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The effects of voltage variations and surface on the performance of an HHO generator using a NaOH catalyst

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Abstract

The objective of this work is to test the HHO generator by implementing innovations on the electrode plate surface and varying the input voltage. Some important indicators, such as H_2 gas production rate, output current, output temperature, and operating time, were carefully tested as an evaluation of the HHO generator's performance. The HHO generator's electrolyte was NaOH as a catalyst, and the concentration was maintained at 60 g/l. This study is mostly interested in how the voltage changed between 12V and 14V when different electrode surface textures were used. The findings demonstrated that an increase in voltage generally exhibits an increasing trend in H_2 gas production rate, output current, and output temperature, along with a decrease in operating time. The most striking was the H_2 production rate, which increased significantly by 422.13% with the voltage variations on the cross surface. Even the output current and output temperature were quite high on the cross surface as a function of voltage variation. In contrast, the operating time showed a sharp decrease with the increase in voltage on the cross surface, from 98.06 s at 12 V to 18.78 s at 14 V. It should be noted that the cross surface revealed the shortest operating time and was also the most efficient in the HHO gas production process compared to other types of surfaces. This research can aid in the addition of gas to improve the performance and emissions of gasoline engines.

Keywords: HHO gas, Surface texture, Voltage, HHO production, Electrolyte

1. Introduction

Many parties consider hydrogen a promising alternative fuel option for the future. It has significant capabilities to address energy and environmental issues and challenges associated with the use of hydrocarbon-based fossil fuels [1, 2]. Among the various hydrogen production methods, water electrolysis is a widely used method. It can produce hydrogen without carbon emissions if supported by renewable energy sources [3-5]. Water electrolysis has not yet reached a significant level of commercial adoption due to high electricity consumption and operational costs [6].

To date, fossil fuels are a highly demanded energy source worldwide, accounting for 82% of the world's entire energy supply [7, 8]. Fossil fuels are one of the major contributors to greenhouse gases that contribute to climate change and global warming [9, 10]. Various efforts have been made to replace hydrocarbons with renewable fuels that are more environmentally friendly. Hydrogen has significant potential as a cleaner alternative energy source compared to hydrocarbon fuels, with significantly lower emissions [2, 10, 11]. Once separated from water through the electrolysis process, the produced gas is known as oxyhydrogen or hydroxy gas (HHO). HHO gas has characteristics such as being colorless, having a very low specific gravity, being flammable, and having a tendency to react with other chemicals [12].

One of the most important areas of research is the implementation of HHO in hybrid internal combustion engines. Engine performance and gas emissions were analyzed for two different types of engines: an older 150 cubic centimeter (cc) engine with a carburetor and a new 1300cc engine equipped with an Electronic Control Unit (ECU). The results showed a 14.8% reduction in fuel consumption for the 150-cc engine and a 16.3% reduction for the 1300-cc engine when using HHO gas. In addition, the utilization of HHO gas led to a 33% reduction in gaseous emissions, including a 24.5% reduction in carbon monoxide (CO) and a 27.4% reduction in HC for the 150-cc engine. For the 1300cc engine, there was a 21% reduction in hydrocarbon (HC) emissions [13].

Ridhwan et al. [14] made efforts to increase gas production by increasing the surface area through engineering the surface with texture variations and adjusting the potassium hydroxide (KOH) catalyst concentration. The study reported that changes in surface texture and variations in catalyst concentration had an important impact on the rate of hydrogen gas production [14]. Oxyhydrogen (HHO) gas, which can serve as an alternative energy source to address the difficulties of fossil fuel scarcity and environmental pollution, is the focal point of this study. Therefore, the aim of the study is to ascertain how variations in voltage and surface texture affect the performance of the HHO generator. This will be accomplished by examining the rate of HHO gas production, output current, output temperature, and operating time as key indicators. Previous research revealed that voltage variations have a significant impact on HHO

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gas production. This was demonstrated in a study by [15], which analyzed the performance of HHO generators at various voltage levels. In addition, the use of KOH as a catalyst has been proven to enhance the efficiency of the electrolysis process due to its ability to reduce electrical resistance in the electrolyte solution [16]. However, several studies, including the one conducted by [17], have not examined the effect of plate surface design on electric current distribution, resulting in a less comprehensive analysis. To fill this gap, this study thoroughly evaluates the combination of voltage variation and plate surface design in improving the efficiency of HHO generators with NaOH catalysts.

