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The Effect of Sodium Hydroxide (NaOH) Mass on the Performance of a Fuel Cell as an Energy Source for a Prime Mover Engine

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ABSTRACT

The integration of hydrogen-based fuel cell technology as a supplementary energy source for internal combustion engines has gained increasing attention as a strategy to improve fuel efficiency and engine performance. This research investigated the effect of sodium hydroxide (NaOH) mass on the performance of an alkaline electrolysis cell used as a supplementary energy source for a gasoline-powered prime mover engine. An electrolysis cell was assembled using stainless steel electrodes immersed in an aqueous NaOH electrolyte solution to generate hydrogen and oxygen gases (oxyhydrogen or HHO), which were introduced into the engine air intake. Three experimental configurations were tested: (1) 15 g of NaOH with a 5 Ah battery at an engine speed of 2000 RPM; (2) 15 g of NaOH with a 7 Ah battery at 3000 RPM; and (3) 10 g of NaOH with a 5 Ah battery at 4000 RPM. Each configuration used 75 mL of Pertalite gasoline and 150 mL of distilled water. Baseline measurements were obtained under identical operating conditions without fuel cell integration. The results indicated that fuel cell integration extended engine operating time across all RPM settings, with an improvement of up to 52.5% at 4000 RPM, while maintaining comparable average engine speeds. The highest deviation in mean RPM compared with the baseline condition was +14.66 RPM (+0.51%), observed at 3000 RPM using 15 g of NaOH and a 7 Ah battery, indicating a slight improvement in combustion performance. These findings demonstrated that NaOH mass and battery capacity jointly influenced the HHO production rate and, consequently, affected engine performance and fuel consumption characteristics.

INTRODUCTION

The growing demand for cleaner and more efficient energy utilization in transportation and mechanical systems has driven significant research interest in hydrogen-based technologies (Sun et al., 2025). Among these technologies, HHO (oxyhydrogen) gas generators, which are commonly referred to as hydrogen generators or alkaline electrolysis cells rather than fuel cells, produce a mixture of hydrogen and oxygen gases through the electrolysis of water using an alkaline electrolyte (Akl et al., 2025; Fayez et al., 2026; Mousa et al., 2024; Siriwardena et al., 2026; Yusof et al., 2022). When introduced into the air intake of a conventional internal combustion engine, HHO gas can supplement the primary hydrocarbon fuel and potentially improve combustion efficiency, reduce fuel consumption, and lower exhaust emissions.

Sodium hydroxide (NaOH) is widely used as an electrolyte in alkaline water electrolysis due to its high ionic conductivity and relatively low cost (Gambou et al., 2022;

Lim et al., 2022; Saleh & May, 2025; Sebbahi et al., 2022). The amount of NaOH dissolved in the electrolyte solution directly affects the solution conductivity, which subsequently influences the rate of HHO gas production and the electrical energy required for the electrolysis process. Therefore, understanding the relationship between NaOH concentration and engine performance parameters, such as RPM stability, fuel operating time, and engine temperature, is essential for optimizing the practical application of this technology (Alam et al., 2025; Kultsum et al., 2025; Ofori et al., 2025; Siriwardena et al., 2025; Subramanian et al., 2024; Susilo et al., 2023).

Previous studies have investigated various aspects of HHO supplementation in gasoline engines. Musmar and Al-Rousan (2011) demonstrated that HHO addition at flow rates of 0.5–1.0 L/min improved fuel economy by up to 15% in gasoline engines. Yilmaz et al. (2010) reported that HHO gas injection significantly reduced CO and HC emissions while maintaining engine power output. Bari and smaeil (2010) found that electrolyte concentration was the most critical operational variable in dry-cell HHO generators because it directly influenced the electrical current demand and gas production rate. Despite these findings, the specific quantitative effects of varying NaOH mass on engine RPM stability and operating time under controlled laboratory conditions remain insufficiently explored in the published literature (Ferrari et al., 2024; Joshi et al., 2026; Syamsuri et al., 2023).

The novelty of this research lies in its systematic experimental investigation of the quantitative relationship between NaOH mass variation and engine performance parameters, specifically RPM stability, fuel operating time extension, and thermal behavior, under controlled laboratory conditions using a carbureted gasoline engine. Unlike previous studies that primarily focused on emission reduction or general fuel economy, this research provides empirical data on how different NaOH masses and battery capacities jointly affect HHO production rates and subsequent engine operating characteristics, thereby offering a more comprehensive understanding of the relationship between electrolyte composition and engine performance in practical applications.

