

Influence of SS316L Plate Surface Texture and NaOH concentration on HHO Gas Production Rate using Distilled Water

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(Received: 09-28-2025; Revised: 05-28-2026; Accepted: 06-20-2026)

Abstrak. Penelitian ini bertujuan menganalisis pengaruh variasi konsentrasi natrium hidroksida (NaOH) dan tekstur permukaan elektroda terhadap kinerja generator HHO menggunakan elektroda plain plate dan textured plate. Konsentrasi NaOH yang digunakan adalah 10, 20, dan 30 g/L. Parameter yang diamati meliputi arus listrik, suhu elektrolit, waktu pengujian, dan laju aliran gas HHO. Hasil penelitian menunjukkan bahwa peningkatan konsentrasi NaOH meningkatkan arus listrik pada kedua jenis elektroda akibat meningkatnya konduktivitas elektrolit. Arus pada elektroda plain plate meningkat dari 5 A menjadi 10 A, sedangkan pada textured plate meningkat dari 5,16 A menjadi 9,20 A. Suhu elektrolit juga meningkat seiring bertambahnya konsentrasi NaOH, namun elektroda bertekstur menghasilkan suhu operasi yang lebih rendah sehingga proses elektrolisis lebih stabil. Laju aliran gas HHO tertinggi diperoleh pada konsentrasi NaOH 10 g/L, yaitu 3,10 L/menit pada elektroda plain plate dan 2,50 L/menit pada textured plate. Pada konsentrasi 20 dan 30 g/L, elektroda bertekstur menghasilkan laju aliran gas yang lebih tinggi dibandingkan elektroda datar. Hasil penelitian menunjukkan bahwa konsentrasi NaOH 10 g/L merupakan kondisi optimum untuk menghasilkan laju aliran gas HHO tertinggi, sedangkan elektroda bertekstur memberikan stabilitas termal dan kinerja yang lebih baik pada konsentrasi elektrolit yang lebih tinggi.

Kata kunci: Generator HHO, elektrolisis, NaOH, elektroda bertekstur, laju aliran, arus listrik.

Abstract. This study aims to analyze the effects of sodium hydroxide (NaOH) concentration and electrode surface texture on the performance of an HHO generator using plain plate and textured plate electrodes. NaOH concentrations of 10, 20, and 30 g/L were investigated. The observed parameters included electric current, electrolyte temperature, operating time, and HHO gas flow rate. The results showed that increasing NaOH concentration increased the electric current for both electrode types due to the enhanced conductivity of the electrolyte. The current increased from 5 A to 10 A for the plain plate electrode and from 5.16 A to 9.20 A for the textured plate electrode. The electrolyte temperature also increased with increasing NaOH concentration; however, the textured plate electrode maintained a lower operating temperature, resulting in a more stable electrolysis process. The highest HHO gas flow rate was achieved at a NaOH concentration of 10 g/L, reaching 3.10 L/min for the plain plate electrode and 2.50 L/min for the textured plate electrode. At NaOH concentrations of 20 and 30 g/L, the textured plate electrode produced higher HHO gas flow rates than the plain plate electrode. These findings indicate that a NaOH concentration of 10 g/L is the optimum operating condition for maximizing HHO gas production, while textured plate electrodes provide better thermal stability and improved performance at higher electrolyte concentrations.

Keywords: HHO generator, electrolysis, sodium hydroxide, textured electrode, flow rate, electric current.

INTRODUCTION

The increasing demand for clean and sustainable energy has accelerated the search for alternatives to fossil fuels. Hydrogen is considered one of the most promising energy carriers because of its high energy density and environmentally friendly combustion,

producing only water as a by-product [1-3]. Among hydrogen technologies, HHO (oxyhydrogen) gas has attracted considerable attention as a supplementary fuel for internal combustion engines because it improves combustion efficiency, reduces fuel consumption, and lowers exhaust emissions [4-6].