In this study, we used an existing HHO gas generator, so modifications were only made to the electrode plates, input voltage variations, and catalyst weight variations. Therefore, the primary objective of this research is to evaluate the influence of voltage variations and plate surfaces on the efficacy of HHO generators using a NaOH catalyst. This research examined the impact of different voltage inputs and plate surface textures on the hydrogen production rate, output temperature, output current, and output duration in a hybrid generator system. Our research findings indicate that the gas production rate is influenced by the texture of the electrode plate surface. Additionally, variations in voltage and the weight of the NaOH catalyst also have a significant impact on the HHO gas production rate in the existing HHO gas generator.

2. Materials and methods

2.1 HHO generator

HHO generators operate based on the principle of water electrolysis. The electrolyzer consists of several components, including a battery, electrolysis cell (available in different types such as dry cell, wet cell, and hybrid cell), water tank, bubble-forming device, and flow rate meter. In this generator, water serves as the conducting medium. The resulting gas stream consists of hydrogen (H_2) and oxygen (O_2). Since each mole of water splits into 2 moles of H_2 and 1 mole of oxygen, the volume of gas produced is equivalent to the total volume of the two gases combined. In other words, when 1 liter of water is processed, approximately 1,866 liters of HHO gas are generated [1, 15].

The core component of an electrolyzer is its cell, which comes in three types: dry cells, wet cells, and hybrid cells. The choice of cell type depends on how the electrodes interact with the electrolyte. The electrolyte fills the space between the electrodes in a dry cell. In a wet cell, all electrodes are immersed in an electrolyte solution in a container of water. Hybrid cell types, on the other hand, have a similar configuration to dry cells, but they store the electrolyte in a container as in wet cells. HHO cells have two sides, namely the positive and negative sides, which operate like the principles of a battery. H_2 gas is produced on the negative side, while O_2 gas is produced on the positive side. The electrodes in these cells are given specific names, with the cathode (+) being the positive electrode and the anode (-) being the negative electrode. This ionic conductivity is possible because the ions within the cell have unrestricted mobility. Once dissolved in water, these ions can transfer either in liquid form or as an aqueous solution. Electrolytes are substances that can dissolve in water. Power supply is provided through Alternating Current (AC) at 220V. Voltammeters and ammeters are used to monitor voltage and current, respectively. The movement of water per unit time is calculated to measure the HHO flow rate, which is calculated as the amount of water accumulated in the measuring cylinder in a given period.

The bubbler prevents backfire from electrolyzer explosions. In the event of a backfire, water from the bubbler will be pumped back to the electrolyzer using a one-way valve [1, 16]. Safety precautions are implemented to prevent explosions and system damage, including the use of flashback prevention devices. The battery is connected to the electrolysis cell via a relay, which automatically shuts down the electrolysis process. The electrical supply for electrolysis is then routed through a circuit breaker, which protects against surges and overheating of the cell.

2.2 Types of HHO cells

The generator used in this study was a hybrid type that combines the characteristics of both dry cells and wet cells. In this hybrid generator, the dry cell configuration is arranged in a way that is similar to the way wet cells are placed in a container of electrolyte liquid. A schematic drawing of a hybrid-type electrolyzer is shown. There is a container that serves as a reservoir containing an electrolyte water solution, and the generator electrodes are submerged in the electrolyte solution. The temperature generated is relatively low due to its ability to be immersed in the electrolyte solution. The water in the container can move efficiently without the need to use a water pump. These advantages are characteristic of hybrid-type HHO generators [14]. Table 1 displays the specifications of the hybrid cell electrolyzer.

Table 1 Specifications of the hybrid electrolyzer.

Parameter	Specification
Material surface	Stainless Steel (316 L)
Cross-sectional area of the surface (mm^2)	100 x 100
Surface thickness (mm)	1
Number of surfaces	7
Distance between electrodes (mm)	2
Gasket material	Rubber
Number of gaskets	5
Input voltage (V)	12 - 14
Box material	Glass
Dimensions of the glass box (mm^3)	30 x 30 x 40
Glass box thickness (mm)	3

2.3 Configuration of electrolyzer cell

A number of factors, such as electrolyte type, electrolyte concentration level, amount of applied electric current, electrolyte temperature, production duration, voltage, and number of surfaces, affect the gas production output. This design was intended to achieve the best HHO production by considering variables such as electrolyte concentration, voltage, electrolyte amperage, and the number of surfaces used.

Table 2 The chemical composition of SS316L (in wt.%) [14]

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

As shown in Table 2, type 316L commercial stainless steel with the following chemical composition: 16% Cr, 10% Ni, 2% Mo, 0.03% C, 2% Mn, 0.045% P, 0.03% S, 0.75% Si, 0.1% N, and the rest Fe (in weight percent) is selected as the surface material. These surfaces have surface area dimensions of approximately 100 mm × 100 mm × 1 mm. In this study, three types of surface textures were used, namely plain surface, linear texture, and cross texture, as shown in Figure 1. This HHO generator is made up of five 316L steel plates, with the electrodes spaced 2 mm apart [14].