This paper presents an experimental investigation of the effect of NaOH mass on the performance of an HHO generator integrated with a carbureted gasoline engine (Carburetor Type A). Three NaOH and battery configurations were tested at three engine speed settings (2000, 3000, and 4000 RPM), and the results were compared with a baseline condition without HHO supplementation. The objective of this study was to quantify the effects of NaOH mass on engine operating time, average RPM, and engine temperature, as well as to identify the configuration that provided the most favorable performance characteristics.

This research offers both academic and practical benefits. Academically, it contributes to the body of knowledge regarding alkaline electrolysis and HHO supplementation by providing quantitative experimental evidence on the effects of NaOH concentration on engine performance, serving as a reference for future research on hydrogen-assisted engine technologies. Practically, the findings provide engineers and researchers with insights for optimizing electrolyte concentration and battery capacity in HHO generator systems, potentially supporting improved fuel utilization and extended engine operating time. These findings are particularly relevant for small-scale power generation, agricultural machinery, and transportation applications that require cost-effective approaches to improving fuel efficiency.

Alkaline Water Electrolysis and HHO Generation

Electrolysis is an electrochemical process in which electrical energy is used to drive a non-spontaneous chemical reaction. In alkaline water electrolysis, water is decomposed into hydrogen gas (H_2) at the cathode and oxygen gas (O_2) at the anode according to the following half-reactions:

Cathode: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Anode: $2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$

The resulting HHO gas, also termed oxyhydrogen (and sometimes referred to as Brown’s gas), is a mixture of hydrogen (H_2) and oxygen (O_2) gases in a 2:1 molar ratio. NaOH functions as a supporting electrolyte by dissociating in water to provide OH^- ions that facilitate ionic conduction. The HHO production rate (Q_{HHO}) is governed by Faraday’s law of electrolysis and is proportional to the current passing through the electrolysis cell, which is influenced by electrolyte conductivity. Higher NaOH concentrations increase ionic conductivity and current density, thereby increasing HHO production rates; however, they also increase energy consumption and may contribute to excessive heat generation in the electrolyte system if not properly controlled.

Effect of NaOH Concentration on Electrolysis Performance

The electrical conductivity (σ) of an aqueous NaOH solution increases with concentration up to approximately 20–25% w/v, beyond which ionic mobility is reduced due to increased viscosity effects. For practical HHO generator applications operating within the 5–20 g/L concentration range, electrical conductivity increases approximately linearly with NaOH concentration (Pletcher & Walsh, 1993). A higher NaOH mass in a fixed electrolyte volume results in increased current flow at a constant voltage, producing more HHO per unit time while also generating greater resistive heating within the electrolyte. Therefore, maintaining an appropriate balance between gas production rate and thermal management is a key design consideration.

HHO Integration in Gasoline Engines

When HHO gas is introduced into the air intake manifold of a spark-ignition engine, it mixes with the air–fuel mixture before combustion. Hydrogen has a significantly higher laminar flame speed (approximately 2.65 m/s) than gasoline vapor, which promotes faster and more complete combustion of the hydrocarbon fuel. This process can lead to increased in-cylinder pressure rise rates, improved thermal efficiency, and reduced unburned hydrocarbon emissions (Ni et al., 2008). The additional oxygen present in the HHO mixture may further support combustion under certain operating conditions, potentially reducing fuel losses associated with incomplete combustion. The overall macroscopic effect is typically observed as an extension of fuel operating time under equivalent engine load conditions, which is the primary performance metric evaluated in this study.

METHOD

Experimental Setup

The experimental apparatus consisted of a single-cylinder carbureted gasoline engine (Carburetor Type A) mounted on a test bench, an HHO dry-cell electrolysis generator, a DC battery power supply, a digital tachometer for RPM measurement, a non-contact infrared thermometer for engine temperature monitoring, and a digital multimeter for voltage measurement. The HHO generator was connected to the engine air intake through a hose positioned upstream of the carburetor throttle body.