Water electrolysis is one of the most effective methods for hydrogen production due to its simple operation, high hydrogen purity, and compatibility with renewable energy sources. In alkaline electrolysis, hydrogen production is influenced by several factors, including electrolyte concentration, electrode material, electrode geometry, current density, and cell configuration. Therefore, optimizing these parameters is essential for improving hydrogen production efficiency while reducing energy consumption [6-8].

Type 316L stainless steel (SS316L) is widely used as an electrode material because of its excellent corrosion resistance, high mechanical strength, good electrical conductivity, and chemical stability in alkaline solutions. The addition of molybdenum improves its resistance to pitting corrosion, enabling stable long-term operation. Previous studies have confirmed that SS316L electrodes provide high durability and reliable hydrogen production performance [5], [9-10].

Electrode surface modification has become an effective approach to enhance electrolysis performance. Surface texturing increases the active electrochemical area, improves electrode-electrolyte interaction, and promotes gas bubble release, thereby reducing polarization and improving hydrogen generation. Various texturing techniques, such as linear grooves, dimples, and laser texturing, have been successfully applied to improve electrochemical performance [11-12], [14-16]. Textured SS316L electrodes have also been reported to produce higher HHO gas output than smooth electrodes, [9].

Electrolyte concentration is another important parameter affecting electrolysis performance. Sodium hydroxide (NaOH) and potassium hydroxide (KOH) are widely used because of their high ionic conductivity and electrochemical stability. Increasing electrolyte concentration generally increases electrical conductivity and hydrogen production, although excessive concentrations may increase heat generation, electrical losses, and electrode degradation [7], [13-14].

Recent studies have shown that NaOH provides hydrogen production comparable to KOH while offering lower cost, greater availability, and easier handling [8]. Moreover, NaOH concentration significantly affects electrical current, electrolyte temperature, operating time, and HHO gas flow rate. Therefore, selecting the optimum NaOH concentration is essential for achieving efficient and stable HHO generation [2], [15].

Although the effects of electrode surface texturing and electrolyte concentration have been widely studied separately, their combined influence has received limited attention. Therefore, this study investigates the combined effects of linear surface texturing and NaOH concentration on the performance of an SS316L-based HHO generator. The results are expected to support the optimization of electrode design and operating conditions for more efficient and sustainable hydrogen production. [9-10], [15].

METODE

Research Design

This study employed an experimental approach to investigate the effect of SS316L electrode surface texture on the performance of an oxyhydrogen (HHO) generator under alkaline water electrolysis. Two electrode types, namely plain and linearly textured electrodes, were compared to evaluate their effects on electrochemical performance and HHO gas production. The experimental procedure included electrode fabrication, HHO generator assembly, electrolyte preparation, performance testing, data collection, and result analysis. All operating conditions were maintained constant except for the electrode surface characteristics to ensure that the observed performance differences were solely attributed to the surface texture. Figure 1 presents the overall research methodology.

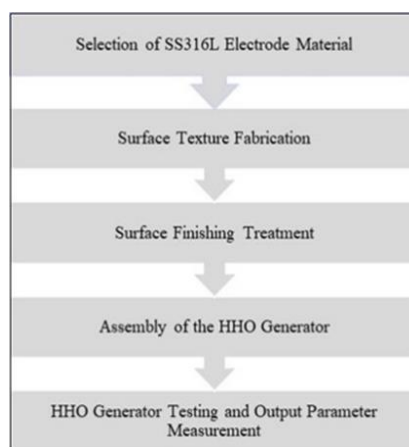


FIGURE 1. Research methodology flowchart of the experimental investigation.

The HHO generator was operated at a constant DC voltage of 13.8 V using sodium hydroxide (NaOH) as the electrolyte. Three NaOH concentrations (10, 20, and 30 g/L) were evaluated to investigate the combined effects of electrolyte concentration and electrode surface texture on HHO generator performance. The measured parameters included electrical current, electrolyte temperature, time required to produce 500 mL of HHO gas, and HHO gas production rate.

Materials

The HHO generator was fabricated using commercially available materials with good mechanical strength, corrosion resistance, and electrical insulation. The housing was made of high-density polyethylene (HDPE) and transparent acrylic, while the electrodes were fabricated from SS316L stainless steel. The specifications of the materials used are summarized in Table 1.