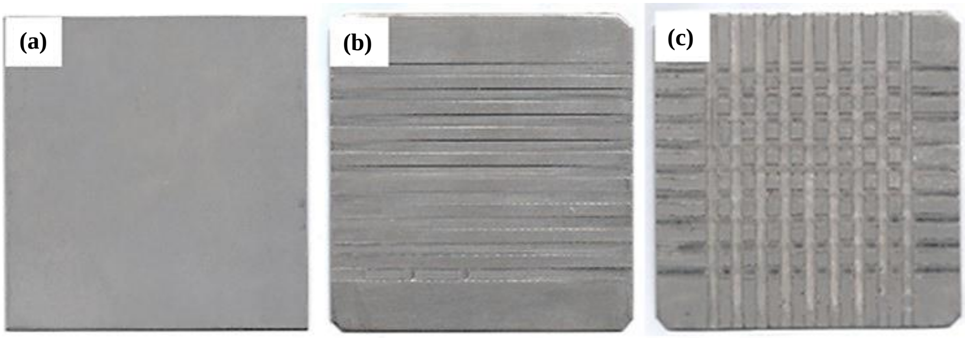

Figure 1 The plate shapes used in HHO generators are (a) plain, (b) linear, and (c) cross surfaces

Herein, a hybrid-type HHO generator was planned and manufactured. There are seven electrode surfaces with a size of 100×100×1 mm^3 made of 316L stainless steel. Between the electrodes, there is a 2 mm-thick rubber gasket made of ethylene propylene diene monomer, which has a role in preventing direct contact between adjacent surfaces. One of the surfaces is connected to a negative charge (cathode), another surface is connected to a positive charge (anode), and the other surface is neutral. The electrolyte flows freely between all these components. The gas produced is drained through a water trap to keep the system safe. The scheme of this HHO generator can be seen in Figure 2. The electrolyte used was NaOH, and the electrolyte capacity in this HHO generator is 1 liter.

Between the two surfaces, there is a carefully placed rubber gasket. This square-shaped rubber gasket serves to maintain a proper distance between the SS316L surfaces in the center. In the process of generating HHO gas through electrolysis, the surface area of the electrodes is completely immersed in water. When voltage is applied, there is an ionic charge transfer between the electrode pairs. Each attached neutral surface has a different polarity in turn. The resulting gas and water introduced into the system flow through this system via inlet and outlet valves. The electric current flows through the SS316L. Most of the electrons flow near the surface towards the negative surface through the electrolyte. Both the anode and cathode are made of the same material. The electric current flows from the anode to the cathode through the electrolyte. The resulting HHO gas feed then enters the bubbler, which functions as a gas storage container. At first, the bubbler is filled with water, and when the HHO gas is filled into it, the excess water flows into the reservoir. A safety valve is placed under the sump for safety purposes. The water from the reservoir is then supplied back to the generator. After the first filling, distilled water is added to the electrolyzer. Flexible rubber gaskets allow the cells to be tightly connected and resistant. The electrolyzer is supplied with slightly acidic water to neutralize any residual NaOH vapor that may be contained in the output gas.

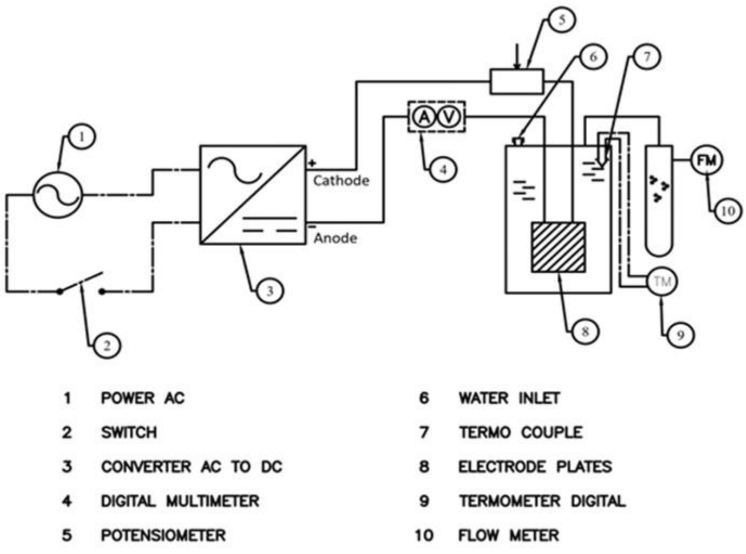

Figure 2 Experimental setup of the HHO generator with connectivity among generator parts.

