

Original Article

Response Surface Methodology-Based Optimization of Alkaline Water Electrolysis Parameters for Hydrogen Production

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Abstract - This study investigates the key effects of the key operational variables, namely the applied voltage, the electrolyte concentration, and the electrode spacing, on the efficiency of the very hydrogen production through the alkaline water electrolysis process. In this work, the stainless steel electrodes were used as both the anode and the cathode materials in order to ensure the material consistency throughout the experiments. Moreover, the experiments were conducted at atmospheric pressure using aqueous potassium hydroxide (KOH) solutions of varying concentrations. To systematically evaluate the influence of the selected parameters, a full factorial experimental design incorporating the Response Surface Methodology (RSM) was employed. Accordingly, this approach was used to analyze the individual effects as well as the interaction effects of the selected operating parameters on the overall system performance. In addition, the quadratic regression models were developed in order to predict the process responses and to check the statistical importance of the results by using the Analysis of Variance (ANOVA) method with the Minitab 19.1.10 software. In this study, the experimental results showed that the applied voltage and the electrode spacing have an important effect on the hydrogen generation rate and also on the overall system efficiency. It is important to note that higher voltage and smaller electrode spacing were found to improve hydrogen production performance. Furthermore, the increase in the very electrolyte concentration improved the underlying electrical conductivity of the solution and also increased the current density in the electrolysis cell. In addition, based on the optimization results, the best operating conditions were obtained at the higher voltage and the smaller electrode distance, and therefore, this confirms the strong effect of the electrochemical parameters on the water splitting efficiency. The results of the study show a contribution to the development of cost-effective and energy-efficient hydrogen production technologies, especially for clean energy applications.

Keywords - Green hydrogen, Hydrogen production, Alkaline water electrolysis, Renewable energy, Response surface methodology, Experimental optimization.

1. Introduction

The natural energy reserves of the world are decreasing steadily because of the continuous increase in the global demand for energy [1]. In particular, the rapid population growth and the ongoing industrial development have significantly intensified the dependence on natural resources, with nearly 80% of the world's energy consumption still being supplied by fossil fuels, for example, oil, natural gas, and coal [1, 2]. However, these energy resources are finite in nature, with the proven reserves estimated at approximately 891 billion tons of coal, 1,688 billion barrels of oil, and 6,558 trillion cubic feet of natural gas [2]. In addition to the issue of resource depletion, the combustion of fossil fuels continues to remain a major contributor to climate change and air pollution on a global scale.

In response to these pressing challenges, there is a growing and urgent need for energy systems that are not only sustainable but also efficient and environmentally safe. Consequently, the renewable energy sources are receiving an increased level of attention, particularly in the sectors with high energy demand, such as the transportation and industrial sectors.

Among the various renewable options, solar energy is considered to be one of the most abundant and widely available renewable resources. However, the intermittent nature of solar energy limits its direct, continuous utilization, thereby making effective energy storage and energy conversion technologies essential components of modern energy systems.



Hydrogen is widely recognized as a clean and versatile energy carrier, primarily because it produces water as the only by-product during utilization and can be generated from renewable energy sources [2]. Among the available hydrogen production methods, the water electrolysis process is considered a promising technique, particularly when it is powered by renewable energy sources [2]. In simple terms, water electrolysis refers to the process of splitting water into hydrogen and oxygen using electrical energy. Nevertheless, despite the extensive research efforts in this area, the many existing studies have mainly focused on the general system performance or the large-scale applications. As a result, limited attention has been given to the optimization of the electrolysis operating parameters under the specific conditions aimed at achieving improved efficiency and practical implementation.

1.1. Research Gap and Problem Statement

Although water electrolysis has been widely studied, there is still a lack of experimental and comparative analysis on how the key operating parameters affect the hydrogen production performance under controlled conditions. It is important to note that the existing literature does not fully explain the combined effects of these parameters on the efficiency and the system behavior. In addition, it does not clearly support reproducibility or practical design optimization.

1.2. Research Objective and Focus

In this study, the gap is addressed by investigating the influence of the selected electrolysis operating parameters on the hydrogen production performance. It is important to note that the aim of the study is to evaluate system behavior and identify conditions that can improve hydrogen generation efficiency. In addition, the main research focus of the study is: How do changes in key electrolysis parameters affect hydrogen production efficiency and operational performance under controlled conditions?

2. Literature Review

Hydrogen has been widely proposed as a preferred energy carrier for the future energy system [3]. From a chemical point of view, hydrogen is made of two hydrogen atoms, which are joined together by a covalent bond to form hydrogen gas. However, it is key to note that hydrogen is rarely found in its molecular form in the natural environment, and therefore it must be produced through different industrial and electrochemical processes.

As a result, the hydrogen is classified as a secondary energy source or, more specifically, as an “energy vector.” In contrast, the fossil fuel combustion processes release the harmful pollutants into the environment, while the hydrogen combustion process produces water vapor as the only by-product and also gives a higher energy content compared to natural gas [4].

Furthermore, it can be said that the research findings show that hydrogen can be used as a more economical and environmentally friendly energy alternative, and therefore, this supports the growing interest in the advancement of a hydrogen-dependent economy [5]. Although the transition toward the hydrogen-based energy systems may include certain costs and possible risks, it is key to note that the existing studies show that these challenges are much smaller compared to those related to the continued use of the hydrocarbon-based economy. Therefore, hydrogen remains a strong candidate for supporting long-term change in the global energy infrastructure. The environmental advantages of hydrogen are very important; it can reduce CO₂ emissions and also support electricity as a major clean energy source [6]. In addition, the hydrogen and the fuel cell technologies show a great potential for achieving a “green revolution”, actually in the transportation sector, by almost removing the CO₂ emissions. However, it should be noted that the research is still focusing on solving the efficiency and production challenges [7]. Hydrogen plays a key role in the sustainable development of modern energy systems [8]. In particular, when hydrogen is used in fuel cells, it produces electricity, with water as the only by-product [9].