TABLE 1. Materials and specifications used for HHO generator fabrication.

No.	Material type	Quantity	Dimensions	Remark
1.	HDPE 40mm	1 pcs	200 × 300 × 40 mm	HHO generator frame
2.	Clear acrylic	2 pcs	200 × 300 × 50 mm	HHO generator frame cover
3.	HDPE 3 mm	2 pcs	100 × 100 × 3 mm	Cell generator cover
4.	HDPE 1 mm	7 pcs	100 × 100 × 1 mm	Frame generator cells
5.	Bubbler	1 pcs	Diameter 50 mm	Gas filters and monitors of the HHO gas

Seven SS316L stainless-steel plates (100 mm × 100 mm × 1 mm) were used in each electrode assembly, consisting of five neutral plates positioned between one cathode and one anode. SS316L was selected for its high corrosion resistance, mechanical strength, and electrochemical stability in alkaline media. The chemical composition and physical properties of SS316L are presented in Table 2.

TABLE 2. Chemical composition and physical properties of SS316L stainless steel.

Fe	Cr	Ni	Mo	Mn	C	P	S	Si	N
Bal.	16	10	2	2	0.03	0.045	0.03	0.75	0.1

The electrolyte was prepared by dissolving analytical-grade NaOH (purity > 97%) in 1 L of distilled water at concentrations of 10, 20, and 30 g/L. The HHO generator system consisted of a custom-built electrolysis cell, DC power supply, digital ammeter, thermometer, stopwatch, gas flowmeter, bubbler, and supporting components. The bubbler was used to prevent flashback and remove moisture from the generated HHO gas before flow measurement.

Experimental Procedure

The experimental procedure consisted of seven sequential stages, beginning with material selection and ending with data analysis. Commercial SS316L stainless steel was selected as the electrode material because of its excellent corrosion resistance and electrochemical stability in alkaline media. Each electrode assembly comprised seven plates ($100\text{ mm} \times 100\text{ mm} \times 1\text{ mm}$), including five neutral plates, one cathode, and one anode. Two electrode configurations were prepared, namely plain and linearly textured electrodes. The linear texture was machined on the five neutral plates using a 5-axis CNC milling machine to produce uniform horizontal grooves (Figure 2), thereby increasing the effective active surface area and facilitating gas bubble detachment during electrolysis.

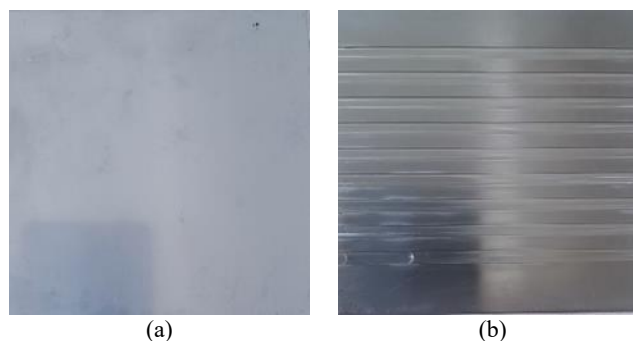


FIGURE 2. Assembly of the HHO generator and electrode arrangement inside the electrolysis cell: (a) Plain plate. (b) Textured plate.

After texturing, all electrode plates were polished with P5000 waterproof silicon carbide abrasive paper to remove machining burrs while preserving the groove geometry and ensuring a uniform surface finish. Subsequently, two HHO generator configurations were assembled, one using plain neutral plates and the other using textured neutral plates. As shown in figure 2, the electrodes were arranged in parallel with a 2 mm inter-electrode gap inside an acrylic–HDPE housing and secured using stainless-steel bolts, rubber seals, and insulating components to ensure uniform electrical contact and prevent electrolyte leakage



FIGURE 3. Experimental setup for HHO production and gas flow measurement: (a) Overall generator, (b) Flow measurement apparatus.