2.4 Fabrication of electrode surface texture

Regarding the electrode surface texture, it is initially created using the CAD program CATIA V5 R20 to obtain accurate and precise results, as shown in Figure 3 and Figure 4. Using this software, the pattern then runs the machining procedure to run the simulation before writing the code. After that, the program code is transferred to the CNC device for further processing. Computer numerical control (CNC) equipment was used to manufacture the textured surface surfaces. Each surface was made in about 20 minutes at a speed of 1150 mm/min during the surface texturing process. In order not to erode the tool and produce surfaces with a good surface finish, coolant is supplied regularly during the machining process to chill and lubricate the area where the surface and the tool make contact. Furthermore, use a tool file to ensure that no cutting residue remains on the electrode surface before polishing with isopropyl.

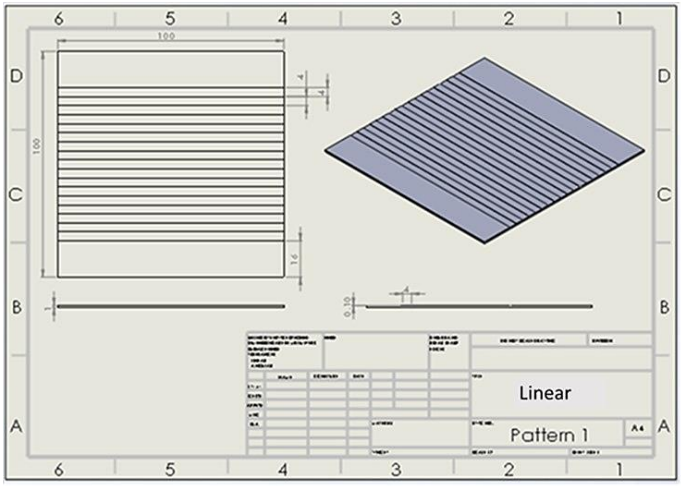

Figure 3 Linear pattern

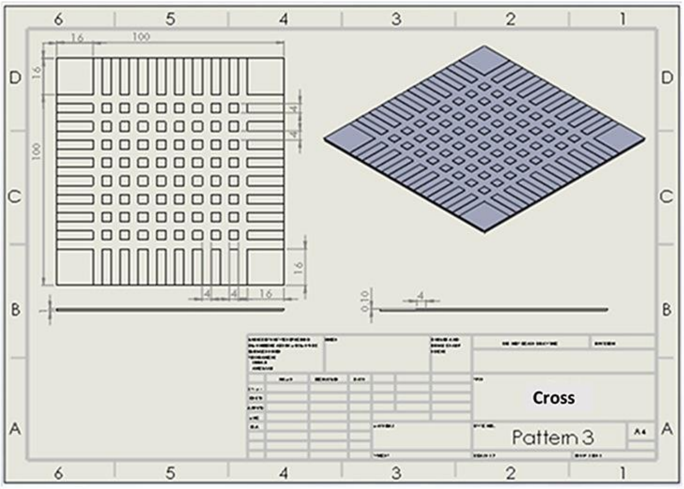

Figure 4 Cross pattern

2.5 Installation of HHO generator

A hybrid HHO generator that combines the principles of a wet-type generator and a dry-type generator is used. The use of this HHO generator was chosen because it has interesting research value and needs to be further analyzed in this study. To evaluate how well the HHO generator produces HHO gas, a calibration method was used. First of all, the HHO generator is determined through a flow meter to calculate the HHO gas production rate expressed in liters per minute. Next, to offer a power source with input voltage changes between 12 V, 12.5 V, 13 V, 13.5 V, and 14 V, an electrical power supply was connected to the HHO generator. When the electric current flows through the HHO generator, the electrolysis process starts using NaOH solution as the electrolyte, which produces HHO gas. The concentration of NaOH used in this study is 60 grams per liter of water. The electrical power supply is equipped with an ammeter and voltmeter display that has an internal 1.5V lithium battery. As an additional safety measure, a bubbler was used to prevent a possible backfire that could cause an explosion in the electrolyzer. These safety precautions are implemented during the operation of the HHO cell to protect the system from possible explosions and damage. The volume flow rate of HHO gas per unit time is measured using a flowmeter. The AC and DC converters are not connected directly to the electrolyzer cell but rather through potentio resistance and current and voltage indicators as part of the system setup.

