Larhyss Journal, ISSN 1112-3680, n°59, Sept 2024, pp.85-100
© 2024 All rights reserved, Legal Deposit 1266-2002

EXPERIMENTAL ANALYSIS AND PARAMETRIC INVESTIGATION OF WATER ELECTROLYSIS PROCESS FOR HYDROGEN GAS PRODUCTION

AMBALIYA SANJAY D.[1*], DHIMAN VIJAY D.[2], MISTRY MANISH K.[2]

[1] Dr S. & S.S. Ghandhy Government Engineering College, Department of Mechanical Engineering, Surat, India
[2] Government Engineering College, Department of Mechanical Engineering, Valasad, India

(*) s.ambaliya1981@gmail.com

Research Article – Available at http://larhyss.net/ojs/index.php/larhyss/index
Received May 3, 2024, Received in revised form August 28, 2024, Accepted September 2, 2024

ABSTRACT

Vehicles and small-scale power generation systems rely on petroleum-based fuels, known as hydrocarbons (HC). When these hydrocarbons burn, they release gases such as CO_2, CO, HC, and NOx, which can have adverse effects on both the environment and human health. Hydrogen gas, generated through water electrolysis, offers a promising alternative to hydrocarbon-derived fuels. This article delves into an experimental investigation focused on H_2 gas production using water electrolysis. The primary objective is to explore the influence of alkaline electrolytic cell operating parameters on hydrogen gas production, cell efficiency, and power consumption. Stainless steel SS316 serves as the electrode material, while potassium hydroxide (KOH) acts as the aqueous electrolyte solution. Operating parameters such as electrolyte concentration (m), electrolyte temperature (°C), and distance between electrodes (mm) are carefully chosen to analyse their impact on reducing power usage. The Taguchi approach, facilitated by MINITAB software, is employed for experiment design selection, with the Signal-to-Noise (S/N) ratio guiding the determination of the optimal operating parameters. Through ANOVA (analysis of variance), the individual contribution of each operating parameter to power utilization is assessed. A regression equation is formulated to predict hydrogen production rate, cell efficiency, and power consumption. Experimental data is compared with predicted values to validate the regression equation's accuracy.

Keywords: Water electrolysis, Hydrogen production, MINITAB, ANOVA

INTRODUCTION

For several decades now, one of the most important worldwide challenges has been environmental pollution (Adjagodo et al., 2016; Hounkpe et al., 2017; Baba Hamed, 2021). The use of fossil fuels is increasing, which is causing environmental problems such air pollution, sea level rise, global warming, and ecological degradation. According to the Intergovernmental Panel on Climate Change (IPCC), if greenhouse gas emissions are not reduced, the sea level is predicted to rise by 6.4 m and the global mean temperature to climb by 4.8 °C by 2100 (Collins et al..,2013; Church et al., 2013). IPCC is an intergovernmental panel, established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in 1988. All nations that have ratified the United Nations Framework Convention on Climate Change (UNFCC) have committed to restricting the rise in global temperatures to less than 1.5 °C, as per the terms of the 2015 Paris Climate Agreement (Collins et al., 2013). New technologies that do not contribute to CO_2 emissions are crucially needed to address the growing energy demands while mitigating climate change. Recognizing this imperative, a multitude of academics are actively investigating the energy controversy and proposing various approaches to tackle it. These researchers are dedicated to developing innovative solutions that can provide sustainable and environmentally-friendly sources of energy (Goran and Jelisavka, 2016; Da Silva Veras et al., 2017; Shah et al., 2023).

New CO_2 emission-free solutions must be developed due to the growing need for energy. Several more recent and green energy-related technologies are being developed by numerous academics and researchers. Hydrogen will play a central role in decarbonisation of the society. The analysis shows that availability of clean energy is the fundament of continued economic growth (Moussi et al., 2003; Espegren et al., 2021; Debbache and Derfouf, 2018). It has been suggested that the ideal fuel for this next energy system is hydrogen (Zeng et al., 2010). Two hydrogen atoms bound together by a covalent bond make up hydrogen gas. According to earlier research, employing hydrogen as an energy source could be far less expensive and cleaner. To develop a hydrogen economy, there are numerous reasons. This economy may offer a significant buffer against issues linked to energy. There are reportedly expenses and hazards associated with quickly developing this economy, but these diminish in comparison to the long-term risks of sticking with the petroleum economy (Dunn, 2002).