The electrolyte was prepared by dissolving analytical-grade NaOH in 1 L of distilled water at concentrations of 10, 20, and 30 g/L, with each solution freshly prepared and thoroughly mixed before testing. Figure 3 presents the experimental setup used for the performance tests, which were conducted at a constant DC voltage of 13.8 V for both electrode configurations using three electrolyte concentrations.

During each experiment, the electrical current, electrolyte temperature, time required to produce 500 mL of HHO gas, and HHO gas flow rate were measured using a digital ammeter, digital thermometer, stopwatch, and gas flowmeter, respectively. Each-

experimental condition was repeated under identical operating conditions to ensure repeatability and reliability. Finally, the collected data were analyzed using descriptive statistics by comparing the measured current, electrolyte temperature, gas production time, and HHO gas flow rate to evaluate the effects of electrode surface texture and NaOH concentration on HHO generator performance and to determine the optimum operating condition. The experimental variables are summarized in table 3.

TABLE 3. Experimental variables and operating conditions.

Category	Parameter	Condition / Value
Independent variables	Electrode surface	Plain plate; textured plate
	NaOH concentration	10, 20, and 30 g/L
Controlled variables	Electrode material	SS316L stainless steel
	Electrode dimensions	100 mm × 100 mm × 1 mm
	Number of electrodes	Seven plates (5 neutral, 1 cathode, 1 anode)
	Electrode spacing	2 mm
	Electrolyte volume	1 L distilled water
	Electrolyte purity	NaOH (>97%)
	Power supply	DC 13.8 V
Measured variables	Ambient condition	Laboratory conditions
	Electric current	Measured using digital ammeter (A)
	Electrolyte temperature	Measured using digital thermometer (°C)
	Gas production time	Time required to produce 500 mL HHO gas (s)
	HHO gas flow rate	Measured using gas flowmeter (L/min)

RESULTS AND DISCUSSION

Table 4 summarizes the measured electric current, electrolyte temperature, the time required to produce 500 mL of HHO gas, and the HHO gas production rate at different NaOH concentrations dissolved in one liter of water in the HHO generator.

TABLE 4. Average measurement results of the HHO generator using plain plates.

No	NaOH Concentration (g/L)	Current (A)		Temperature (°C)		Time (second/s)		Flow Rate (L/min)	
		Plain	Texture	Plain	Texture	Plain	Texture	Plain	Texture
1	10	5	5.16	37.9	33.0	161.29	200	3.1	2.50
2	20	6.59	6.51	41.4	33.2	322.58	231.48	1.55	2.16
3	30	10	9.2	40.8	34.6	427.35	364.96	1.17	1.37

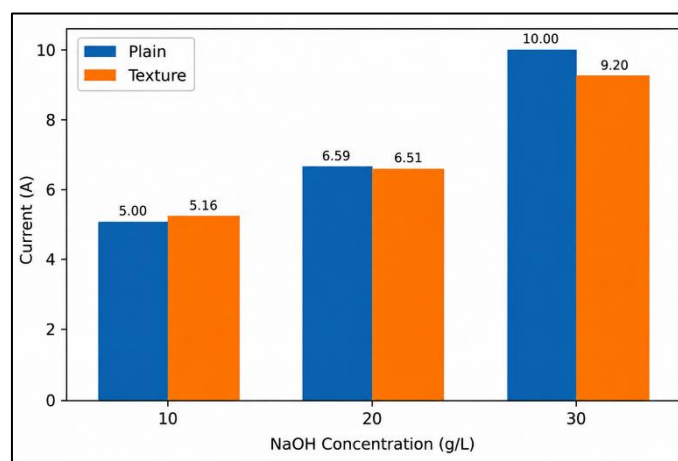


FIGURE 4. Effect of NaOH concentration on current using plain plate and textured plate electrodes.

Figure 4 shows the relationship between electric current and NaOH concentration. As the NaOH concentration increased from 10 g/L to 30 g/L, the electric current increased for both electrode types. For the plain-plate electrode, the current increased from 5.00 A to

10.00 A, while for the textured-plate electrode, it increased from 5.16 A to 9.20 A. This increase indicates that higher NaOH concentration enhances the electrical conductivity of the electrolyte solution, thereby reducing electrical resistance and allowing a greater current to flow. At a concentration of 30 g/L, the plain-plate electrode produced a slightly higher current than the textured-plate.