Furthermore, hydrogen is generally considered to be as safe as conventional fuels because of its low density. As a result, the leaked hydrogen gas can spread quickly into the atmosphere, and therefore the risk of accumulation and ignition is reduced. However, although hydrogen can also be produced from different sources, the most common method used today is still the hydrocarbon reforming process, which is known to be not sustainable and also harmful to the environment over the full life cycle of the system [10]. Therefore, there is an increasing interest in the development of cleaner hydrogen production methods. These methods include methane reforming and, more importantly, the water electrolysis process, which can be powered by renewable energy sources such as hydropower, notable wind energy, and solar energy [11]. Consequently, many studies have investigated the hydrogen production from renewable resources [11]. In addition, these studies show that hydrogen has a growing role as an effective energy carrier in the renewable energy storage systems, especially for supporting the integration of the intermittent renewable energy sources into the energy system [12]. Water electrolysis has received a large amount of research attention because of its simple operation, its clean process, and its ability to produce high-purity hydrogen [13]. In fact, this process can produce hydrogen with a purity of up to 99.999 vol%, which makes it very suitable for energy and industrial applications [14]. However, it is key to note that the performance of the electrolysis cell must be carefully improved to increase the overall efficiency of the process.

In addition, hydrogen can also be produced through the photocatalysis or the thermochemical processes that are

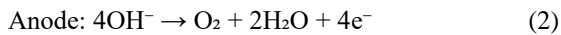
powered by solar energy [15]. Nevertheless, these alternative methods currently suffer from low reaction rates and high operational costs, which limit their practical implementation. Therefore, water electrolysis continues to remain the most promising method for the large-scale production of hydrogen [16].

Among the various electrolysis technologies, alkaline water electrolysis, which employs an aqueous potassium hydroxide (KOH) electrolyte, is widely used for its simplicity, technological maturity, and cost-effectiveness. Despite these advantages, this technology still suffers from drawbacks, such as low current density and limited system efficiency [17]. During the electrolysis process, the hydrogen molecules form on the cathode surface and gradually accumulate until the gas bubbles detach and rise through the electrolyte.

Similarly, oxygen is generated at the anode through the discharge of the hydroxyl ions. As a consequence, the presence of the gas bubbles within the electrolyte can increase the electrical resistance of the solution and, in turn, reduce the overall system efficiency [18].

Furthermore, previous studies have mainly examined how individual operating parameters, including temperature, electrode spacing, and applied current, influence electrolysis efficiency [19]. However, these studies have often considered the parameters in an independent way, and therefore, this limits the understanding of the combined effects of these parameters on the hydrogen production performance.

The basic reactions in the alkaline electrolysis cell are shown in equations (1) and (2):



The hydrogen that is produced at the cathode is collected by using the water displacement method. The efficiency of hydrogen generation can be calculated using equation (3) [20]

$$\text{Efficiency (\%)} = (V_{\text{H}_2,\text{real}} / V_{\text{H}_2,\text{ideal}}) \times 100 \quad (3)$$

Using Faraday's law, the ideal hydrogen volume ($V_{\text{H}_2,\text{ideal}}$) is given by equation 4:

$$V_{\text{H}_2,\text{ideal}} = (I \times V_m \times t) / (2 \times F) \quad (4)$$

where V_m is the molar gas volume at 298.15 K and 1 atm, I is the current (A), t is the ultimate time (s), and F is Faraday's constant (96,485 C/mol). The actual hydrogen volume ($V_{\text{H}_2,\text{real}}$) is determined by correcting the measured gas volume for temperature using equation (5):

$$V_{\text{H}_2,\text{real}} = V_{\text{H}_2}(\text{measured}) \times (T_{\text{standard}} / T_{\text{measured}}) \quad (5)$$

Despite the technological maturity of the alkaline H_2O electrolysis process, the hydrogen production efficiency of the system remains largely suboptimal due to a number of interrelated operational factors, including the electrode spacing, the applied voltage, and the electrolyte concentration. In particular, the accumulation of gas bubbles on the electrode surfaces increases electrical resistance and, at the same time, decreases the system's current efficiency. Furthermore, the inappropriate design or the inadequate control of these parameters can further limit the overall performance of the electrolysis process.

Moreover, most of the existing studies reported in the literature have addressed these operational variables largely in isolation, without adequate evaluation of their combined and interactive influence on the overall system efficiency. The current understanding of the integrated effects of these parameters remains limited [2]. Therefore, there is a strong and clear need for a systematic experimental study to measure and improve the key operational parameters that affect hydrogen generation efficiency in alkaline electrolysis systems. Accordingly, the objective of the present study is to investigate and optimize the effects of the key operational parameters, namely the applied voltage, electrode spacing, and electrolyte concentration, on hydrogen generation efficiency in the alkaline H_2O electrolysis process using stainless steel electrodes [4, 7].

2.1. Novelty and Research Contribution

The previous studies on the alkaline water electrolysis process have mainly focused on the individual operating parameters that include the temperature, the electrolyte type, or the applied current, which are often studied in an independent way and under fixed operating conditions [13, 19, 20]. Although these studies have given some important insights into the specific parts of the hydrogen generation process, it is important to note that they provide only limited guidance on how the multiple operational parameters work together to affect the overall system efficiency. As a result, the practical optimization methods for the alkaline electrolysis systems are still not clearly defined in the existing literature.

In this context, the novelty of the present study lies in the systematic and combined evaluation of the applied voltage, electrode spacing, and electrolyte concentration within a single, unified experimental framework. Unlike the earlier studies, which considered these variables separately, the present study examines their combined effects on the hydrogen generation efficiency. Therefore, this integrated approach makes it possible to clearly identify the interactions of the parameters that affect the gas evolution behavior, the electrical resistance, and the current efficiency of the system.

