

Performance Assessment of Dry-Cell Oxyhydrogen (HHO) Production under Varying Electrical Operating Conditions

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ABSTRACT

Using hydrogen technology to split water with electrical energy is an environmentally friendly way to use energy. This project focuses on the production of hydrogen using a stack of cells with two electrodes forming an electrolyzer. A dry cell was used where the electrolyte was fed to the electrolyzer through gravity. In this experiment, various parameters influencing the production of hydrogen as oxyhydrogen gas in an electrolyzer cell were studied. These include applied voltage, current, electrolyzer temperature, and electrolyte concentration. Through the study, it was concluded that the optimum voltage of each cell of the stack needs to be between 2.0 and 2.2 volts. Also, temperatures above 60°C provide additional overpotential due to kinetic effects and resistance, resulting in steam formation, which may accelerate electrode degradation. Furthermore, effective production of gas was observed with a 30 percent KOH electrolyte solution. These findings could be beneficial for developing the design and control mechanism of the electrolyzer.

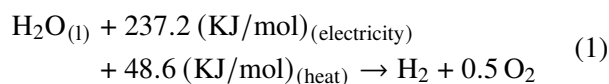
1. Introduction

Growing concerns over environmental degradation, global climate change, and diminishing fossil fuel reserves are moving the world toward hydrogen as a viable alternative energy carrier. Beyond the issue of limited supply, the combustion of fossil fuels, whether coal, crude oil, or natural gas, is a significant source of air pollution. Scientists have widely acknowledged the adverse effects of carbon-based fuel use. Consequently, green energy sources have become a prominent focus of scientific research. There is now a clear and urgent need to transition away from conventional fuel resources toward cleaner alternatives, with the goal of decreasing the carbon footprint and mitigating the wider consequences of global warming.

Among the various energy resources under exploration, hydrogen energy has drawn considerable attention from researchers due to its potential as an adaptable and clean fuel. It offers a viable means of minimizing the carbon footprint across highly energy-intensive sectors, including manufacturing, transportation, maritime shipping, and waste management [1, 2]. In essence, it is perceived to be a naturalistic synthetic fuel. Replacing traditional fuel with hydrogen would drastically minimize hazardous emissions, i.e., CO₂, CO, SO_x, and organic acids [3]. In addition, hydrogen stands out as

a strong combustion fuel owing to its minimal carbon output [4].

Hydrogen can be generated through various methods. Its production is classified into two groups of so-called grey, blue, or green hydrogen, depending on the technique of its production [4]. The green one is produced through the splitting of water through electrolysis; water is the only input; hence, it is essentially carbon-free. The process involves the use of an electrolyzer, which is a device that has two plates: the anode and the cathode. The diagram in Figure 1 below illustrates the process of the electrolyzer: it consumes electrical energy but converts water into hydrogen and oxygen, as shown in equation (1).



This method of electrolysis is divided into three broad categories: (i) alkaline water electrolyzer, (ii) exchange membrane electrolyzer, (iii) solid oxide electrolyzer cell. Among these, the alkaline one is the most widespread and relatively inexpensive; moreover, it has matured over time [5]. With an efficiency range of approximately 52–62%, they offer a reasonable balance between performance and affordability suitable for large-scale deployment. [6]

Besides the simple installation, oxyhydrogen generators

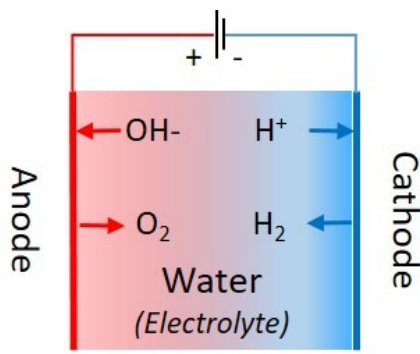


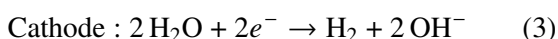
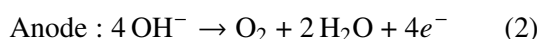
Fig. 1. Schematic diagram of a water electrolyzer

are available in two distinct types, typically referred to as the dry-cell and wet-cell configurations [7]. In a dry cell configuration, the electrodes are embedded in a gas-permeable housing, with the electrolyte confined to only the inter-electrode spaces [8]. Whereas, in the wet-cell configuration, the electrodes are immersed fully into the electrolyte solution [9]. PEM electrolyzers are performing above their size in terms of current density, purity, and working scope, and their efficiencies stand at 54–64 percent [10]. However, their high cost, including titanium contacts and iridium-loaded catalysts, has limited their uptake in full-scale commercial deployments.