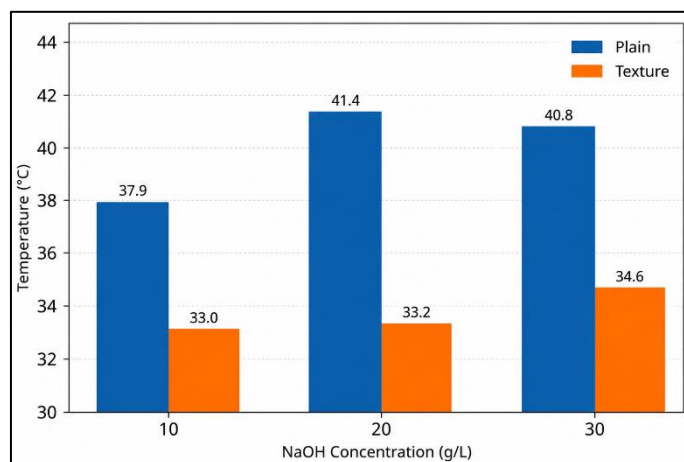


FIGURE 5. Effect of NaOH concentration on electrolyte temperature using plain plate and textured plate electrodes.

Figure 5 shows the relationship between electrolyte temperature and NaOH concentration. The results indicate that the electrolyte temperature generally increased as the NaOH concentration increased. For the plain-plate electrode, the temperature increased from 37.9°C at a concentration of 10 g/L to 41.4°C at 20 g/L, before slightly decreasing to 40.8°C at 30 g/L. In contrast, for the textured-plate electrode, the temperature increased gradually from 33.0°C to 34.6°C over the same concentration range. These results indicate that the textured-plate electrode operated at a lower temperature than the plain-plate electrode, resulting in reduced heat-related energy losses and a more stable electrolysis process.

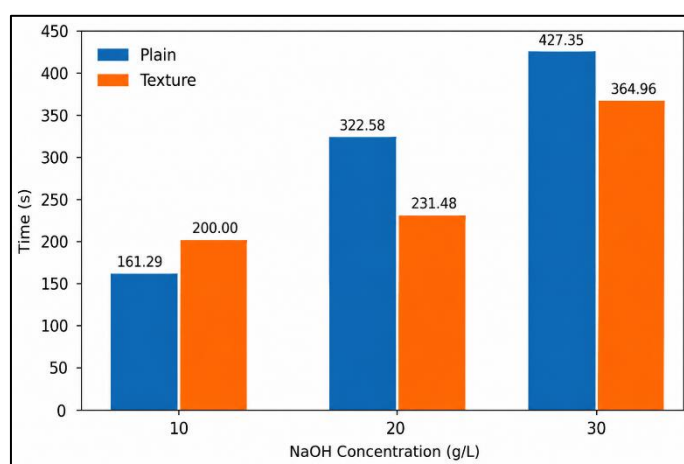


FIGURE 6. Effect of NaOH concentration on HHO generator operating time using plain plate and textured Plate electrodes.

Figure 6 shows the relationship between measurement time and NaOH concentration. The results indicate that the measurement time increased as the NaOH concentration increased. For the plain-plate electrode, the measurement time increased from 161.29 s to 427.35 s, while for the textured-plate electrode, it increased from 200.00 s to 364.96 s. At a concentration of 10 g/L, the plain-plate electrode required a shorter measurement time than the textured-plate electrode. However, at 20 g/L and 30 g/L, the increase in

measurement time for the textured-plate electrode was less pronounced than that of the plain-plate electrode. These findings indicate that the textured-plate electrode exhibited better process stability at higher electrolyte concentrations.