Around 94% of the hydrogen gas produced worldwide comes from fossil sources. According to Bodner et al. (2015), the bulk of hydrogen is created utilising fossil fuel-based processes including partial oxidation (up to 96%) and steam reforming, both of which result in the creation of CO_2 and other noxious pollutants. Hydrogen can also be produced using water electrolysis, photo catalysis, and thermochemical cycles, which are non-fossil fuel methods. Electrolysis, although an old process, faced challenges in terms of economic viability and efficiency in the twentieth century. However, in recent times, there has been a renewed interest in utilizing electrolysis for specific purposes, particularly in hydrogen production. Many researchers are actively involved in improving the electrolysis process by exploring new avenues such as developing advanced electrodes, enhancing the quality of electrolytes, and discovering novel electrocatalysts.

These advancements aim to overcome the limitations of traditional electrolysis and make it a more efficient and viable method for hydrogen generation. However, electrolysis process still produces just 4% of hydrogen compared to other ways (Dincer et al., 2015).

WATER ELECTROLYSIS PROCESS

Three forms of electrolysis can be distinguished based on the electrolyte employed: solid oxide electrolysis (SOEC), proton exchange membrane electrolysis (PEMEC), and alkaline water electrolysis (AWE). The most developed and proven technique among these is the AWE, which makes use of an aqueous (usually KOH, NaOH) solution electrolyte and continues to be improving (Rashid et al., 2015). Numerous scientists and researchers have shown interest in water electrolysis due to its simplicity, ecological cleanliness, and ease of maintenance (Hosseini et al., 2016). This process yields hydrogen with a high purity of 99.99 Vol% (Ursua et al., 2011). A high performance is needed from the water electrolysis cell in order to increase its efficiency.

Principle of water electrolysis process

Hydrogen production by alkaline water electrolysis is very mature technology among all type of electrolysis. Alkaline water electrolysis is simplest in construction, easiest in operation and eco-friendly method. Alkaline water electrolysis uses an aqueous solution (usually NaOH or KOH) as an electrolyte with a concentration of 25% to 40% wt. The operation is mostly carried out at room temperature and pressure. Temperature and pressure ranges are 30°C - 90°C and 1-30 bar, respectively. At the cathode, $H_2 + OH^-$ is liberated, whereas at the anode, O_2 is liberated. (Ursua et al., 2011). Here's a breakdown of the process:

Hydrogen evolution reaction: $2H_2O + 2e^- \rightarrow H_2 + OH^-$ (1)

Oxygen evolution reaction: $4OH^- \rightarrow O_2 + 2H_2O + 4e^-$ (2)

Final reaction: $H_2O \rightarrow H_2 + \frac{1}{2}O_2$ (3)

The efficiency of water electrolysis depends on various factors, including the voltage applied, the type of electrolyte used, the design of the electrolytic cell, and the condition of the electrodes (Bouaouine et al., 2015; Achour and Chabbi, 2017). Additionally, the process can be optimized by controlling parameters such as temperature, pressure, and electrode materials to enhance hydrogen production while minimizing energy consumption.

Alkaline water electrolysis (AWE) has the potential for producing hydrogen on a large scale, has superior gas purity and energy efficiency (Haug et al., 2017) to other electrolyzers mainly because the electrode material and electrolyte are more readily available and less expensive (Schalenbach et al., 2018). The effect of electrode composition, the electrolyte concentration, the voltage and amperage applied on volume of hydrogen produced are experimentally investigated. The results showed that the performance of alkaline water electrolysis is significantly affected by these various factors (Ezzahra Chakik et al., 2017). Numerous experimental investigations have demonstrated the significant impact of these elements on the electrolysis cell's performance. Several of these investigations showed that:

- Reducing the distance between electrodes during water electrolysis was discovered to be the ideal condition for hydrogen generation. (Nagai et al., 2003)
- When low quantities of an ionic liquid, such as electrolyte, are used along with low carbon steel as the electrode material, water electrolysis can effectively create hydrogen (De Souza et al., 2007).
- Potassium hydroxide KOH, is an electrolyte that improves hydrogen generation (Sellami et al., 2017).

There are several metals that are suggested and employed in the case of electrodes. These metals must have the following qualities when chosen: minimal overvoltage, strong resistivity against corrosion, and maximum activity. Noble metals like platinum and gold are well known to be the best cathode materials in conventional electrolysis cells (Mazloomi et al., 2012). However, transition metals were experimented with as a substitute for these noble metals owing to their high cost. Therefore, there is a financial gain when non noble metals like Ni or Fe are used for the electrode (Cossar et al.,2019). In this regard, the AWE now holds the largest market share in the practical field (David et al.,2018). Hydrogen bubbles are recognized to influence energy, mass transfer and reaction efficiency in gas-evolving electrodes (Avci et al., 2022). Nevertheless, the current investigation does not take into account the dynamics of hydrogen gas bubbles or how they migrate across the electrodes during the alkaline electrolysis process.