2.6 Measurement parameters

Concerning the measurement of output temperature, operating time, HHO gas production rate, and output electric current, it is important to understand how to determine their values by utilizing the results of the experiments that have been conducted. The NaOH catalyst was obtained from Merck, made in Germany, with a molarity of 40 g/mol. The first step is to weigh 60 grams of NaOH catalyst, then fill a measuring vessel with a capacity of 1 liter with distilled water. After that, NaOH was dissolved in the vessel. After the NaOH catalyst is completely dissolved, the solution is filled into the HHO generator until the water runs out and the entire electrode surface is completely immersed in the solution. Pressing the "on" button and plugging the cable into the power supply will then start the HHO generator system. The HHO generator uses a technique to calculate its value by keeping it in this state for half an hour or until a stable state is reached. For 30 minutes, the applied voltage was set at various levels, namely 12V, 12.5V, 13V, 13.5V, and 14V, and a stopwatch was turned on. During the gas production process, the water volume on the flowmeter rose periodically until it reached a certain level (up to 10 cm), indicating the increase in water volume as a result of H_2 gas generation. The digital power supply screen shows the output electric current value. In order that the recorded volume increase can be used to calculate the HHO gas production rate. In order that the recorded volume increase can be used to calculate the HHO gas production rate. In addition, the output temperature is displayed on the screen. The operating time can be seen from the numbers on the stopwatch.

The different types of electrode surface surfaces will be correlated with the data collected for each parameter in this investigation. Furthermore, voltage variations were also applied to the HHO gas generator containing a 60 g/l NaOH catalyst solution. The purpose of this study is to examine how changes in application voltage affect HHO gas production, output current, output temperature, and operating time on different types of electrode surface surfaces at voltage levels of 12V, 12.5V, 13V, 13.5V, and 14V. Based on the observation that the HHO gas production value and electric current gradually increased at electrolyte concentrations up to 60 g/l, this investigation was carried out. Consequently, it is also interesting to observe and examine the changes in the applied voltage.

3. Results and discussion

3.1 Effect of voltage input on HHO gas production rate

Current and voltage have an impact on the rate of HHO gas production. At a temperature of about 25 °C and with a NaOH concentration of 60 grams in 1 liter equivalent, the HHO gas production process was observed through SS316L electrodes. As seen in Table 3 and Figure 5, the applied voltage varied from 12 V to 14 V, while the current supplying the voltage was the output of the 20.8A power supply seen on the device. The rate of gas production in cells that are in the wet state continues to increase with increasing applied voltage. This is due to the acceleration of kinetic reactions and ion exchange on the electrode surface, as well as an increase in charge density [1].

Table 3 Effect of applied voltage on H_2 gas production rate at varying surface surfaces.

Voltage (V)	H_2 gas production rate at varying surface surfaces (in L/min)		
	Plain surface	Linear surface	Cross surface
12.0	215.73	291.09	305.93
12.5	363.22	493.32	542.37
13.0	479.52	761.30	978.59
13.5	854.09	1033.37	1363.64
14.0	1013.73	1367.52	1597.34

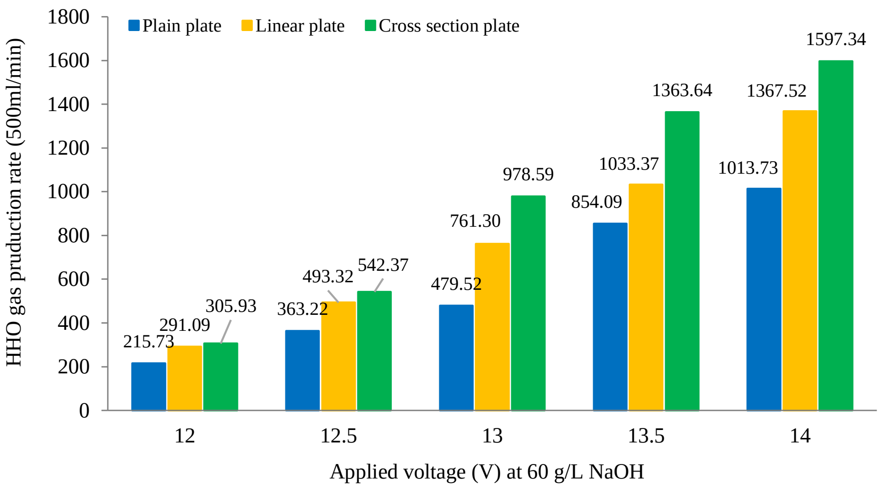

Figure 5 HHO gas production rate as a function of input voltage variations with different surface surfaces.