It can also be noted that such combined and interaction-based analysis is still limited in the previous studies, especially for the small- to medium-scale alkaline electrolysis systems using the stainless steel electrodes. Furthermore, recent review studies have clearly shown the need for improved efficiency and reduced costs in hydrogen production technologies to support large-scale use of hydrogen energy systems [3, 4, 17].

However, many recent experimental studies rely on advanced materials or complex system designs, which may not be economically viable for widespread, practical application. In contrast, the present work advances the field by focusing on the operational optimization using conventional materials and simple cell configurations. As a result, the findings of the study are more directly applicable and relevant for the practical and scalable hydrogen production systems.

2.2. Comparison with Existing and Recent Studies

A comparative analysis with existing research clearly shows that the reported hydrogen production efficiencies are often constrained by high internal resistance, excessive gas bubble accumulation, and suboptimal electrode configurations in electrolysis systems [18, 21]. In particular, studies such as those by [13] and [20] demonstrate that efficiency improvements are achievable through appropriate control of individual operating parameters. However, these studies did not give a detailed evaluation of how the combinations of the operating parameters work together to affect the overall system behavior. As a result, the understanding of the combined effects of the parameters has remained limited in the previous literature. In contrast, the present study builds on the earlier findings by showing that the combined adjustment of the applied voltage, the electrode spacing, and the electrolyte concentration can lead to clear improvements in the efficiency, which are higher than those reported in the single-parameter optimization studies. Therefore, this study provides a more complete knowledge of the operational optimization of the alkaline water electrolysis systems. Furthermore, the recent literature has highlighted the importance of reproducibility and practical relevance in electrolysis research [16, 17].

Accordingly, the experimental design used in the present study focuses on the controlled operating conditions, the clear definition of the parameters, and the reproducible measurement methods. As a result, this structured approach allows the direct comparison with the published results and also gives a clearer explanation of why the improved performance is obtained. Specifically, reduced electrode spacing reduces ohmic losses in the electrolyte, optimized electrolyte concentration improves ionic conductivity, and proper voltage selection reduces excessive gas bubble formation. Taken together, these combined effects improve the hydrogen generation efficiency of the alkaline electrolysis system.

2.3. Advancement of the Field and Research Gap Closure

Although the alkaline water electrolysis is a mature technology, the limitations in the performance still reduce its competitiveness with the other hydrogen production methods [10, 15]. Existing literature acknowledges these limitations but does not sufficiently address how operational optimization alone can improve efficiency without reliance on expensive materials or complex system modifications. This study contributes new knowledge by demonstrating that meaningful efficiency gains can be achieved through careful control of basic operating parameters.

3. Methodology

The design of the research for the test models for the electrochemical water analysis equipment is illustrated in the section that follows. In addition, a general full factorial experimental design was utilized to evaluate the effects of the electrolysis system's operating parameters across a number of experimental runs.

3.1. Experimental Apparatus

A number of experimental test models are created in order to examine the variables influencing hydrogen production through alkaline water electrolysis [4]. The experimental equipment for alkaline water electrolysis is shown in Figure 1. A transformer is typically used in an AC-driven unregulated power supply in order to change the mains voltage to a different and, in most cases, a lower voltage level. Subsequently, a rectifier is employed when a DC output is required from the AC input supply. In addition, to further smooth the voltage signal coming from the rectifier, a capacitor is commonly used within the circuit. It is important to note that, despite the smoothing process, the small periodic variations in the form of ripples may still exist in an otherwise steady direct current. Moreover, the frequency of these pulsations is generally similar to that of the original AC power source.

In practice, the simplest unregulated key DC power supply circuit can be created by connecting a single diode and a resistor in series with the AC supply [11]. As a result, this basic configuration is widely used in low-power applications, such as rechargeable flashlights, where the precise voltage regulation is not strictly required.

An electrode is a fundamental component of an electrochemical cell and is generally classified as either an anode or a cathode [14]. Specifically, the anode is the electrode at which the oxidation reaction occurs, and the electrons leave the cell, whereas the cathode is the electrode at which the reduction reaction takes place and the electrons enter the cell [16]. Depending on the voltage applied to the electrochemical cell, each electrode may actually function as either the anode or the cathode [16]. Furthermore, an electrode capable of functioning as both a cathode and an anode in the two cells is referred to as a bipolar electrode.

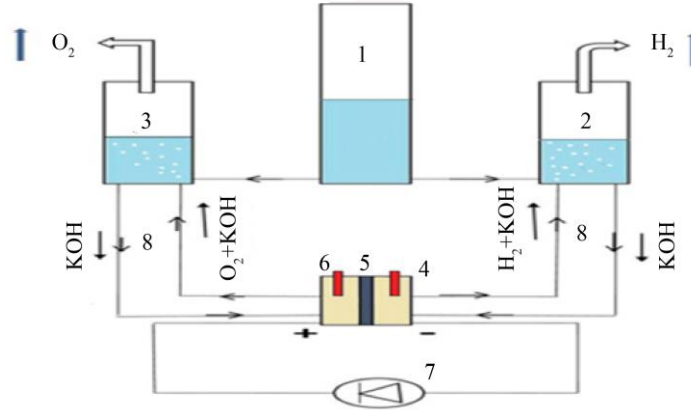


Fig. 1 Experimental apparatus for the alkaline water electrolysis

Where,

1. Electrolyte reservoir, 2. The Hydrogen separator, 3. Oxygen separator, 4. The Cell Assembly, 5. Membrane, 6. Heaters, 7. The DC stabilized power supply, 8. Electrolyte circulation Piping.