It is clear from the aforementioned findings that the majority of researchers have made an effort to compare the operational parameters (electrolyte concentration, electrode gap, and electrolyte temperature etc.) by holding one parameter constant while examining the effects of changing the other variables. For the generation of hydrogen gas, researchers have only looked at one parameter and conducted a comparative analysis.

MATERIALS AND METHODS

This research work presents the experimental investigation on producing H_2 gas through alkaline water electrolysis. The objective of this work is to explore the effect of alkaline electrolytic cell operating parameters on hydrogen gas production, Cell efficiency, and Power consumption. As an electrode, stainless steel SS316 is employed, and potassium hydroxide is used as an aqueous electrolyte solution. Electrolyte concentration (m), electrolyte temperature (°C), and distance between electrodes (mm) are selected as operating parameters for analyzing and assessing the electrolytic cell performance. To determine the interactive impacts of several linked parameters, the Taguchi L^9 experimental design tool was employed (Moosa et al., 2021; Golakiya et al., 2022). Using MINITAB software, the experiment design is selected by the Taguchi approach and the

S/N ratio is used to determine the best operating parameter, that optimize power consumption during hydrogen production. The adopted methodology for this investigation is depicted in a flowchart in Fig. 1.

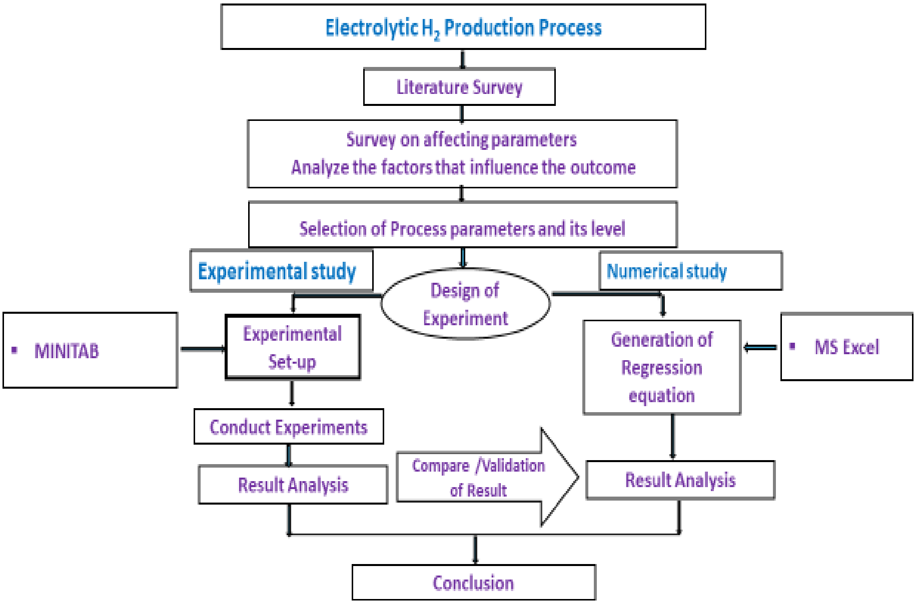

Figure 1: Flowchart of adopted methodology for this study

Taguchi Design Method

Taguchi proposed an experimental design in which the process parameters and their appropriate levels are arranged using orthogonal arrays. Unlike testing every conceivable combination, the Taguchi approach just evaluates pairs of combinations. This makes it possible to get the information required to identify the variables that have the most impact on process with the least amount of experimentation, saving time and money. Independent variables considered for the experiment are concentration of electrolyte, temperature of electrolyte and distance between electrodes. Three levels for each parameter are considered based on literature survey. Table 1 shows independent parameters and their levels.

Table 1: Control parameters

Parameter	Level 1	Level 2	Level 3
Concentration of electrolyte (m)	0.1m	0.3m	0.5m
Temperature of electrolyte (°C)	30°C	50°C	70°C
Distance between electrodes (mm)	1mm	3mm	5mm

Total 27 numbers of experiments with full factorial design of experiment (DOE) are to be performed, but number of experiments is reduced to 9 by using orthogonal array. MINITAB software is used to carry out Taguchi based Design of Experiment. Based on three factors with three level for DOE matrix, Taguchi L^9 orthogonal array is selected to reduce number of experiments. The resultant DOE matrix using is tabulated in Table 2.