The study conducted by Felgenhauer and Hamacher revealed that PEM electrolyzers have a rate of degradation that is 2 times higher than that of alkaline, at 1.57% versus 0.78%, respectively [6]. This is a bit more complex in the example of the solid oxide electrolyzer cells: they are very efficient (above 90 percent), but too costly to be produced in large quantities in a business-like setting [11]. Consequently, alkaline electrolyzers continue to hold a competitive advantage from an economic standpoint [12].

The economic analysis of alkaline and PEM electrolyzers, which included investment costs, maintenance costs per year, and the cost of running one unit of the electrolyzer per unit of hydrogen, found that alkaline units should be favored, particularly when you need to produce over 25 kg H₂/h. A related study [13] highlighted a key structural difference between the two technologies, namely the separator between the hydrogen and oxygen production chambers. A Porous diaphragm is used as a separator in alkaline electrolyzers. This diaphragm allows the free flow of hydroxyl ions (usually supplied by potassium hydroxide); however, in PEM systems, the separator is a solid polymer that only allows the free flow of protons required for electrolysis.

Lastly, this segment narrows down to the alkaline electrolyzer. Electrical power is conducted in an alkaline system in a solution of water and electrolyte. The resultant reaction is displayed in equations (2) and (3), by which the input electricity splits the water into hydrogen and oxygen gas. The combined gaseous product is commonly known as oxyhydrogen or Brown's gas [14]



The oxidation rate of hydrogen is high, and the stoichiometric ratio is maintained, with the mixture premixed with oxygen [15]. This oxyhydrogen gas exhibits rare behaviour at atmospheric pressure. The conceptual model of combustion states that the temperature of hydrogen gas can reach up to 2045°C, and the main zone of the oxyhydrogen flame can reach up to 3036°C [16]. Oxyhydrogen gas has a high temperature that is useful in cutting, welding, and polishing industries [17]. Hydrogen is a primary constituent of oxyhydrogen; its flammability range is wide and may vary between 4% and 74.2% [18]. During the combustion of hydrogen, it results in a nonluminous flame that is not visible in daylight. As the molecules of hydrogen in oxyhydrogen gas are smaller, they can easily penetrate through porous material [19]. On-demand production is the safest approach to oxyhydrogen application [12]. Using this technique helps utilize oxyhydrogen as needed. This will help in reducing the need for expensive storage and transportation of hydrogen [19]. Such an approach is predominantly seen in various research works concerning combustion engines when applied in the case of oxyhydrogen [20,21]. This will also minimize the risk factors for flashback and leakage, which are of great concern for hydrogen storage. Hydrogen generated through renewable means such as PV or wind can have great potential to be used on demand, which can utilize hydrogen as a fuel [22].

Electrolysis needs 1.24 V to decompose at 0.1 MPa of pressure and 25°C of temperature. Nonetheless, with a higher electrolyte temperature (80°C) and the addition of electrolyte (KOH solution), the voltage required to conduct an electrolysis process can rise to 2–2.5 V [22]. This is attributed to the thermoneutral voltage in the electrolysis. The presence of hydrogen and oxygen bubbles between the electrodes increases the volume fraction in the aqueous solution, thereby elevating electrical resistance and consequently reducing the efficiency of water electrolysis. In the absence of membrane separation (ion-conductive membrane), hydrogen and oxygen gases will intermix. This will result in the development of a 2:1 volumetric (hydrogen/oxygen) mixture of H₂ and O₂. It is estimated that 1 kilogram of water requires 22.9 MJ of electric power to produce approximately 1860 L of oxyhydrogen gas, which consists of 1240 L of hydrogen and 620 L of oxygen [23]. At a pressure of 0.1 MPa and a temperature of 0°C, the density of hydrogen and oxygen gas is 0.09 kg/m³ and 1.42 kg/m³ respectively [24]. This mixture (oxyhydrogen) has a specific density of 0.54 kg/m³ at 25°C [21]. Ion transfer is dependent on the electrolyte content (in the case of a liquid), the membrane (in the case of a solid), and the separation distance between the cathode and the anode [22]. The current flow in the cell is also dependent on the electrolyte concentration in the alkaline electrolyzer. The greater the concentration of the electrolyte solution, the higher the conductivity, and the lower the electrical potential [23]. This leads to an increase in the flow of current in the cell. Since the rate

of production of HHO output in an alkaline electrolyzer depends on the number of cells and the current, the higher the concentration of the electrolyte, the higher the production of HHO gas [25].

