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Hydrogen enriched combustion in a small spark-ignition engine using a NaOH-based alkaline electrolyzer: experimental evaluation at 0.5 kg/cm² brake load

Suci Rahmadhani Irawan, Ahmad Ilham Wicaksono, Annisa Wulan Sari, Awaludin Martin*
Department of Mechanical Engineering, University of Riau, Pekanbaru 28293, Indonesia
*Corresponding author: awaludinmartin01@gmail.com

Abstract

The increasing concern over greenhouse gas emissions from fossil fuels has driven the exploration of hydrogen as a clean energy source. However, the practical application of hydrogen in internal combustion engines is still limited by the stability of on-demand hydrogen production systems and their integration with conventional engines. This study aims to design and evaluate a NaOH-based alkaline electrolyzer for on-demand hydrogen production and its application in a small spark-ignition engine. The electrolyzer was fabricated using 8 cell stacks with electrode dimensions of 16×16 cm, an inter-electrode gap of 2 mm, and a thickness of 1.2 mm. Experimental tests were conducted at currents of 40 A and 50 A with 30 wt.% NaOH solution. The produced hydrogen gas was directly supplied to a 97cc spark-ignition engine under a constant braking load of 0.5 kg/cm². The result showed that hydrogen production reached 0.9 L/min at 40 A and 1.25 L/min at 50 A. The addition of hydrogen significantly improved engine performance, with brake power increasing by up to 20.8%, brake thermal efficiency by 6.2%, and volumetric efficiency by 9.1%, while reducing brake specific energy consumption by 28%. These findings indicate that hydrogen generated from an alkaline electrolyzer can enhance combustion efficiency and improve overall engine performance, supporting the development of cleaner and more efficient energy systems.

Keywords:
Alkaline electrolyzer, hydrogen, internal combustion engine, brake power, sustainable energy.

1 Introduction

Riau Province ranks among the largest contributors to Greenhouse Gas (GHG) emissions in Indonesia, recording a total of 39,877.15 Gg in 2023 [1]. Carbon dioxide (CO_2) dominates these emissions, primarily generated from the combustion of fossil fuels such as petroleum, coal, and natural gas, as well as from cement production processes [2]. In the transportation sector alone, emissions in 2023 amounted to 8,500 Gg, representing about 20% of the national total [1].

The continuous increase in CO_2 emissions significantly contributes to rising global temperatures and accelerates global warming [3]. The international community, through the COP21 Paris Agreement, has committed to limiting the increase in global temperature to below 1.5°C, a target that also serves as a critical reference point for Indonesia in formulating its climate change mitigation policies [4]. Despite this commitment, fossil fuels remain the predominant global energy source, although they are inherently non-renewable [5]. Forecasts indicate that fossil fuels will maintain their dominance, potentially contributing up to 75% of total energy production by 2050 [6]. This persistent reliance poses a substantial challenge to environmental sustainability, thereby reinforcing the necessity of a systematic transition towards low-carbon, renewable, and environmentally sustainable energy alternatives [4].

Hydrogen gas has emerged as a promising source of green energy. It is regarded as an environmentally sustainable fuel since its combustion does not generate carbon emissions and it exhibits high energy density, positioning it as a strong candidate to address future energy needs [7], [8]. The gravimetric energy density of hydrogen is approximately 142.18 MJ/kg (HHV) and 120 MJ/kg (LHV), values that are considerably greater than those of conventional fossil fuels [9]. Owing to these characteristics, hydrogen is recognized as an efficient energy carrier for renewable energy systems, applicable in both fuel cell technologies and internal combustion engines [10].

Hydrogen is the most prevalent element in the universe, making up over 90% of all existing matte [11]. On earth, however, it is rarely found in its pure form and is instead present in compounds such as water, fossil fuels, and biomass [12]. At present, approximately 94% of hydrogen worldwide is still produced from fossil fuels through steam reforming, a process that releases greenhouse gas emissions and produces hydrogen of lower quality compared to water electrolysis [13]. For this reason, water electrolysis is increasingly being promoted as a cleaner and more sustainable method of hydrogen production [14].