Table 2: Design of Experiment Matrix

Sr. N°.	Concentration of Electrolyte (m)	Temperature of Electrolyte (°C)	Distance between Electrodes (mm)
1	0.1	30	1
2	0.1	50	3
3	0.1	70	5
4	0.3	30	3
5	0.3	50	5
6	0.3	70	1
7	0.5	30	5
8	0.5	50	1
9	0.5	70	3

Material and instruments

Various materials and instruments used in the current experiment are shown in Fig. 2.

Figure 2: Material and instruments

Potassium hydroxide (KOH) in pallet form and sample size 5.6 gm is selected for electrolyte solution due to its stability, high conductivity, less degradation effect on most of the electrodes compare to NaOH (Sakr et al., 2011; Mahrous et al., 2011) and easily availability. Demineralized water with 0.03 TDS (total dissolved saults) is used to obtain desired concentration of electrolyte.

Stainless steel of grade SS316 is selected (Ahmad et al., 2024) because it gives less degradation, high hydrogen generation and high activity compare to mild steel and carbon electrodes. Dimension of electrode is decided on a basis of manufacturing limits and space available inside vessel. Total 10 number of plates selected as an electrode with dimension of 4×(45mm×140mm), 4×(55mm×140mm) and 2×(63mm×140mm) (Sakr et al, 2011; Symes et al. 2015).

Partially transparent airtight container is used as a hydrogen generator with pressure capacity up to 5 bar.

Sealed Lead Acid (SLA) battery is used as a DC power source for the electrolytic process (Battery specification Capacity: 12 V Battery rating: 35 Ah).

Electronic thermometer is used to measure temperature of electrolyte with range of -50°C to +300°C and accuracy of ± 0.1°C.

EXPERIMENTAL SETUP

Based on selection of various materials for electrolytic hydrogen production, series of experiments were carried out at atmospheric pressure (assuming constant pressure) as per Design of Experiment by varying electrolyte concentration (m), temperature (°C), and distance between electrodes (mm).

Figure 3: Experiment setup

Readings of voltage and current are measured using an electrical multimeter. The temperature of the electrolyte is measured and a video of the volume measuring set up taken by *vlc* media player to determine the production rate (ml/sec) of gas generated within the electrolytic cell.

Experimental Hydrogen production rate (gm/s), efficiency, and power consumption is evaluated for all experiments. Using MINITAB software, the S/N ratio for power consumption is calculated based on the lower the better criteria. Graphical representation of results obtained are presented.

ANOVA (analysis of variance) approach is used to identify the individual contribution of selected parameters. The purpose of applying ANOVA is to acquire individual percentage contributions of parameters that affect power consumption.

Regression equation for hydrogen production rate and power consumption is generated to predict the output. The regression equation is validated by comparing experimental results and predicted results.

RESULTS AND DISCUSSION

Series of experiment are carried out as per Design of Experiment matrix parameter combination. The readings of generated voltage (v), electrical current (A) and time required to fill 600 ml container by hydrogen gas at 1atm is tabulated as shown in Table 3. The hydrogen production rate in (g/sec), process efficiency, and power consumption are calculated based on the experimental results as shown in Table 4.

MINITAB software is utilised to conduct the analytical study and perform various calculations and obtain graphical results. As the purpose of this study is to reduce power usage, the S/N ratio was calculated using the smaller-is-better criterion as shown in Table.5.

Table 3: Experiment data of voltage, current and time

Sr. no.	Concentration of Electrolyte (m)	Temperature of Electrolyte (°C)	Distance Between Electrodes(mm)	voltage (v)	Current (A)	Time Requiredto Fill 600ml (sec)
	Input parameters			**Output parameters**		
1	0.1	30	1	12	8.80	39.81
2	0.1	50	3	12	10.50	33.357
3	0.1	70	5	12	11.60	30.394
4	0.3	30	3	12	11.50	30.567
5	0.3	50	5	12	11.80	29.947
6	0.3	70	1	12	14.00	25.495
7	0.5	30	5	12	12.50	29.46
8	0.5	50	1	12	14.00	26.388
9	0.5	70	3	12	14.80	24.596