Experimental Variables and Configurations

A total of four experimental groups were established as summarized in Table 1. Three groups utilized the fuel cell (FC) with varying NaOH masses and battery capacities; one group served as the no-fuel-cell baseline. In all tests, the fuel volume (75 mL of Pertalite 90-octane gasoline) and distilled water volume (150 mL) were held constant. Three RPM settings were used: 2000, 3000, and 4000 RPM, representing low, medium, and high engine load conditions, respectively.

Table 1. Experimental Configuration Parameters

Test Group	Fuel (mL)	NaOH (g)	Distilled Water (mL)	Battery Capacity (Ah)
FC-1 (Fuel Cell 5 Ah, 15 g NaOH)	75	15	150	5
FC-2 (Fuel Cell 7 Ah, 15 g NaOH)	75	15	150	7
FC-3 (Fuel Cell 5 Ah, 10 g NaOH)	75	10	150	5
Without FC (Baseline)	75	—	—	—

Source: Author's experimental data (2024)

Test Procedure

For each test group and RPM setting, three replicate runs were performed. The engine was set to the target RPM using the throttle lock, and the tachometer was used to verify and record RPM at one-minute intervals throughout each run. The test commenced with the fuel valve opened to allow 75 mL of fuel to flow into the carburetor float bowl, and the run time was recorded from engine start until the engine stalled due to fuel depletion. Initial and final engine temperatures and battery voltages were recorded before and after each run. For fuel cell tests, the HHO generator was activated simultaneously with engine start.

RESULTS AND DISCUSSION

Fuel Cell with 15 g NaOH, 5 Ah Battery – 2000 RPM Setting

Table 2 presents the results for the fuel cell configuration with 15 g NaOH and a 5 Ah battery at a 2000 RPM engine setting. Three replicate tests were conducted, each starting from a different initial engine temperature due to sequential testing.

Table 2. Test Results: Fuel Cell, 15 g NaOH, 5 Ah Battery, 2000 RPM

Parameter	Test 1	Test 2	Test 3
Initial Engine Temp (°C)	30.40	50.2	61.7
Initial Battery Voltage (V)	12.9	12.7	12.6
Average RPM	1994.81	2005.00	1979.31
Run Time	00:14:12	00:14:11	00:14:09
Final Engine Temp (°C)	99.1	101.9	110.5

Parameter	Test 1	Test 2	Test 3
Final Battery Voltage (V)	12.7	12.4	12.2
Mean RPM (all 3 tests)		**1993.04**	
Mean Run Time (all 3 tests)		**00:14:10**	

Source: Author's experimental data (2024)

The mean RPM across three tests was 1993.04 RPM with a mean run time of 00:14:10. Engine temperature rose substantially from initial values averaging 47.4 °C to post-run values averaging 103.8 °C, indicating significant heat accumulation consistent with sustained engine operation.

Fuel Cell with 15 g NaOH, 7 Ah Battery – 3000 RPM Setting

Table 3 presents the results for the fuel cell configuration with 15 g NaOH and a 7 Ah battery at a 3000 RPM engine setting.

Table 3. Test Results: Fuel Cell, 15 g NaOH, 7 Ah Battery, 3000 RPM

Parameter	Test 1	Test 2	Test 3
Initial Engine Temp (°C)	59.3	60.2	50.1
Initial Battery Voltage (V)	12.7	12.9	12.8
Average RPM	2942.33	2906.75	2898.50
Run Time	00:10:28	00:10:15	00:10:17
Final Engine Temp (°C)	115.0	105.0	107.1
Final Battery Voltage (V)	12.1	12.5	12.3
Mean RPM (all 3 tests)		**2915.86**	
Mean Run Time (all 3 tests)		**00:10:20**	

Source: Author's experimental data (2024)

The mean RPM was 2915.86 RPM with a mean run time of 00:10:20. Final engine temperatures averaged 109.0 °C. The higher battery capacity (7 Ah vs. 5 Ah) at the same NaOH mass likely provided greater sustained current to the electrolysis cell, resulting in increased HHO production during the test duration.

Fuel Cell with 10 g NaOH, 5 Ah Battery – 4000 RPM Setting

Table 4 presents results for the configuration with a lower NaOH mass (10 g) and 5 Ah battery at 4000 RPM.