One of the widely used technologies for hydrogen production is the alkaline electrolyzer cell, which utilizes an electric current to decompose water into hydrogen and oxygen gases [15]. This system commonly employs liquid electrolytes such as KOH or NaOH due to their low cost, high stability, and relatively high hydrogen production efficiency [16] [17].

Furthermore, several studies have reported that hydrogen enrichment in internal combustion engines can improve combustion efficiency, increase engine performance, and reduce fuel consumption. Gad et al [18], a study was conducted to investigate the use of HHO gas produced from a dry-cell electrolyzer as a supplementary fuel in an internal combustion engine. The hydrogen was supplied at a flow rate of 0.5 L/min and tested under an engine operating condition of 3000 rpm. The experimental results indicated that the addition of hydrogen–gasoline mixture improved engine performance, with volumetric efficiency increasing by 7.5%, thermal efficiency by 8%, and the air–fuel ratio by 11%. These findings demonstrate the potential of HHO gas as an effective supplementary fuel to enhance combustion characteristics and overall engine efficiency.

Martin et al. [19], the tested hydrogen gas produced from electrolysis was tested on a 4-stroke, three-cylinder gasoline engine with a hydrogen flow rate of 0.4 L/min supplied through the intake manifold at a constant engine speed of 2200 rpm. The experimental results showed improvements in engine performance, with the highest increases observed in effective shaft power (4.9%), thermal efficiency (3.19%), volumetric efficiency (5.35%), and air–fuel ratio (6.7%), along with a reduction in Brake Specific Energy Consumption (BSEC) of 3%.

However, during the testing process, yellowish-brown deposits were observed on the surface of the stainless steel plates, indicating the occurrence of oxidation (corrosion), which may affect the long-term durability and performance of the electrolyzer system. For instance, previous research using stainless steel 316L electrodes demonstrated improvements in brake power, thermal efficiency, and volumetric efficiency. However, these studies also reported the formation of yellowish-brown deposits on the electrode surface, indicating oxidation and corrosion issues that can affect hydrogen production stability [19], [20]. These results emphasize that ensuring consistent hydrogen generation and enhancing electrode corrosion resistance remain critical challenges for practical applications in internal combustion engines.

However, previous studies on hydrogen-assisted internal combustion engines still face several limitations, including unstable hydrogen production, limited evaluation on small-scale engines, and electrode degradation due to corrosion. In addition, most studies have not comprehensively analyzed the combined effects of hydrogen addition on multiple engine performance parameters under controlled loading conditions. Therefore, further investigation is required to improve hydrogen production stability, enhance electrode durability, and evaluate its impact on engine performance in a more integrated manner.

This research develops and experimentally evaluates a novel wet-type alkaline electrolyzer. It features stainless steel 317L electrodes and a NaOH electrolyte. Compared to 316L, the 317L material's higher molybdenum content (approximately 4%) offers superior corrosion resistance, promising a more stable HHO gas supply. The generated hydrogen is directly applied to a 97 cc spark-ignition engine operating under a constant braking load of 0.5 kg/cm². Its effects on brake power, brake thermal efficiency, volumetric efficiency, and brake specific energy consumption are then evaluated. This study enhances the understanding of hydrogen-assisted combustion systems and offers practical insights for developing on-demand hydrogen generation technologies for small-scale internal combustion engines [21].

2 Research methodology

The research method used in this study involves the design, fabrication, and testing of an alkaline electrolyzer cell applied to an internal combustion engine. The research begins with a literature review on alkaline electrolyzer technology and the use of hydrogen gas (HHO) as an additional fuel in internal combustion engines. This literature review is utilized to determine the design parameters of the wet-type alkaline electrolyzer cell. Table 1 are the design parameters of the alkaline electrolyzer cell [22].