3.2. Experimental Design

The test models had Plexiglas plates that measured 30 cm in height, 6 cm in width, and 0.5 cm in thickness. Depending on the distance between the electrodes, 4 test models were created and designated as E1, E2, E3, and E4. Using “Lambda (λ)” to represent the distance between the electrodes, it uses values of 4 mm for the first Experimental (E1), 6 mm for the second, 8 mm for the third, and 10 mm for the fourth model (E4). The solutions’ strengths were 10%, 20%, and 30%, respectively, while the voltage ranged from 2 to 5 volts. Table 1 shows the variables and levels for the general full factorial design.

Before the start of the experiments, all of the system components were carefully positioned and checked to ensure the proper alignment and operation [17]. Thereafter, the electrolyte solution was prepared by dissolving the required amount of potassium hydroxide in the clean water in order to obtain the desired concentration [11]. Once the electrodes were placed inside the electrolysis vessel and the specified electrical voltage was applied, the water electrolysis process was started. Indeed, the process was started in a simple way

and in controlled conditions. During the experiment, the cell voltage, the electrical current, and the water mass were carefully monitored and also recorded within a predetermined time interval, both before and after the test. In fact, the measurements were taken in order to make a clear understanding of the process. After that, the applied voltage was adjusted again so that the electrolysis cell could continue to operate under the same electrolyte concentration condition. Therefore, this was done to ensure consistency in the experimental procedure across different test runs and to make the results more reliable and clear.

In addition, the measurement uncertainties were carefully considered in the analysis of the results. The margins of error associated with the measurements were estimated to be 2% for the mass, 3% for the current (I), and 4% for the voltage (V), which were taken into account during the interpretation of the experimental findings.

3.3. Statistical Analysis

To fit the experimental results, a second-order polynomial equation was selected. This model depicts the interactions between the process variables (supplied voltage, electrolyte strength, and distance between electrodes) and the response variable (hydrogen production rate). The general form of the model is shown in equation 6.

Table 1. Variables and levels for the general full factorial design

Voltage (V)	Concentration (C)%	Gap Between Electrodes (D)			
		4	6	8	10
2	10	2,10,4	2,10,6	2,10,8	2,10,10
	20	2,4,20	2,20,6	2,20,8	2,20,10
	30	2,4,30	2,30,6	2,30,8	2,30,10
3	10	3,10,4	3,10,6	3,10,8	3,10,10
	20	3,20,4	3,20,6	3,20,8	3,20,10
	30	3,30,4	3,30,6	3,30,8	3,30,10
4	10	4,10,4	4,10,6	4,10,8	4,10,10
	20	4,20,4	4,20,6	4,20,8	4,20,10

	30	4,30,4	4,30,6	4,30,8	4,30,10
5	10	5,10,4	5,10,6	5,10,8	5,10,10
	20	5,20,4	5,20,6	5,20,8	5,20,10
	30	5,30,4	5,30,6	5,30,8	5,30,10

$$Y = b_0 + b_1A + b_2B + b_3C + b_{12}AB + b_{13}Ac + b_{23}BC + b_{11}A^2 + b_{22}B^2 + b_{33}C^2 \quad (6)$$

where,

Y is the key predicted response, b_0 is the model constant; b_1 , b_2 , and b_3 are the key linear coefficients; b_{12} , b_{13} , and b_{23} are the key cross product coefficients, and b_{11} , b_{22} , and b_{33} are the key quadratic coefficients. Minitab 19.1.10 statistical program software was used to establish the validity of the key models on the basis of ANOVA.

3.4. Data Sources and Sample Selection

All of the data used in the study were generated experimentally under controlled laboratory conditions. In particular, no secondary data or simulated data were used at any stage of the research. Instead, the primary data consisted of measured electrical parameters, including cell voltage and electrical current, as well as electrolyte properties, electrode configuration details, and the volume of hydrogen gas produced during each experimental run. Collectively, these measurements were the main basis for the calculation of the hydrogen production efficiency and also for the evaluation of the overall system performance. In fact, the measurements were very important for understanding the behavior of the system. With regard to the sample selection, the experiments followed a structured full factorial experimental design in order to ensure a full coverage of the selected operating parameters. Moreover, each experimental run was a unique combination of the applied voltage, electrolyte concentration, and electrode spacing, as shown in Table 1. In addition, the selected parameter ranges were based on the commonly reported values in the alkaline water electrolysis studies and also on the practical operating limits of the laboratory-scale systems. Therefore, this systematic approach ensured that the dataset was a representative dataset, a balanced dataset, and also a dataset that was fully suitable for the subsequent statistical analysis.

3.5. Definition and Control of Experimental Parameters

Three key operating parameters were selected for the investigation because they have a well-known influence on the performance of the alkaline electrolysis process. In fact, these parameters were the applied voltage, the electrolyte concentration, and the electrode spacing. In particular, the applied voltage was varied between 2 V and 5 V in order to cover the minimum electrolysis threshold and also the higher operational voltage levels, while at the same time avoiding the excessive heating and the operational instability of the electrolysis system. Similarly, the potassium hydroxide (KOH) electrolyte concentrations of 10%, 20%, and 30% by weight were selected to represent the low, the medium, and the high ionic conductivity conditions that are commonly used in the alkaline electrolysis systems. In addition, the electrode spacing was varied between 4 mm and 10 mm in order to study its effect on the ohmic resistance and also the gas bubble behavior in the electrolyte solution. Moreover, the

stainless steel electrodes were used in all of the experiments so that the material-based variability can be avoided and the comparability of the results can be ensured. Furthermore, all of the experiments were conducted for the same duration and under similar ambient conditions, and the influence of the external factors on the hydrogen generation process was minimized. Finally, the measurement uncertainties were carefully controlled and also quantified in the experimental analysis. The known error margins were applied to the voltage, the current, and the mass measurements in order to support the reliability and the accuracy of the reported results.