Table 3 shows the highest flow rates at each voltage as follows: at 12V of 305.93 ml/min, at 12.5V of 542.37 ml/min, at 13V of 978.59 ml/min, at 13.5V of 1363.64 ml/min, and at 14V of 995.72 ml/min. According to these data, the cross-surface produced the highest gas production rate compared to the other surfaces. A higher concentration of NaOH electrolyte causes the molecules in the water to move faster, intensifying the collisions between H_2 and O_2 molecules. With the increase in molecular collision intensity, the kinetic energy between molecules also increases, resulting in increased HHO gas production. These findings unequivocally show that the application voltage has a significant impact on the rate of HHO production. This suggests that the surfaces' surface texture has a significant impact on the rate of HHO production. This texture may have an impact on the surface roughness of the surface, which may change the surface area of the surface. The amount of nickel in the used surfaces is another factor to consider. SS316L, in particular, is often used as an electrode in situations where the cathode undergoes an H_2 evolution reaction with the base medium due to its high nickel content. The reaction at the cathode during electrolysis results in the production of H_2, while the anode produces oxygen. The amount of H_2 produced during the process is twice that of oxygen. To provide more information, the following chemical processes will take place [14, 18]:

Reactions at the cathode: $2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$ (1)

Reaction at the anode: $4OH^-(aq) \rightarrow O_2(g) + 2H_2O(l) + 4e^-$ (2)

Overall reaction: $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$ (3)

In addition, the nickel element content of SS316L has the potential to react with NaOH, the electrolyte, forming nickel hydrate on the surface of the steel surface. The use of NaOH electrolyte is effective in influencing the H_2 evolution reaction, increasing the rate of H_2 production. This occurs as a result of nickel hydrate forming on the surface of the steel surface, which makes it less susceptible to corrosion and influences higher HHO production rates. These results also show that the overall performance of the 316L steel electrode is quite stable. Therefore, it is important to keep an eye on the development of surface roughness on 316L steel surfaces in HHO generators to improve their applicability and accelerate the H_2 gas production rate in the future.

3.2 Effect of input voltage variations on output current

The relationship between input voltage and output current is compiled in Table 4. Meanwhile, the trend of output current as a function of input voltage is demonstrated in Figure 6. The highest output currents at each application voltage are as follows: at 12V of 9.95A, at 12.5V of 12.37A, at 13V of 17.85A, at 13.5V of 18.55A, and at 14V of 18.99A. At all input voltages from 12V to 14V, it is shown that the cross-surface surface had a higher output current compared to the plain surface and linear surface.

Table 4 Effect of input voltage on output current at varying surface surfaces.

Voltage (V)	Output current (A)		
	Plain surface	Linear surface	Cross surface
12.0	7.01	7.47	9.95
12.5	8.91	10.77	12.37
13.0	11.33	14.58	17.85
13.5	15.66	17.43	18.55
14.0	17.19	18.30	18.99

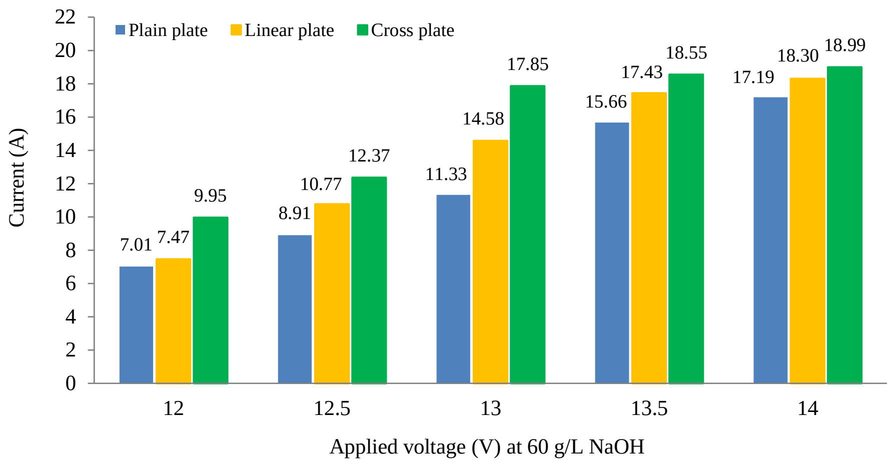

Figure 6 Output current as a function of input voltage variations with different surface surfaces.

With an increase in output current as a function of input voltage, it promotes an increase in the rate of H_2 gas production. This happens because the electrode surface undergoes faster bubble formation, which results in a larger current. Bubbles occur when the HHO generator receives the application voltage. Nevertheless, electrode instability is caused by electrode surface bubbles, which also changes the flow of electric current [1]. Higher voltage leads to greater electron exchange and positively charged H_2 ions. An increase in current leads to an increase in effective ion collisions and electrode conductance. As current production increases, the rate of increase in electron transport between the electrodes also increases. The number of electrons transported affects how quickly the water dissociates. An increase in current causes the temperature in the HHO gas generator to increase [19].