Table 1. Design parameters of alkaline electrolyzer cells

Parameters	Equations	Units
Moles of H_2	$\mathrm{Mol} = \mathrm{mol\ fuel} \times 20\%$	Mol
Fuel consumption	$\dot{m}\mathrm{bb} = \frac{V_{bb\,.\,\rho_{bb}}}{t}$	L/m
Supplied current	$I = \frac{\mathrm{mhidrogen}\,.\,n\,.\,F}{t\,.\,M}$	A
Surface area	$A = \frac{I}{j}$	cm^2
Cell voltage	$V_{cell} = V_{rev} + V_{act} + V_{ohmic}$	V
Reversible voltage	$V_{rev} = E^{o}_{rev} + (T - T_{ref})\ \frac{\Delta S^{o}}{n\,.\,F} + \frac{R\,.\,T}{2\,.\,F}\left[\ln\left(\frac{\left((P - P_{H2O})^{\frac{2}{3}}\right)}{\frac{P_{H2O}}{P^{o}_{H2O}}}\right)\right]$	V
Activation overpotential	$V_{act-a,b} = b_{a,c}\ln\left(\frac{j_{a,c}}{j_{o-a,c}}\right)$	V
Ohmic overpotential	$V_{ohmic} = I\,(R_{ele} + R_{ely})$	V

Following the design stage, the alkaline electrolyzer was developed according to the design parameters that had been identified, including in Table 2.

Table 2. The design calculation results

Parameters	Result
Theoretical volume of hydrogen + oxygen (L/min)	0.4125 L/min
Electrode plate surface area (S)	200 cm²
Theoretical gas mass production (g/min)	0.0369 g/min
Reversible voltage (V_{rev})	1.29 V
Ohmic voltage (V_{ohm})	0.04388 V
Activation overpotential of stainless steel 317L (V_{act})	0.1619 V
Total cell voltage (V_{cell})	1.49 V
Number of electrolyzer cell stacks (N_{cell})	8.023 stacks

To ensure clarity and reproducibility of the experimental setup, the design and operating parameters of the alkaline electrolyzer used in this study are systematically summarized. The electrolyzer was developed as a wet-type system employing stainless steel 317L electrodes and a NaOH-based electrolyte, with key design considerations focused on enhancing corrosion resistance and maintaining stable hydrogen production. The complete specifications of the electrolyzer system are presented in Table 3.

Table 3. Specification of alkaline electrolyzer

Parameters	Result
Type of electrolyzer	Wett cell
Type of electrode	Stainless steel 317
Dimension of electrode	1 mm × (16 × 16) cm
Number of plates	15 plates
Number of stacks	8 plates
Number of neutral plates	7 plates
Electrolyte volume	4.6 liters
Water type	Distilled water (aquades)

This study employed an experimental method to evaluate the performance of a hydrogen-assisted internal combustion engine using an alkaline electrolyzer system. The electrolyzer was designed as a wet-type cell utilizing distilled water (aquades) with a total volume of 4.6 liters mixed with a 30 wt.% NaOH electrolyte. The electrolyzer was powered by a Direct Current (DC) power supply with current variations of 40 A and 50 A. The generated HHO gas was directly supplied to the intake manifold of a 97 cc single-cylinder spark-ignition engine. The engine was operated under a constant braking load of 0.5 kg/cm² to evaluate its performance under controlled conditions (Fig. 1).

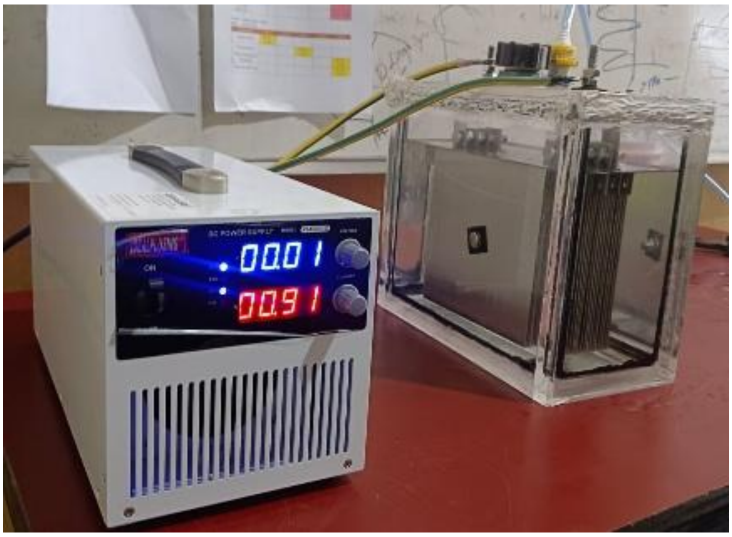

Fig. 1. Alkaline electrolyzer cell.