Table 4: H_2 production rate, efficiency and power consumption

Sr. no.	Hydrogen Production Rate (ml/sec)	Hydrogen Production Rate (g/sec)	Efficiency	Power Consumption (kW/gram)
1	10.0477	0.00090	0.835	e
2	11.9915	0.00108	0.835	116.905
3	13.1605	0.00118	0.841	117.680
4	13.0860	0.00118	0.838	117.330
5	13.3569	0.00120	0.842	117.949
6	15.6894	0.00141	0.851	119.136
7	13.5777	0.00122	0.878	122.914
8	15.1584	0.00136	0.881	123.308
9	16.2628	0.00146	0.868	121.502

Table 5: S/N ratio for power consumption

Sr. no.	Concentration of Electrolyte (m)	Temperature ofElectrolyte (°C)	Distance Between Electrodes (mm)	Power Consumption (kW/gram)	S/N Ratio
1	0.1	30	1	116.9319092	-41.3191
2	0.1	50	3	116.9053738	-41.3732
3	0.1	70	5	117.6803738	-41.4141
4	0.3	30	3	117.3299399	-41.3731
5	0.3	50	5	117.9487984	-41.4486
6	0.3	70	1	119.1355140	-41.5084
7	0.5	30	5	122.9138852	-41.7781
8	0.5	50	1	123.3084112	-41.8074
9	0.5	70	3	121.5022697	-41.6682

It is clear from the Table 5 that the 8th number of experimental parameters result in lower power consumption. Thus, optimal parameters achieved for reduced power consumption are 0.5 m concentration of electrolyte, 50°C temperature of electrolyte, and 1 mm distance between electrodes for selected water electrolysis hydrogen production cell.

MINITAB programme generates graphs based on S/N ratio values.

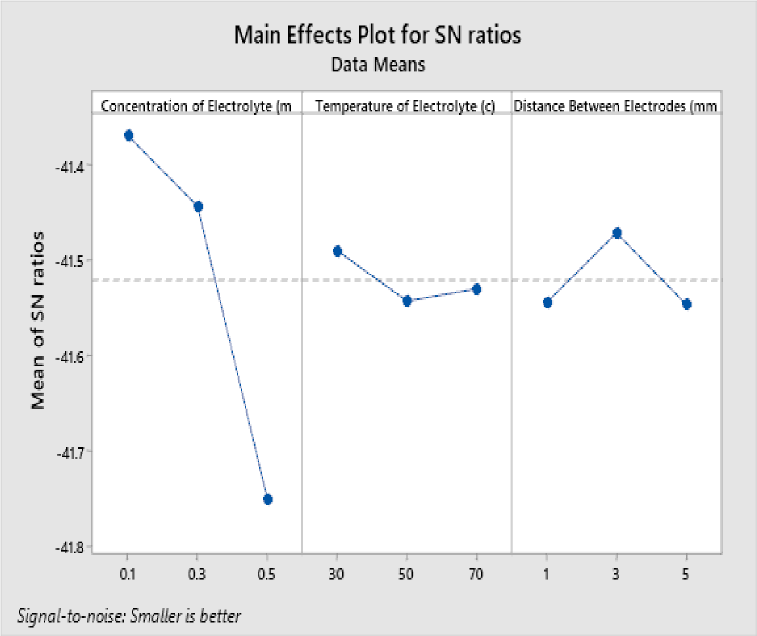

Figure 4: Main Effects Plot for S/N ratios

The S/N ratios at each level of a factor are plotted in a main effects plot (Fig. 4). These plots are used to compare the magnitudes of the various primary effects and their relative strength across parameters. From the graphical results it is evident that the power consumption reduces when, concentration of electrolyte and temperature of electrolyte increases. But as distance between electrodes decreases, the power consumption reduces. Some temperature inconsistencies are related to the relationship between electrode distance and electrolyte temperature.

A response Table 6 is prepared to determine the impact of chosen parameters on power usage. However, the tabulated response only displays the rank of the parameters, not their individual contributions.

Table 6: Response Table for S/N ratio

Level	Concentration of Electrolyte (m)	Temperature of Electrolyte (°C)	Distance Between Electrodes (mm)
1	-41.37	-41.49	-41.54
2	-41.44	-41.54	-41.47
3	-41.75	-41.53	-41.55
Delta	0.26	0.19	0.09
Rank	1	2	3

Table 6 shows that, the concentration of electrolyte has the greatest impact on power consumption value, while the distance between electrodes has the least impact.

In addition, Individual parameters contribution was determined ANOVA approach. ANOVA is a statistical approach for drawing major findings from experimental data analysis. This technique is extremely effective for determining the level of significance of a factor's influence or interaction with other factors on a specific response. It divides the entire response variability into separate contributions from each factor as well as the error.