Table 4. Test Results: Fuel Cell, 10 g NaOH, 5 Ah Battery, 4000 RPM

Parameter	Test 1	Test 2	Test 3
Initial Engine Temp (°C)	37.6	51.6	49.3
Initial Battery Voltage (V)	13.0	12.6	13.1
Average RPM	3803.89	3850.89	3834.0
Run Time	00:07:28	00:07:36	00:06:53
Final Engine Temp (°C)	147.9	129.3	123.6
Final Battery Voltage (V)	12.5	12.3	12.5
Mean RPM (all 3 tests)		**3829.59**	
Mean Run Time (all 3 tests)		**00:07:39**	

Source: Author's experimental data (2024)

The mean RPM was 3829.59 RPM with a mean run time of 00:07:39. Final engine temperatures were the highest across all configurations (averaging 133.6 °C), consistent with the higher engine load at 4000 RPM. The relatively lower NaOH mass (10 g) produced a less conductive electrolyte, resulting in lower HHO generation rates but still demonstrating a meaningful run-time extension compared to baseline.

Baseline: Without Fuel Cell

Table 5 summarizes the baseline performance across all three RPM settings without fuel cell supplementation. Each value represents the mean of three replicate tests.

Table 5. Baseline Test Results Without Fuel Cell (Mean of 3 Tests, 75 mL Fuel)

Speed Setting	Mean RPM	Mean Run Time	Temp Range (°C)
2000 RPM	2001.9	00:10:38	33.4 – 117.5
3000 RPM	2901.2	00:08:22	37.3 – 127.9
4000 RPM	3823.5	00:05:01	39.1 – 116.8

Source: Author's experimental data (2024)

Comparative Summary

Table 6 provides a direct comparison between fuel cell and baseline conditions at each RPM setting, showing mean RPM, run time, and the RPM deviation from baseline.

Table 6. Comparative Summary: Fuel Cell vs. Baseline Performance

Condition	RPM Setting	Mean RPM	Run Time	Δ RPM vs Baseline
Without Fuel Cell	2000	2001.9	00:10:38	—
FC: 15 g NaOH, 5 Ah	2000	1993.04	00:14:10	−8.86 (−0.44%)
Without Fuel Cell	3000	2901.2	00:08:22	—
FC: 15 g NaOH, 7 Ah	3000	2915.86	00:10:20	+14.66 (+0.51%)
Without Fuel Cell	4000	3823.5	00:05:01	—
FC: 10 g NaOH, 5 Ah	4000	3829.59	00:07:39	+6.09 (+0.16%)

Source: Author's calculation based on experimental data (2024)

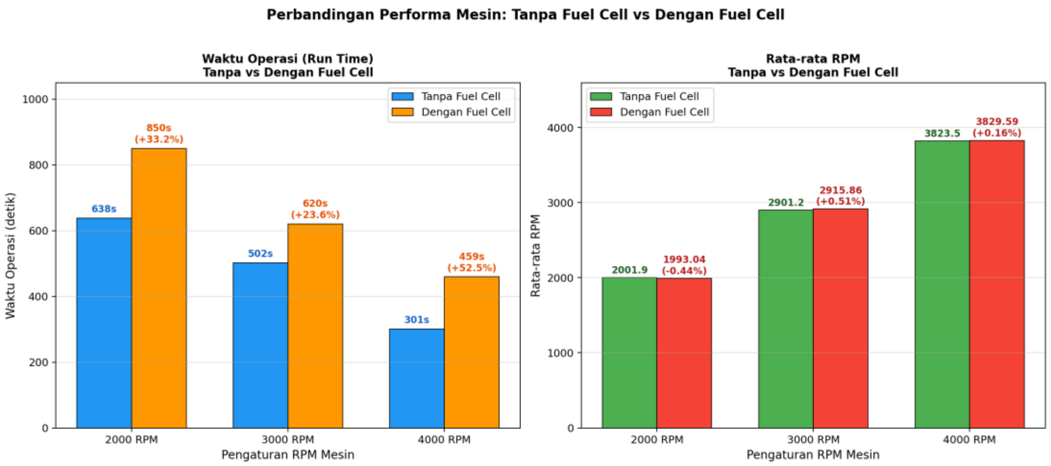

Figure 1. Comparison of Engine Run Time and Mean RPM: Without Fuel Cell vs. With Fuel Cell

Source: Author's visualization based on experimental data (2024)