The experimental procedure was conducted in several stages. First, the electrolyzer system was prepared by filling it with the electrolyte solution and ensuring all electrical connections were properly installed. The system was then operated at the specified current levels (40 A and 50 A) to generate HHO gas. The produced gas was channeled continuously into the engine intake system. During this stage, supporting components were also selected and installed, including a water trap, flow meter, flashback arrestor, and a DC power supply. The experimental setup for testing the alkaline electrolyzer cell was prepared accordingly. The results of the design and fabrication of the alkaline electrolyzer cell are as Fig. 2.

Subsequently, engine performance tests were conducted under steady-state conditions with a constant braking load. The engine was allowed to stabilize before measurements were taken. Key performance parameters, including brake power, Brake Thermal Efficiency (BTE), volumetric efficiency, Air-Fuel Ratio (AFR), and BSEC, were measured and recorded for each test condition. Each experiment was repeated to ensure the reliability and consistency of the obtained data.

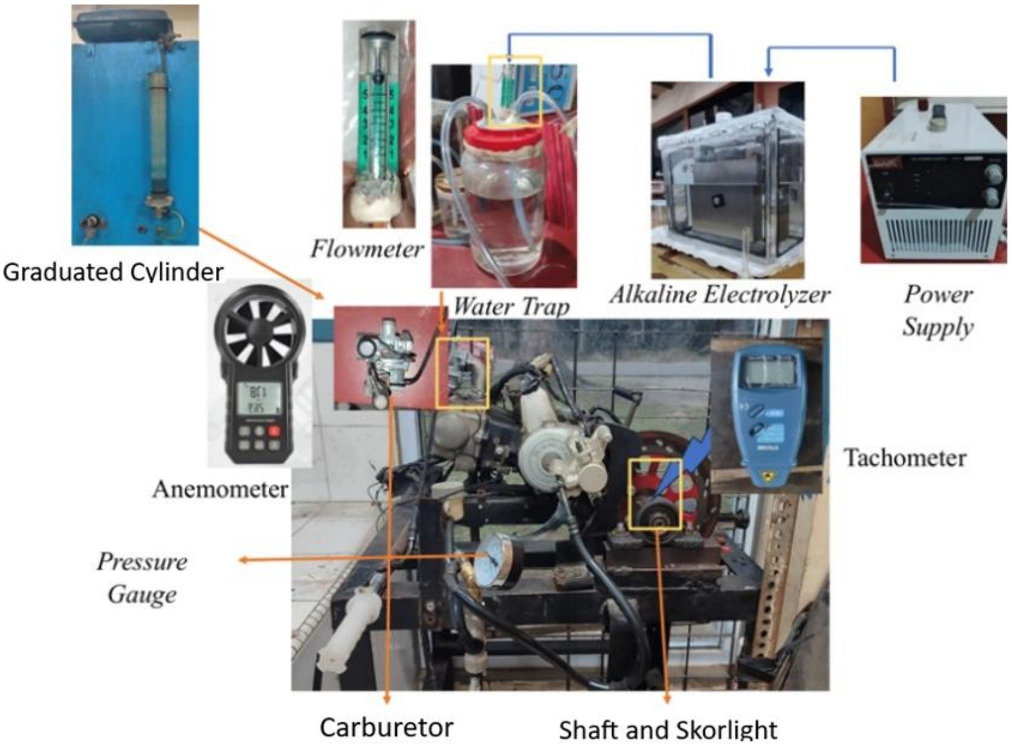

Fig. 2. Experimental setup alkaline electrolyzer.