Table 7: Analysis of Variance for S/N Ratios

Source	DF	Adj SS	Adj MS	P-Value	Contribution
Concentration of Electrolyte (m)	2	26.5688	13.4835	0.035	51.47%
Temperature of Electrolyte (°C)	2	16.8590	8.4178	0.239	32.66%
Distance Between Electrodes (mm)	2	7.4281	4.0641	0.443	14.39%
Error	2	0.7639	0.0446		1.48%
Total	8	51.62			

The influence of each selected parameter on power consumption is estimated using the ANOVA approach as shown in Table 7. It shows, Electrolyte concentration contributing 51.47%, temperature contributing 32.66%, and distance between electrodes contributing 14.39 % in power consumption**.**

With the help of MS Excel software, a regression equation is generated. Many similar applications, such as MINITAB and MATLAB, can also generate regression equations. However, the study prefers Microsoft Excel due to its simplicity and ability to handle three parameters.

The Regression equation for hydrogen generation:

$$\text{Hydrogen production rate (g/sec)} = 0.000496773+(0.000702707\times A)+(8.74491\times 10^{-6}\times B)+(0.000130643\times C)+(5.26837\times 10^{-6}\times AB)+(-1.80255\times 10^{-6}\times BC)+(-0.00013747\times CA)$$

Where, A = concentration of electrolyte, B = temperature of electrolyte, C = distance between electrodes.

The optimal operating parameters are found same in this regression equation as the S/N ratio result. For the conformation test, all of the operational parameters entered into the regression equation and output value calculated. The experimental and expected values compared in the conformation test as stated in the Table 8 below.

Table 8: Experimental data and predicted data of H_2 production

Sr. no	Concentration of Electrolyte (m)	Temp. of Electrolyte (°C)	Electrode Gap (mm)	Hydrogen Production Rate (g/sec)	Predicted from Regression	Error %
1	0.1	30	1	0.00090309	0.00090802	0.545
2	0.1	50	3	0.0010778	0.00111094	3.075
3	0.1	70	5	0.00118287	0.00116965	-1.117
4	0.3	30	3	0.00117617	0.00112332	-4.493
5	0.3	50	5	0.00120052	0.00122023	1.641
6	0.3	70	1	0.00141016	0.00139359	-1.175
7	0.5	30	5	0.00122037	0.00122865	0.679
8	0.5	50	1	0.00136244	0.00138886	1.939
9	0.5	70	3	0.0014617	0.00145185	-0.674

The Regression equation for power consumption

$$\text{Power consumption (kW/gram)} = 114.7013031 + (35.85589119 \times A) + (0.084524962 \times B) + (-3.803064403 \times C) + (-0.555608907 \times AB) + (0.042917104 \times BC) + (3.40734074 \times CA)$$

Where, A = concentration of electrolyte, B = temperature of electrolyte, C = distance between electrodes.

The optimal operating parameters are found same in this regression equation as the S/N ratio result. For the conformation test, all of the operational parameters entered into the regression equation and output value calculated. The experimental and expected values compared in the conformation test as stated in the Table 9 below.

Table 9: Experimental data and predicted data for power consumption

Sr. no	Concentration of Electrolyte (m)	Temperature of Electrolyte (°C)	Electrode gap (mm)	Power Consumption (kW/gram)	Predicted Power Consumption	Error%
1	0.1	30	1	116.9319	116.9510	0.02
2	0.1	50	3	116.9054	115.7357	-1.00
3	0.1	70	5	117.6804	117.9537	0.23
4	0.3	30	3	117.3299	118.4233	0.93
5	0.3	50	5	117.9488	118.0251	0.06
6	0.3	70	1	119.1355	119.7204	0.49
7	0.5	30	5	122.9139	122.6215	-0.24
8	0.5	50	1	123.3084	122.7617	-0.44
9	0.5	70	3	121.5023	121.4641	-0.03

CONCLUSION

A study was carried out for hydrogen gas production by alkaline water electrolysis. As an electrode SS316 material and KOH solution as an electrolyte is used to optimize the operating parameters viz. concentration of electrolyte, temperature of electrolyte, and distance between electrodes with respect to power consumption. The experimental investigation utilized a Taguchi-based Design of Experiment (DOE) methodology, and MINITAB software was used to determine the L^9 orthogonal array. Below is a list of the outcomes based on operational parameters.