3.6. Reproducibility and Experimental Validity

To ensure the reproducibility of the experimental outcomes, each experimental condition was clearly defined and also carefully executed by following the same procedural steps throughout the whole study. In fact, the electrolyte preparation method, the electrode placement procedure, the voltage application sequence, and the data recording process were all kept the same throughout the entire experimental program. Moreover, the calibration of the measurement instruments was done before the data collection in order to reduce the systematic measurement error and also to improve the accuracy of the recorded data. In addition, the use of a full factorial experimental design also improved the reproducibility because it allowed the independent verification of the individual parameter effects and also the interaction effects among the operating variables. With respect to the data analysis, the statistical modeling approach was carefully selected in order to support the reproducible interpretation of the experimental results. Specifically, the second-order polynomial model made it possible to evaluate both the individual effects and the interaction effects among the selected operating parameters. Furthermore, the model validity was checked by using the ANOVA, and the statistical significance was determined at the standard confidence levels. Therefore, this well-defined methodological structure allows other researchers to repeat the study by using the same parameter ranges and also the same analytical framework.

3.7. Statistical Tests, Assumptions, and Uncertainty Analysis

The experimental data were analyzed using regression analysis and ANOVA to evaluate the effects of operating

parameters on hydrogen production efficiency. In fact, the ANOVA technique was used to determine the statistical significance of the main effects and also the interaction terms included in the second-order polynomial model. Moreover, a confidence level of 95% was used to assess the adequacy of the model and also the significance of the individual parameters. In addition, the statistical analysis was based on standard assumptions, including the normal distribution of the residuals, the independence of the observations, and the constant variance across the experimental runs. These assumptions are commonly used in factorial experimental designs and also in the response surface modeling approaches. Furthermore, the goodness of fit of the very developed model was evaluated by using the coefficient of determination (R^2) together with the very significant values obtained from the ANOVA results[16]. With regard to the measurement uncertainty, this factor was also carefully considered during the data analysis stage. The known error margins of $\pm 2\%$ for mass measurements, $\pm 3\%$ for current measurements, and $\pm 4\%$ for voltage measurements were included in the interpretation of the experimental results to

support the reliability of the findings. As a result, these uncertainty limits were taken into account when comparing hydrogen production efficiency across different operating conditions, thereby ensuring that the observed trends were not solely due to measurement variability.

Finally, the present study was based entirely on the quantitative experimental data. No qualitative data were collected or analyzed. All data processing and statistical evaluation procedures were performed using Minitab 19.1.10, in accordance with standard, widely accepted statistical practices.

4. Results and Discussion

The experimental investigation included a total of 48 experiments. The empirical models showing percentage mass loss as a process responding to the factors were built using the real data gathered from the testing. Table 2 displays the test findings that were collected.

Table 2. Design matrix and the results of the general full factorial design

Run Order	Voltage	Concentration	Distance	Mass Loss
1	5	20	4	3.3
2	4	20	8	1.63
3	2	30	6	0.86
4	2	10	4	0.50
5	4	10	6	1.50
6	4	30	10	2.20
7	4	30	4	2.84
8	3	10	8	0.77
9	2	20	4	0.72
10	4	10	4	2.01
11	2	10	10	0.31
12	2	10	6	0.46
13	4	10	8	1.46
14	5	10	4	2.99
15	5	10	6	2.82
16	3	20	8	1.48
17	3	20	6	1.76
18	5	30	4	4.01
19	3	30	8	2.13
20	3	20	10	1.89
21	4	20	6	1.97
22	3	10	4	0.98
23	5	10	10	1.65
24	4	20	4	2.08
25	4	30	8	2.45
26	5	20	8	3.13
27	5	10	8	2.70
28	3	20	4	1.89
29	2	30	4	0.92
30	5	20	10	2.98
31	2	30	10	0.63

32	5	30	8	3.61
33	5	20	6	3.22
34	3	10	6	0.89
35	2	20	6	0.63
36	4	10	10	1.01
37	2	10	8	0.39
38	4	30	6	2.70
39	2	30	8	0.74
40	3	30	6	2.25
41	2	20	8	0.42
42	2	20	10	0.38
43	3	10	10	0.72
44	5	30	6	3.82
45	3	30	4	2.49
46	3	30	10	2.07
47	5	30	10	3.38
48	4	20	10	1.57

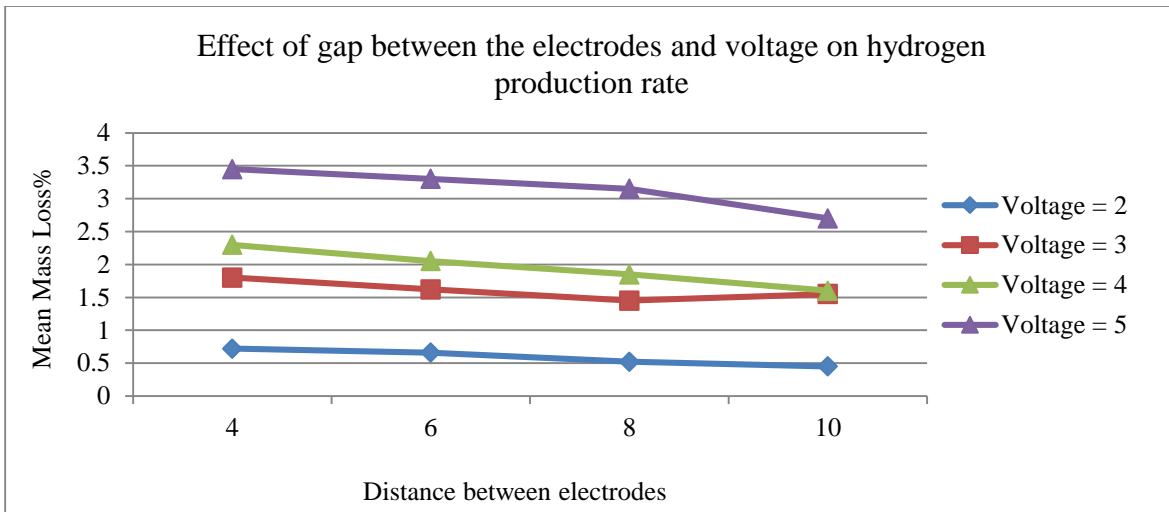


Fig. 2 Interaction plot showing the combined effect of applied voltage (2–5 V) and electrode spacing (4–10 mm) on hydrogen production rate, expressed as percentage water mass loss, at a fixed electrolyte concentration of 20% KOH