To better understand the effect of hydrogen addition on engine performance, a comparison of key properties between hydrogen and gasoline is presented in Table 4.

Table 4. The design calculation results

Properties	Hydrogen	Petrol
Molar mass (Kg/kmol)	2.02	114.232
Lower heating value (MJ/Kg)	120.21	44.14
Higher heating value (MJ/Kg)	142.18	46.32
Laminar flame speed (cm/s)	230	135
Stoichiometric AFR on mass basis	34.3	12

These properties indicate that hydrogen has superior combustion characteristics, including molar mass, heating value, laminar flame speed, and stoichiometric AFR, all of which contribute to improved combustion efficiency when used as a supplementary fuel. Following the HHO gas production, performance testing was conducted on the internal combustion engine.

3 Results and discussion

After conducting experiments on the addition of hydrogen gas to a 4-stroke, single-cylinder, 97 cc gasoline engine, an increase in effective shaft power and a decrease in brake specific energy consumption were observed, indicating an improvement in the engine's capability to deliver useful mechanical output. The experimental results of effective shaft power and brake specific energy consumption are presented in Fig. 3.

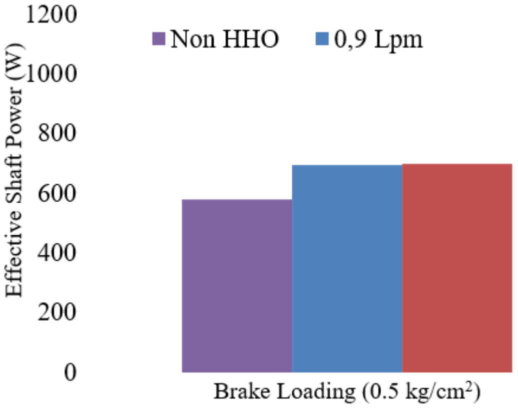

Fig. 3. Brake loading vs effective shaft power.

As shown in the Fig. 3, the effective shaft power increases with the addition of HHO gas. This improvement is consistent with previous studies, such as [18], which reported an increase of up to 4% in shaft power, and [20], which observed an increase of 5.1%. In the present study, the effective shaft power increased by 20.8%, indicating a more significant enhancement in engine performance. This improvement can be attributed to hydrogen's combustion characteristics, which include a higher flame speed and lower ignition energy compared to conventional fossil fuels. Consequently, the combustion process is faster and more stable, leading to improved energy conversion efficiency and increased shaft power. Furthermore, rapid flame propagation reduces the ignition delay period, allowing peak cylinder pressure to occur closer to the optimal crank angle, thereby enhancing overall engine performance [23].

Meanwhile, the BSEC shows a decreasing trend with the addition of HHO gas (Fig. 4). A higher current supplied to the electrolyzer results in increased hydrogen production, which enhances the combustion process and consequently reduces BSEC.

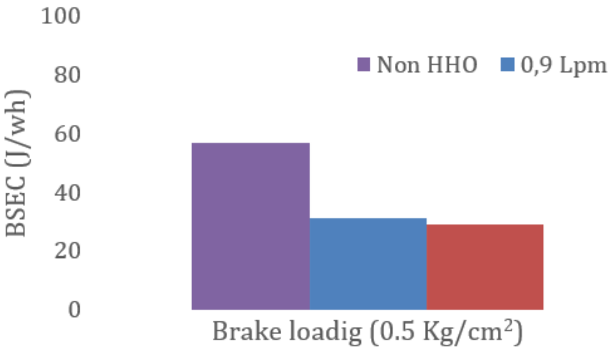

Fig. 4. Brake loading vs BSEC.

At a current of 50 A, the highest hydrogen production rate of 1.25 L/min was achieved. These results are consistent with previous studies, such as [24], which reported a BSEC reduction of up to 18%, and [20], which reported a 3% reduction. In this study, BSEC decrease until 28%. This occurs because HHO has superior combustion characteristics, including high flame speed, wide flammability limits, and low ignition energy requirements [25]. These properties promote more complete and rapid combustion, leading to a greater conversion of the fuel's chemical energy into useful mechanical work [26]. As a result, less fuel energy is required to produce the same output power, leading to a lower BSEC. Furthermore, the high diffusivity of hydrogen enables better mixing with air, resulting in a more homogeneous air–fuel mixture and improved combustion stability. This ultimately enhances engine performance while reducing fuel consumption [23].

