment and electronic fuel injection control is complex. At higher engine speeds, the reduced residence time for combustion and the adaptive response of the ECU may limit the extent of fuel savings and emission reduction. These findings highlight the importance

of further optimization, including coordinated control strategies between hydrogen supply and fuel injection parameters.

Overall, the present findings confirm that hydrogen-assisted combustion via on-board electrolysis can enhance fuel economy and reduce harmful exhaust emissions without requiring major mechanical modifications. This positions the proposed system as a practical retrofit solution for existing motorcycle fleets. Future research should focus on long-term durability assessment, optimization of hydrogen production efficiency, and integration with electronic fuel mapping to maximize performance benefits under a wider range of operating conditions.

Conclusion

This study investigated the application of hydrogen-assisted combustion generated through a PWM-controlled wet-cell electrolyzer on a fuel-injected four-stroke motorcycle under real-road operating conditions. The research was motivated by the need for practical and cost-effective strategies to reduce fuel consumption and exhaust emissions from the existing motorcycle fleet without extensive mechanical modifications.

The findings demonstrate that controlled on-board hydrogen generation can positively influence combustion behaviour in fuel-injected motorcycles, leading to improved fuel utilization and reduced incomplete combustion products. The consistent reduction in carbon monoxide and unburned hydrocarbon emissions, accompanied by an increase in carbon dioxide concentration, indicates a shift toward more complete oxidation during the combustion process. These outcomes are closely aligned with the research objectives defined in the introduction and confirm the effectiveness of hydrogen-assisted combustion as a supplementary enhancement technique rather than a replacement for conventional fuels.

From a broader perspective, this work contributes to the advancement of hydrogen-assisted combustion research by extending its application to fuel-injected motorcycles evaluated under real-road conditions, with an emphasis on system-level integration and electrical power regulation using PWM control. The results provide experimental evidence that such systems can be feasibly implemented as retrofit solutions, thereby offering a practical pathway for incremental emission reduction and fuel economy improvement in regions with high motorcycle usage.

Future research should focus on long-term operational durability, detailed electrical energy balance analysis, and coordinated control between hydrogen supply and electronic fuel injection parameters. Further investigations under a wider range of driving conditions and engine loads are also recommended to fully assess the scalability and robustness of hydrogen-assisted combustion systems for real-world motorcycle applications.

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