4.1. Operating Parameters

This section examines how the hydrogen generation process is impacted by the gap size between the two electrodes and the potassium hydroxide concentration. 4 distinct gaps were looked at in order to have a thorough grasp of how the distance between the two electrodes affects the rate of hydrogen production [2, 6]. The pair of electrodes was subjected to DC voltages ranging from 2 to 5 volts throughout each test. Additionally, several electrolyte solution concentrations were examined.

4.2. Effects of the Gap between the Two Electrodes

The experimental results summarized in Table 2 clearly show that hydrogen production increases with applied voltage and reduced electrode spacing. In particular, Figure 2 illustrates the rate of the hydrogen synthesis as a function of the given input voltage at the various electrode spacing values and at a fixed potassium hydroxide concentration of 20%

(that is, the solution strength expressed as a percentage of the solute by mass in the solution). In this case, the hydrogen production rate is expressed as the percentage loss in the water cell mass [1, 3].

Furthermore, Figure 3 demonstrates how the magnitude of the applied voltage at the electrode terminals has a significant impact on the percentage loss of the water mass. Specifically, when the applied voltage is increased, a greater amount of the mass is lost while the distance between the two electrodes remains constant.

This behavior can be explained by the corresponding increase in the electrical current flowing through the electrolyte, which results from the higher voltage level. As a consequence, the increase in the electrical current directly leads to the observed rise in the percentage of mass loss.

In addition, the results presented in Figure 2 indicate that the proportion of mass lost is partially dependent on the distance between the two electrodes [8]. More specifically, the percentage of the water mass loss increases as the distance between the electrodes decreases[8]. This trend occurs because the reduction in the electrode spacing leads to a corresponding decrease in the electrical resistance between the electrodes, which in turn causes an increase in the electrical current. Therefore, at the higher input voltage levels, it becomes clear that the reduced distance between the electrodes significantly enhances the rate at which the hydrogen is produced.

Finally, the response surface plot shown in Figure 3 provides a comprehensive visualization of how the combined effects of the applied voltage and the electrode gap influence the water electrolysis process and, consequently, the hydrogen production performance[11].

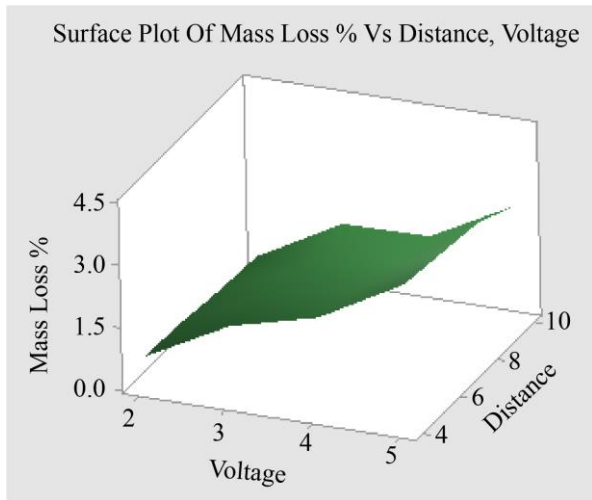


Fig. 3 The response surface plot representing the effect of the gap between the electrodes and supplied voltage on water electrolysis

4.3. Effects of Solution Strength on Water Mass Loss

As shown in Figure 2, decreasing electrode spacing significantly increases hydrogen production at higher voltages. Figures 4 and 5 show how the concentration of potassium hydroxide in the key electrolyte solution affects system performance[3].

Figure 4 shows that the rate of hydrogen production increases progressively with the increase in the concentration of the potassium hydroxide in the key electrolyte solution.

In general, this behavior can be explained by the corresponding increase in the electrical conductivity of the solution, which is directly brought about by the higher potassium hydroxide concentration.

As a result, across all investigated experimental models, an increase in electrical conductivity leads to a higher electrical current flowing through the electrolyte, thereby resulting in an overall increase in the hydrogen production rate.

Furthermore, Figure 5 presents the response surface plot, shown in the wire-frame form, which clearly illustrates how the concentration of the key potassium hydroxide influences the rate of the water mass loss during the electrolysis process[5].

Taken together, these graphical results show the important role of electrolyte concentration in controlling the electrochemical performance and hydrogen generation efficiency of the alkaline water electrolysis system. In fact, the electrolyte concentration is a very important factor for the overall behavior of the system.