From the data obtained (Table 4), the highest output currents at each application voltage are as follows: 9.95 A at 12V, 12.37 A at 12.5V, 17.85 A at 13V, 18.55 A at 13.5V, and 18.99 A at 14V. Generally, at all input voltages supplied, i.e., from 12V to 14V, it is clear that the cross-surface surface produced a higher output current compared to the other two surface types. Electrode conduction and the rate at which electrons move between electrodes are both determined by the presence of electrolyte, which ultimately increases the amount of electric current received at various surface textures, which in turn affects the rate of HHO gas production. However, electrolyte concentration increases electric current and decreases electrical resistance, while electrolyte resistance decreases electrical conductivity and reduces potential. However, conversely, reverse reactions, side reactions, and contaminants in the electrode material can cause resistance in the electrolyte and electrode solution, which can impact the value of the electric current produced. It is shown that the texture of the surface, i.e., plain surface and linear surface, can somewhat reduce the mobility of ions in the electrolyte solution relative to the barrier-free cross-surface of the surface, which is reflected in the results, a phenomenon resulting from the interaction between the flow of electron-carrying ions as they pass through a surface with a certain roughness. Cross-surface texture effects can lower the output current achieved at the surface due to its more complicated shape than plain and linear surfaces, which increases the surface area. In addition, a pair of electrodes placed relatively close to each other—about 2 mm apart—can lower the electrical resistance between them, which affects the increase in electric current [20].

3.3 Effect of input voltage variations on output temperature

Table 5 shows the effect of input voltage on output temperature at varying surface plate, whereby electrolyte temperature, potential, and gas production all increase as the voltage on the cell increases. However, the cell efficiency decreased due to the higher voltage. The observed increase in HHO gas production is due to the increase in potential [18, 19]. The highest output temperature at each application voltage (Figure 7) is as follows: at 12 volts, the temperature reaches 46.55°C (cross surface). At 12.5V, the output temperature reaches 49.59°C (linear surface). Then, in the voltage range of 13V to 14V, the output temperature increased significantly to 77.90°C, 87.35°C, and 92.58°C for the cross surface, respectively. Temperature is a key parameter in the water electrolysis process, as it is directly related to the voltage applied to the HHO gas generator system.

Observation of HHO gas production as a function of time shows an increase in temperature in the HHO generator. This increase in temperature improves the efficiency of the generator and reduces energy consumption during the production process. In addition, a gradual increase in temperature reduces the breaking potential of water molecules, increases electrolyte electrical conductivity and ionic conductivity, and strengthens electrode surface reactions. These observations can be explained by the concept of ion mass transfer that occurs during the electrolysis process. Since an increase in temperature favors more intense collisions of ion molecules, the amount of HHO gas produced also increases. This result is more consistent with Faraday's Law, which states that the amount of substance deposited or released on an electrode is proportional to the magnitude of the electric current flowing through the electrolyte [21].

Increasing the production time results in increased temperatures in the production of HHO gas and lower energy usage. As the temperature rises, the electrolysis process accelerates the creation of HHO gas. An increase in operating time leads to an increase in temperature due to electron mobility and an increase in the heat transfer rate of the surfaces from the start of operation. The rise in production temperature reduces the potential for water molecules to decompose, thus increasing the ionic conductivity of the electrolyte and surface reactions on the electrodes. An increase in operating temperature and current consumption results in a decrease in electrical resistance in the electrolyte and potential. Higher resistance in the electrolyte and electrodes leads to heating in the electrolysis process. An increase in temperature results in increased molecular collisions between ions, leading to increased HHO gas production in accordance with Faraday's law. An excessive increase in electrolyte temperature results in an increase in electrolyte concentration and the evaporation of water. Until the electrolyte concentration reaches the intended working condition, it must first be kept to a minimum. The electrolysis process should be given high current at low operating temperatures and low current at high operating temperatures; this is done to start the operation and prevent overheating. An excessive increase in temperature can achieve rapid reaction kinetics and may cause an explosion [7].

Table 5 Effect of input voltage on output temperature at varying surface plate.

Voltage (V)	Temperature (°C)		
	Plain Plate	**Linear Plate**	**Cross Plate**
12.0	42.50	45.14	46.55
12.5	47.54	49.59	48.71
13.0	47.54	57.83	77.90
13.5	48.89	58.93	87.35
14.0	57.93	65.10	92.58