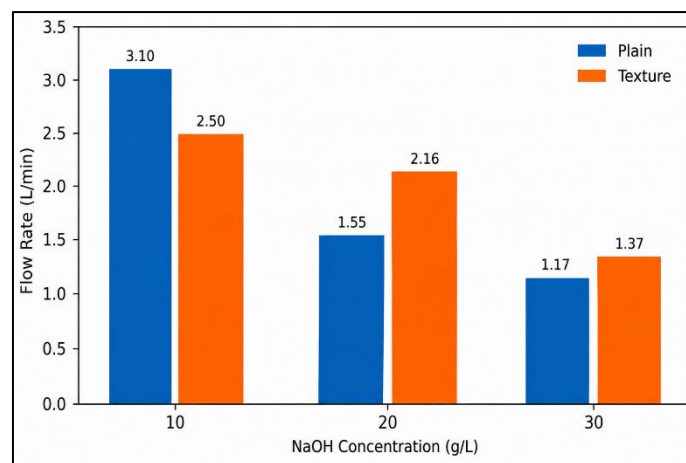


FIGURE 7. Effect of NaOH concentration on HHO gas flow rate using plain plate and textured plate electrodes.

Figure 7 shows the relationship between HHO gas flow rate and NaOH concentration. The results indicate that the HHO gas flow rate decreased as the NaOH concentration increased for both electrode types. For the plain-plate electrode, the gas flow rate decreased from 3.10 L/min to 1.17 L/min, while for the textured-plate electrode, it decreased from 2.50 L/min to 1.37 L/min. At a concentration of 10 g/L, the plain-plate electrode produced the highest gas flow rate. However, at 20 g/L and 30 g/L, the textured-plate electrode achieved higher gas flow rates than the plain-plate electrode. These findings indicate that, although increasing NaOH concentration enhances the electric current, [8] the HHO gas flow rate does not increase proportionally. Based on the experimental results, a NaOH concentration of 10 g/L represents the optimal operating condition, as it produced the highest HHO gas flow rate.

The findings of this study are consistent with previous research on the effect of NaOH concentration on HHO gas production. A study investigating various NaOH concentrations (2%, 4%, 6%, 8%, and 10%) combined with different numbers of electrode plates (2, 4, and 6 plates) demonstrated that increasing both the NaOH concentration and the number of electrode plates contributed to higher HHO gas production and hydrostatic pressure. The highest pressure and hydrogen production rate were achieved at a 10% NaOH concentration using six electrode plates [16].

The present study also confirms this trend, where increasing the NaOH concentration from 10 g/L to 20 g/L resulted in a significant increase in the HHO gas production rate from 3.92 L/min to 5.79 L/min, reinforcing the conclusion that higher electrolyte concentrations enhance ion mobility and improve the efficiency of the electrolysis process.

The direct correlation between electric current and HHO gas production observed in this study is consistent with findings reported in the literature. The use of a NaOH electrolyte increases the ion concentration in the solution, thereby enhancing its electrical conductivity. At different electrolyte concentrations, both the amount of hydrogen produced and the effect of electrode spacing are influenced by input power and applied voltage. This supports the observation in the present study that increasing NaOH concentration from 10 g/L to 20 g/L increased the electric current from 4.77 A to 5.29 A, which is a direct consequence of enhanced ionic conductivity and is consistent with Faraday's law of electrolysis [17].

CONCLUSION

Based on the experimental results, increasing the NaOH concentration from 10 to 30 g/L increased the electric current for both plain-plate and textured-plate electrodes due to the improved electrical conductivity of the electrolyte. However, this increase in current did not lead to a higher HHO gas flow rate. As the NaOH concentration increased, the electrolyte temperature also tended to rise, while the textured-plate electrode consistently operated at a lower temperature than the plain-plate electrode, indicating a more stable electrolysis process. The highest HHO gas flow rates were achieved at a NaOH concentration of 10 g/L, reaching 3.10 L/min for the plain-plate electrode and 2.50 L/min for the textured-plate electrode. At higher NaOH concentrations (20 and 30 g/L), the textured-plate electrode produced more HHO gas than the plain-plate electrode, suggesting that surface texturing can improve electrolysis stability and enhance hydrogen production under higher electrolyte concentrations.

Acknowledgements

The author gratefully acknowledges Universitas Nasional, Jakarta, Indonesia, and Universiti Teknikal Malaysia Melaka for their support and research facilities.

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