- As the concentration of electrolyte, temperature of electrolyte increases, and distance between electrodes decreases, the power consumption reduces.
- At 0.5 m electrolyte concentration, 50°C electrolyte temperature and 1 mm distance between electrodes, the lowest power consumption is realized.
- According to the ANOVA method, "concentration of electrolyte has the greatest impact on power consumption, followed by temperature of electrolyte and distance between electrodes." The percentages contributions are 51.47, 32.66, and 14.39 percent, respectively.
- For a particular set of operating parameters, the regression equation was validated, and the conformation test revealed good agreement between anticipated and experimental output values (hydrogen production rate, temperature of electrolyte and distance between electrodes).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

ACHOUR S., CHABBI F. (2017). Study of oxidation/disinfection steps of treatment plant of Ain Tinn (Mila, eastern Algeria), Larhyss Journal, No 31, pp. 233-247. (In French)

Ahmad A., Yadav A.K. (2024). Parametric analysis of wastewater electrolysis for green hydrogen production: A combined RSM, genetic algorithm, and particle swarm optimization approach, International Journal of Hydrogen Energy, Vol. 59, pp. 51-62.

ADJAGODO A., AGASSOUNON DJIKPO TCHIBOZO M., KELOME AHOUANGNIVO N., LAWANI R. (2016). Flow of pollutants linked to anthropic activities and risks on worldwide surface water resource (literature review), Larhyss Journal, No 28, pp. 7-23. (In French)

AVCI A.C., TOKLU E. (2022). A new analysis of two phase flow on hydrogen production from water electrolysis, International Journal of Hydrogen Energy, Vol. 47, Issue 11, pp. 6986-6995.

BABA HAMED S. (2021). Impact of water pollution on public health and the environment in Oran, Larhyss Journal, No 45, pp. 203-222.

BODNER, M., HOFER A., HACKER V. (2015). H2 generation from alkaline electrolyzer. WIREs: Energy and Environment Vol. 4, Issue 4, pp. 365-381.

BOUAOUINE O., KHALIL F., CHTIOUI H., ZAITAN H., HARRACH A. (2015). Treatment by electrocoagulation of leachate from the controlled public landfill in the city of Fes (Morocco), Larhyss Journal, No 23, pp. 53-67. (In French)

Church J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, P.D. and Payne, A.J., (2013). Sea level change, PM Cambridge University Press.

Collins M., Knutti R., Arblaster J., Dufresne J.L., Fichefet T., Friedlingstein P., Gao X., Gutowski W.J., Johns T., Krinner G., Shongwe M., (2013). Long-term climate change: projections, commitments and irreversibility, Cambridge University Press, Cambridge, UK and New York, USA pp.1029-1136

COSSAR E., OYARCE BARNETT A., SELAND F., BARANOVA E. A. (2019). The performance of nickel and nickel-iron catalysts evaluated as anodes in anion exchange membrane water electrolysis, Catalysts, Vol. 9, Issue 10, pp. 814-831.

DA SILVA VERAS, T., MOZER, T. S., DA SILVA CÉSAR, A. (2017). Hydrogen: trends, production and characterization of the main process worldwide, International Journal of hydrogen energy, Vol. 42, Issue 4, pp. 2018-2033.

DAVID M., OCAMPO-MARTÍNEZ C., SÁNCHEZ-PEÑA R. (2019). Advances in alkaline water electrolyzers: A review, Journal of Energy Storage, Vol. 23, pp. 392-403.

DEBBACHE M., DERFOUF S. (2018). Analysis of the induction effect on the performance of wind turbine, Larhyss Journal, No 33, pp. 25-39.

DE SOUZA R.F., PADILHA J.C., GONÇALVES R.S., DE SOUZA M.O., RAULT-Berthelot J. (2007). Electrochemical hydrogen production from water electrolysis using ionic liquid as electrolytes: towards the best device, Journal of Power Sources, Vol. 164, Issue 2, pp. 792-798.

Dincer I., ACAR C. (2015). Review and evaluation of hydrogen production methods for better sustainability, International journal of hydrogen energy, Vol. 40, Issue 34, pp. 11094-11111.

DUNN S. (2002). Hydrogen futures: toward a sustainable energy system, International Journal of hydrogen energy, Vol. 27, Issue 3, pp. 235-264.

ESPEGREN K., DAMMAN S., PISCIELLA P., GRAABAK I., TOMASGARD A. (2021). The role of hydrogen in the transition from a petroleum economy to a low-carbon society, international Journal of hydrogen energy, Vol. 46, Issue 45, pp. 23125-23138.