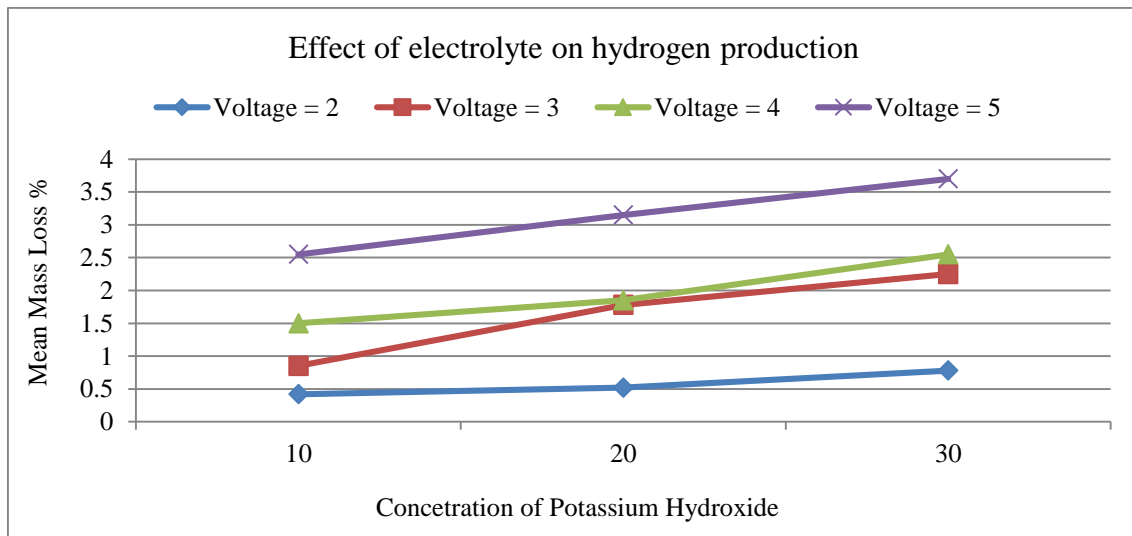


Fig. 4 Effect of potassium hydroxide concentration on the rate of water mass lost

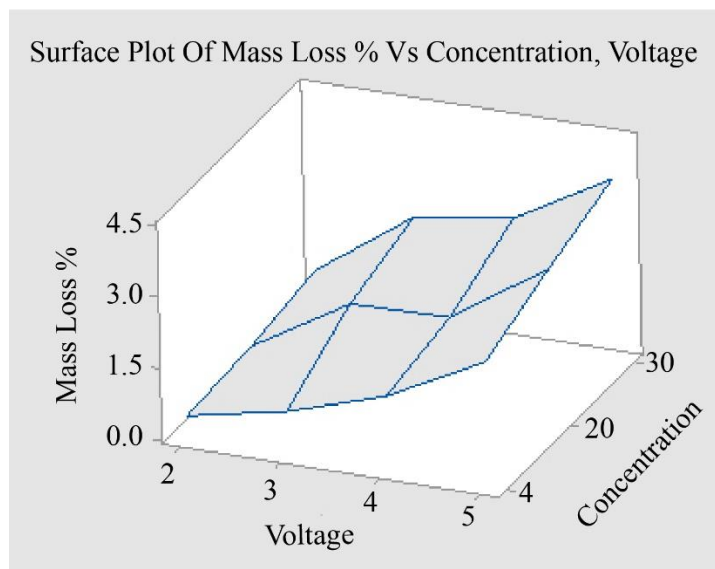


Fig. 5 The response surface plot representing the effect of potassium hydroxide concentration on the rate of water mass lost

5. Discussion

In this study, the observed improvement in the hydrogen production at the reduced electrode spacing can be clearly explained by the reduction in the ohmic resistance in the electrolyte solution. In particular, the shorter distance between the electrodes reduces the ionic path length, and therefore, this results in a higher current density and also an improved electrolysis efficiency. Therefore, this behavior is in agreement with the basic electrochemical theory and also shows a close similarity with the findings reported by [13, 18].

When it is compared with the previous studies, which mainly investigated the individual operating parameters separately, the present study shows that the combined optimization of the applied voltage, the electrolyte concentration, and the electrode spacing gives a better hydrogen production performance. On the other hand, unlike the methods that depend on the advanced materials or the complex system designs, this method uses the normal stainless steel electrodes to achieve improved efficiency. As a result, the proposed method becomes more practical and also more suitable for real-world and scalable hydrogen production applications.

In addition, it is also important to note that the experimental results show that an increase in the key electrolyte concentration improves the ionic conductivity of the solution, and this helps to improve the charge transport and the hydrogen evolution process [6]. However, at the same time, a very high electrolyte concentration can also bring some operational problems, such as a higher corrosion rate and the excess heat generation. Therefore, it is clear that there is a need for a balanced optimization of the electrolyte concentration so as to achieve a good performance without affecting the stability of the system.

6. Conclusion and Recommendations

6.1. Conclusion

The study examined the effects of applied voltage, electrolyte concentration, and electrode spacing on hydrogen production efficiency, which is achieved through the alkaline water electrolysis process using stainless steel electrodes. In order to do this, a full factorial experimental design together with the RSM was used. Accordingly, the empirical models were developed to describe and also to analyze and optimize the relationships between the selected operating parameters.

The experimental results clearly showed that higher applied voltage and reduced electrode spacing can significantly increase the hydrogen production rate. At the same time, it is also observed that an increase in the electrolyte concentration improves the electrical conductivity of the solution and, therefore, improves the overall key efficiency of the system. Furthermore, the statistical analysis confirmed that all of the selected operating parameters had a notable influence on the hydrogen output, with the strong interactive effects observed among them. Based on the optimization results, the optimal operating conditions were achieved at approximately 5 V, 20–30% potassium hydroxide (KOH) concentration, and 4–6 mm electrode spacing.

Overall, the findings confirm that the process optimization using the RSM is an effective and reliable approach for improving the performance of the alkaline electrolysis systems. In this regard, the present study contributes to the development of sustainable, energy-efficient hydrogen production technologies aligned with global clean energy goals. However, although the optimized operating conditions demonstrated improved hydrogen production efficiency, the findings of the study are limited to the laboratory-scale experiments conducted under controlled

conditions. Therefore, the results should be interpreted within this context, and the direct industrial application of the proposed approach requires further validation through pilot-scale or large-scale studies.