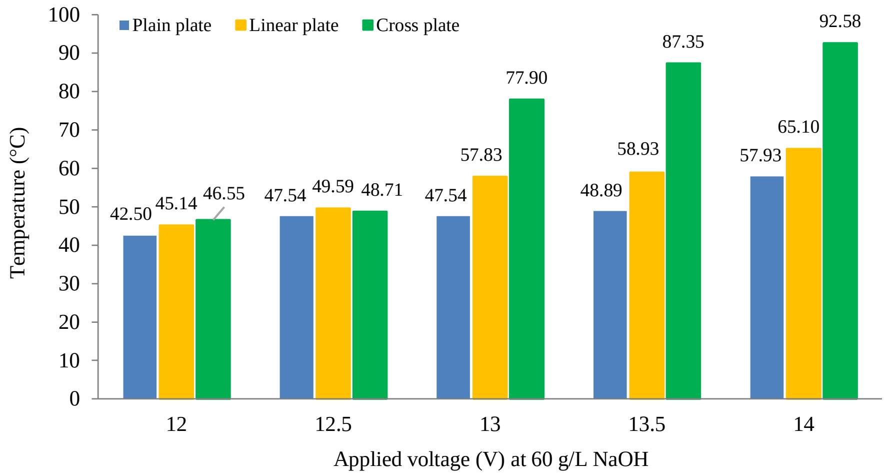

Figure 7 Output temperature as a function of input voltage variations with different surface surfaces.

3.4 Effect of input voltage variations on output temperature

The relationship between electrolyte content and NaOH operating time shown in Figure 8 is shown to improve the performance of the HHO generator. The highest operating times at each application voltage are as follows: at 12V is 98.06s, at 12.5V is 55.31s, at 13V is 30.66s, at 13.5V is 22.00s, and at 14V is 18.78s. In the voltage range between 12V and 14V, it can be seen that the dominant cross-surface surface has a faster time compared to the linear surface and plain surface. The concentration of the electrolyte solution has a direct impact on how fast the temperature rises. Theoretically, the solution will take less time to reach a certain temperature if the concentration is higher because less energy is needed to get it there. Moreover, the detailed results are summarized in Table 6. In addition, the conductivity of water can be increased by adding high concentrations of NaOH electrolyte, resulting in a faster electrolysis process [21].

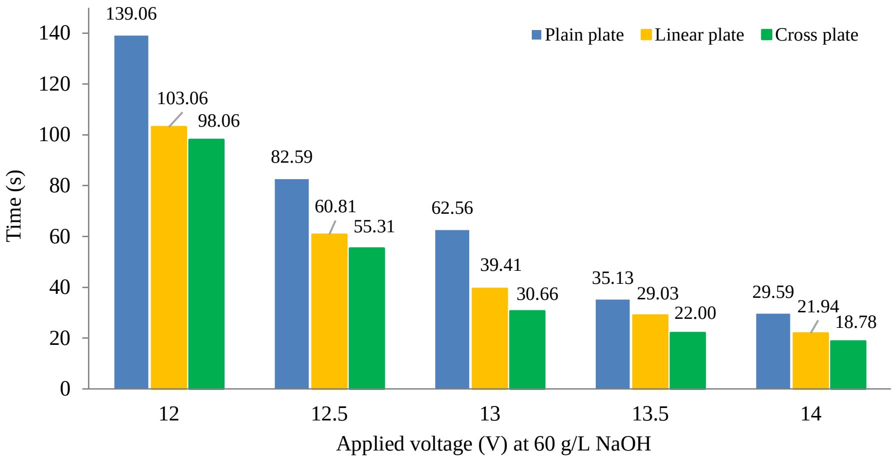

Figure 8 Operating time as a function of input voltage variations with different surface surfaces.

Table 6 Effect of input voltage on operating time at varying surface surfaces

Voltage (V)	Time (s)		
	Plain Surface	Linear Surface	Cross Surface
12.0	139.06	103.06	98.06
12.5	82.59	60.81	55.31
13.0	62.56	39.41	30.66
13.5	35.13	29.03	22.00
14.0	29.59	21.94	18.78

4. Conclusions

The study conclusively demonstrates that the variation in voltage and electrode surface texture significantly affects the rate of HHO gas production, output current, electrolyte temperature, and operating time. With a constant NaOH concentration of 60 g/L and input voltages ranging from 12 V to 14 V, the results clearly highlight the superior performance of the cross-textured surface. The cross-textured electrode consistently achieved the highest gas production rate across all voltages, with the lowest output current observed on plain surfaces and the highest on cross-textured ones. Temperature measurements revealed that the cross-textured surface led to the highest output temperatures at most voltage levels, particularly at 13 V, 13.5 V, and 14 V, reaching up to 92.58 °C at the maximum voltage. Additionally, the cross-textured surface also delivered the fastest operating times across all tested conditions. These findings emphasize that modifying the electrode plate surface to include a cross-texture design increases surface area, thereby enhancing the HHO generator's performance. In conclusion, the cross-textured surface design is the most effective for maximizing HHO gas production, improving output current and temperature stability, and optimizing operating time.

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