EZZAHRA CHAKIK F., KADDAMI M., MIKOU M. (2017). Effect of operating parameters on hydrogen production by electrolysis of water, International Journal of Hydrogen Energy, Vol. 42, Issue 40, pp. 25550-25557.

GOLAKIYA V.D., CHUDASAMA M.K., RAVAL H.K. (2022). Analyze and Optimize Thinning and Forming Force in Single Point Incremental Forming on AA6061-T6 Using the Finite Element Method. In Recent Advances in Manufacturing Modelling and Optimization: Select Proceedings of RAM 2021, Singapore: Springer Nature Singapore, pp. 353-369.

GORAN R., JELISAVKA B. (2016). Possibility of use of water in the economy of Montenegro, Larhyss Journal, No 25, pp. 7-30.

HAUG P., KOJ M., TUREK T. (2017). Influence of process conditions on gas purity in alkaline water electrolysis, International Journal of Hydrogen Energy, Vol. 42, Issue 15, pp. 9406-9418.

HOSSEINI S. E., WAHID M. A. (2016). Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development, Renewable and Sustainable Energy Reviews, Vol. 57, pp. 850-866.

MAHROUS A.F.M., SAKR I.M., BALABEL A., IBRAHIM K. (2011). Experimental investigation of the operating parameters affecting hydrogen production process through alkaline water electrolysis, International Journal of Thermal & Environmental Engineering, Vol. 2, Issue 2, pp. 113-116.

MAZLOOMI S.K., SULAIMAN N. (2012). Influencing factors of water electrolysis electrical efficiency, Renewable and Sustainable Energy Reviews, Vol. 16, Issue 6, pp. 4257-4263.

MOOSA I.S., KAZEM H.A., AL-IESSI L.M.R. (2021). Production of Hydrogen via Renewable Energy and Investigation of Water Molecular Changes During Electrolysis Process, Journal of Renewable Energy and Environment, Vol. 8, Issue 4, pp. 19-28.

MOUSSI A, SAADI A., BETKA A., ASHER G.M. (2003). Photovoltaic pumping systems technologies trends, Larhyss Journal, No 2, pp. 127-150.

NAGAI N., TAKEUCHI M., KIMURA T., OKA, T. (2003). Existence of optimum space between electrodes on hydrogen production by water electrolysis, International Journal of Hydrogen Energy, Vol. 28, Issue 1, pp. 35-41.

RASHID M.D., AL MESFER M.K., NASEEM H., DANISH M. (2015). Hydrogen production by water electrolysis: a review of alkaline water electrolysis, PEM water electrolysis and high temperature water electrolysis, International Journal of Engineering and Advanced Technology, Vol. 4, Issue 3, pp. 80-93

SAKR M., MAHROUS A.F., BALABEL A., IBRAHIM K. (2011). Experimental investigation into hydrogen production through alkaline water electrolysis, ERJ, Engineering Research Journal, Vol. 34, Issue 1, pp. 37-41.

SCHALENBACH M., KASIAN O., MAYRHOFER K.J. (2018). An alkaline water electrolyzer with nickel electrodes enables efficient high current density operation, International journal of hydrogen energy, Vol. 43, Issue 27, pp. 11932-11938.

SELLAMI M.H., LOUDIYI K. (2017). Electrolytes behavior during hydrogen production by solar energy, Renewable and Sustainable Energy Reviews, Vol. 70, pp. 1331-1335.

SHAH S.M.H., QAMAR N., QURESHI H.U., MUSTAFFA Z., TEO F.Y., SALEEM S., QAMAR N., AHMED F., ALI Z., HUSSAIN S. (2023). Performance analysis of a tubular solar still incorporated with porous soil to improve distillate output, Larhyss Journal, No 54, pp. 25-41.

SYMES D., AL-DURI B., BUJALSKI W., DHIR A. (2015). Cost-effective design of the alkaline electrolyser for enhanced electrochemical performance and reduced electrode degradation, International Journal of Low-Carbon Technologies, Vol. 10, Issue 4, pp. 452-459.

URSUA A., GANDIA L.M., SANCHIS P. (2011). Hydrogen production from water electrolysis: current status and future trends, Proceedings of the IEEE, Vol. 100, Issue 2, pp. 410-426.

ZENG K., ZHANG D. (2010). Recent progress in alkaline water electrolysis for hydrogen production and applications, Progress in energy and combustion science, Vol. 36, Issue 3, pp. 307-326.