6.2. Recommendations

Based on the findings of this study, the following recommendations are proposed:

1. The optimized parameters should be validated at pilot or industrial scale to assess performance under practical operating conditions and confirm the scalability of the developed models.
2. Further research should investigate alternative electrode materials or surface treatments that can improve catalytic activity, corrosion resistance, and long-term stability.
3. The optimized electrolysis system should be integrated with renewable energy technologies, such as solar or wind power, to enable sustainable, carbon-free hydrogen production.
4. Future studies should also examine the long-term stability of the electrodes, the degradation of the electrolyte, and the durability of the system during continuous operation, so as to evaluate the commercial feasibility of the system.

References

- [1] Mikael Höök, and Xu Tang, "Depletion of Fossil Fuels and Anthropogenic Climate Change: A Review," *Energy Policy*, vol. 52, pp. 797-809, 2013. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [2] N. Abas, A. Kalair, and N. Khan, "Review of Fossil Fuels and Future Energy Technologies," *Futures*, vol. 69, pp. 31-49, 2015. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [3] Kai Zeng, and Dongke Zhang, "Recent Progress in Alkaline Water Electrolysis for Hydrogen Production and Applications," *Progress in Energy and Combustion Science*, vol. 36, no. 3, pp. 307-326, 2010. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [4] Ibrahim Dincer, "Green Methods for Hydrogen Production," *International Journal of Hydrogen Energy*, vol. 37, no. 2, pp. 1954-1971, 2012. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [5] Inga Schulte, David Hart, and Rita van der Vorst, "Issues Affecting the Acceptance of Hydrogen Fuel," *International Journal of Hydrogen Energy*, vol. 29, no. 7, pp. 677-685, 2004. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [6] Magdalena Momirlan, and T.N. Veziroglu, "The Properties of Hydrogen as Fuel Tomorrow in Sustainable Energy Systems for a Cleaner Planet," *International Journal of Hydrogen Energy*, vol. 30, no. 7, pp. 795-802, 2005. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [7] C. Koroneos et al., "Life Cycle Assessment of Hydrogen Fuel Production Processes," *International Journal of Hydrogen Energy*, vol. 29, no. 14, pp. 1443-1450, 2004. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [8] Leonardo De Silva Muñoz et al., "Hydrogen Production by Electrolysis of a Phosphate Solution on a Stainless Steel Cathode," *International Journal of Hydrogen Energy*, vol. 35, no. 16, pp. 8561-8568, 2010. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [9] Seth Dunn, "Hydrogen Futures: Toward a Sustainable Energy System," *International Journal of Hydrogen Energy*, vol. 27, no. 3, pp. 235-264, 2002. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [10] P.P. Edwards et al., "Hydrogen and Fuel Cells: Towards a Sustainable Energy Future," *Energy Policy*, vol. 36, no. 12, pp. 4356-4362, 2008. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [11] A. Balabel, I.M. Sakr, and K. Ibrahim, "Potential of Renewable Hydrogen Production Technologies for Energy Requirements in Egypt," *Proceedings of the Seventh Conference of Egyptian Rural Development: Water, Energy and Rural Development, Faculty of Engineering*, pp. 13-15, 2009. [[Google Scholar](#)]
- [12] W.G. Colella, M.Z. Jacobson, and D.M. Golden, "Switching to a U.S. Hydrogen Fuel Cell Vehicle Fleet: The Resultant Change in Emissions, Energy Use, and Greenhouse Gases," *Journal of Power Sources*, vol. 150, pp. 150-181, 2005. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]

Ethics, Transparency, and Compliance

This study did not involve human participants or animal subjects; therefore, ethical approval was not required. The authors declare no conflicts of interest and received no external funding for this research. All cited references were selected based on relevance to the study topic, and no author or journal self-citations were included. The manuscript was prepared in accordance with the journal's ethical and formatting guidelines.

Data Availability

The data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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- [13] Øystein Ulleberg et al., “Modeling of Advanced Alkaline Electrolyzers: A System Simulation Approach,” *International Journal of Hydrogen Energy*, vol. 28, no. 1, pp. 21-33, 2003. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [14] S. Srinivasan, and F.J. Salzano, “Prospects for Hydrogen Production by Water Electrolysis to be Competitive with Conventional Methods,” *International Journal of Hydrogen Energy*, vol. 2, no. 1, pp. 53-59, 1977. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [15] Kaveh Mazloomi, and Chandima Gomes, “Hydrogen as an Energy Carrier: Prospects and Challenges,” *Renewable and Sustainable Energy Reviews*, vol. 16, no. 5, pp. 3024-3033, 2012. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [16] Belkhir Negrou et al., “Valuation and Development of the Solar Hydrogen Production,” *International Journal of Hydrogen Energy*, vol. 36, no. 6, pp. 4110-4116, 2011. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [17] Alfredo Ursua, Luis M. Gandia, and Pablo Sanchis, “Hydrogen Production from Water Electrolysis: Current Status and Future Trends,” *Proceedings of the IEEE*, vol. 100, no. 2, pp. 410-426, 2012. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [18] M. Hassen Sellami, and K. Loudiyi, “Electrolytes Behavior during Hydrogen Production by Solar Energy,” *Renewable and Sustainable Energy Reviews*, vol. 70, pp. 1331-1335, 2017. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [19] R. Domga, G.B. Noumi, and J.B. Tchatchueng, “Study of Some Electrolysis Parameters for Chlorine and Hydrogen Production using a New Membrane Electrolyzer,” *International Journal of Chemical Engineering and Analytical Science*, vol. 2, no. 1, pp. 1-8, 2017. [[Google Scholar](#)]
- [20] M. Sakr et al., “Experimental Investigation into Hydrogen Production Through Alkaline Water Electrolysis,” *Engineering Research Journal*, vol. 34, no. 1, pp. 37-41, 2011. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [21] H.B Suffredini et al., “Recent Developments in Electrode Materials for Water Electrolysis,” *International Journal of Hydrogen Energy*, vol. 25, no. 5, pp. 415-423, 2000. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]