Fig. 5 shows that hydrogen gas produced from the electrolysis process also influences thermal efficiency. The higher the current applied to the electrolyzer, the more hydrogen is generated and utilized in combustion. At 50A current with a catalyst concentration of 30 wt.%, the highest HHO gas production of 1.25 Lpm was achieved, which improved thermal efficiency since more energy was converted into power. These findings are consistent with [27], which the reported a 2.9% increase in thermal efficiency, and [20], which reported a 3% increase. In this study, thermal efficiency increased by 6.2%. The improvement in thermal efficiency occurs because the addition of hydrogen promotes more complete combustion. Hydrogen has a wide flammability range, low ignition energy, and high diffusivity, which allows it to mix more uniformly with air and ignite more readily [28]. As a result, the combustion process becomes faster and more stable, minimizing unburned fuel and heat losses [29]. This enhanced combustion quality improves the conversion of chemical energy into useful mechanical work, thereby increasing the overall thermal efficiency of the engine [27].

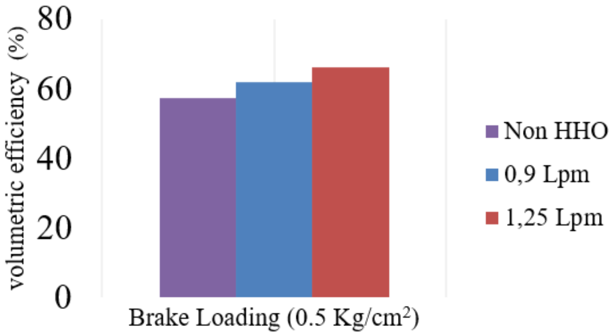

Fig. 5. Thermal efficiency vs volumetric efficiency.

Meanwhile, volumetric efficiency also increased as higher current produced more hydrogen. The greater quantity of hydrogen supported more efficient combustion inside the chamber, allowing more energy to be transformed into thrust within the cylinder. As a result, the engine rotation accelerated due to the more complete combustion, and the shaft continued to rotate even under higher brake loads. This is in line with [30], which reported a 7.5% increase in volumetric efficiency, and [20], which recorded a 5.35% increase. In this study, volumetric efficiency increased by 9.1%. The improvement in volumetric efficiency can be attributed to hydrogen's combustion characteristics. Due to its wide flammability range, high diffusivity, and low ignition energy, hydrogen mixes more uniformly with intake air and ignites more easily compared to conventional fuels [31]. This promotes a more stable and complete combustion process, thereby reducing the amount of residual gases in the cylinder. With fewer residual gases occupying the combustion chamber, a larger volume of fresh air-fuel mixture can be drawn in during the intake stroke, consequently enhancing the engine's volumetric efficiency.

4 Conclusions

An alkaline electrolyzer cell was designed and tested for on-demand hydrogen generation to support hydrogen-enriched combustion in a small spark-ignition engine. The electrolyzer employed stainless steel 317L electrodes with an effective surface area of 200 cm², an inter-electrode gap of 5 mm, and a thickness of 1.2 mm, operating at a cell voltage of 1.49 V. Using eight electrolyzer stacks and a 30 wt.% NaOH electrolyte, the system produced hydrogen flow rates of 0.9 L/min at 40 A and 1.25 L/min at 50 A. Experimental results showed that supplying hydrogen at 1.25 L/min improved engine performance under a constant brake load of 0.5 kg/cm². Effective shaft power increased by 20.8%, brake thermal efficiency increased by 6.2%, and volumetric efficiency increased by 9.1%, while brake specific energy consumption decreased by 28%. These findings indicate that hydrogen supplementation from an alkaline electrolyzer improves combustion efficiency and energy conversion, demonstrating its feasibility as a practical method for enhancing small-engine performance.

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