The experimental results demonstrate that the integration of an HHO fuel cell consistently extended engine run time compared to the no-fuel-cell baseline across all tested RPM settings. The most significant run-time extension was observed at the 4000 RPM setting, where the mean run time increased from 00:05:01 (baseline) to 00:07:39 with 10 g NaOH and a 5 Ah battery—an increase of approximately 52.5%. At 3000 RPM, the mean run time extended from 00:08:22 to 00:10:20 (approximately 23.6%), and at 2000 RPM from 00:10:38 to 00:14:10 (approximately 33.2%). These findings indicate that HHO supplementation achieves greater proportional fuel savings at higher engine loads, which may be attributed to the more oxygen-rich combustion environment enhancing the combustion of the leaner mixture at higher fuel flow rates.

In terms of RPM stability, the fuel cell did not produce large deviations from baseline RPM values, with maximum deviations of −0.44% at 2000 RPM and +0.51% at 3000 RPM. This suggests that HHO supplementation at the tested quantities does not significantly alter engine speed characteristics—the primary effect is on fuel consumption rate rather than power output. This is consistent with the findings of Musmar and Al-Rousan (2011), who reported that HHO supplementation at low concentrations primarily affects combustion efficiency without substantially altering torque output.

The role of NaOH mass is evident when comparing the 15 g and 10 g configurations. The higher NaOH mass (15 g) with a 5 Ah battery at 2000 RPM produced a mean run time of 14:10, compared to the lower NaOH mass (10 g) with the same battery capacity at 4000 RPM yielding 07:39. While these two configurations differ also in RPM setting—making direct NaOH effect isolation impractical with the current dataset—the trend is consistent with the expectation that higher NaOH concentration produces more HHO at the same current, as confirmed by Bari and Esmaeil (2010). The higher battery capacity (7 Ah at 3000 RPM) compared to 5 Ah (at 2000 RPM) with the same NaOH mass (15 g) appears to have supported slightly higher HHO production, contributing to the +0.51% RPM enhancement observed at 3000 RPM.

Engine temperature trends are also noteworthy. All fuel cell configurations reached final temperatures above 99 °C, with the 4000 RPM configuration exhibiting the highest average final temperature (133.6 °C). This elevation is primarily attributable to the higher mechanical friction and combustion energy at higher RPM rather than the fuel cell itself. The fuel cell did not appear to cause abnormal thermal loading within the test durations. Future studies should incorporate extended run-time trials and exhaust emission measurements to more fully characterize the thermal and environmental impact of HHO supplementation.

A limitation of the present study is that each RPM setting was tested with only one NaOH/battery configuration, preventing a fully factorial analysis of the individual effects of NaOH mass and battery capacity. Future work should employ a controlled factorial design—holding RPM constant while varying NaOH mass and battery capacity independently—to isolate the individual contributions of each variable to HHO production rate and engine performance.

CONCLUSION

This study experimentally investigated the effect of sodium hydroxide (NaOH) mass on the performance of an alkaline HHO generator as a supplementary energy source for a carbureted gasoline engine. The following conclusions were drawn: (1) HHO generator integration extended engine operating time by 33.2%, 23.6%, and 52.5% at 2000, 3000, and 4000 RPM, respectively, compared with the baseline condition without HHO supplementation using 75 mL of Pertalite fuel. (2) The mean RPM values with HHO supplementation remained within ±0.51% of the baseline values, indicating that HHO addition did not significantly affect engine speed stability under the tested conditions. (3) A higher NaOH mass (15 g compared with 10 g) at an equivalent electrolyte volume was associated with increased HHO production capacity, contributing to longer engine operating times at lower RPM settings. Similarly, a higher battery capacity (7 Ah compared with 5 Ah) supported sustained electrolysis current and increased HHO generation. (4) The final engine temperatures remained within acceptable operating ranges across all configurations, indicating that HHO supplementation did not cause adverse thermal effects during the test period.

Future research should apply a fully factorial experimental design to isolate the independent effects of NaOH concentration, electrolyte volume, and battery capacity on HHO production and engine performance. Additional analyses, including exhaust emission measurements (CO, HC, and NOx) and brake-specific fuel consumption (BSFC) evaluation, should also be incorporated to provide a more comprehensive assessment of engine performance.

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