This paper examines the effect of four critical operating parameters: (i) applied voltage, (ii) current, (iii) electrolyte temperature, and (iv) electrolyte concentration on the rate of oxyhydrogen gas production. The experimental work was conducted using a dry cell electrolyzer setup.

2. Materials and Method

A commercial dry-cell electrolyzer (12 V, 30 plates; GreenFuelH₂O, Orem, UT, USA) was used. It contains 30 SS316 plates (181.94 cm² each) arranged in five stacks of six cells, i.e., 30 cells in total. Each stack has two electrode plates. Cells within a stack are connected electrically in series, and the stacks are connected in parallel (as shown in Figure 2). Adjacent plates are separated by a 2 mm rubber gasket, which sets the inter-electrode gap and confines the electrolyte to the gasket-bound region. Electrolyte was fed by gravity from an external reservoir. No membrane was used, so H₂ and O₂ leave together as HHO.

Thermodynamically, water can be broken down with an electrical potential of 1.23 V, but the kinetic constraints require an extra overpotential of more than 1.8 V to activate the reaction. Therefore, a voltage range of 1.8–2.2 volts per electrolyzer cell was set for this experiment, corresponding to 10.8–13.2 volts for each of the five stacks. Also, caution was exercised against voltages above 13.2 volts, as they can cause an increase in temperature, which generates bubbles and hence results in slowing down the electrolysis process.

For effective production of HHO gas, four different parameters were considered in the study, which include current, voltage, temperature, and concentration of electrolyte. This is because these parameters have a direct effect on the efficiency of the electrolytes, which can be measured by the HHO gas flow rate.

All these variables control the efficiency of the electrolyzer by controlling the rate of evolved HHO flow. The following equation (4) was used to measure the efficiency of each parameter:

$$\eta = \frac{\text{Output Energy}}{\text{Input Energy}} \quad (4)$$

$$\text{Input Energy} = \text{Voltage} \times \text{Current} \times \text{Time} \quad (5)$$

$$\eta_{\text{energy}} = \eta_{\text{Faraday}} \frac{V_{\text{thermoneutral}}}{V_{\text{cell}}} \quad (6)$$

Faraday efficiency is the fraction of the electrical current of an electrolyzer that goes into producing the HHO gas.

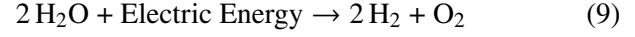
Commonly, specifically HHV (Higher Heating Value) and LHV (Lower Heating Value) based energy efficiency

is explained in equations (7) & (8), respectively:

$$\% \eta_{\text{HHV}} = \eta_{\text{Faraday}} \frac{1.48}{V_{\text{cell}}} \quad (7)$$

$$\% \eta_{\text{LHV}} = \eta_{\text{Faraday}} \frac{1.25}{V_{\text{cell}}} \quad (8)$$

For splitting of water by applying input power, hydrogen and oxygen will evolve due to the electrolysis process as shown in equation (9)



$$\text{Output Energy} = \text{HHO}_{\text{lpm}} \times 0.67 \times 3.3 \quad (10)$$

For output power, the combustion energy of hydrogen was required to be calculated. As H₂O was split into HHO gas, which comprises of 2 moles of hydrogen and 1 mole of oxygen, equation (9) will be used to calculate the output energy in electrical terms from hydrogen [2]. Based on the 67% efficiency of the alkaline electrolyzer [22], output energy can be calculated by using equation (10).

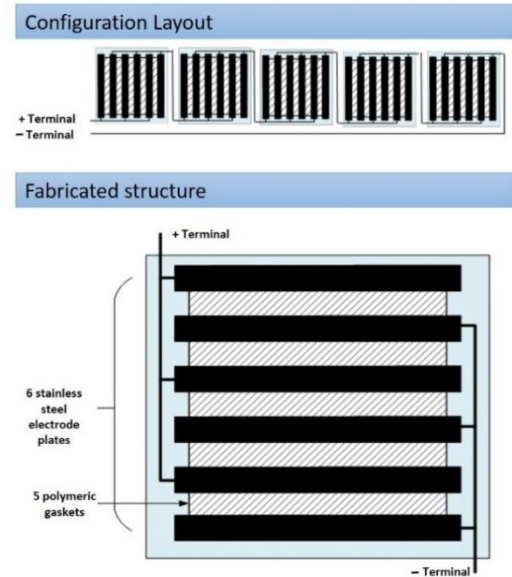


Fig. 2. Configuration layout of the electrolyzer under test

To study the characteristics of the electrolyzer's operation, a system was designed according to the schematic diagram (Figure 3(a)).

A Sorensen SG Series DC supply was operated in constant-voltage mode with a set current limit. Voltage and current were read using an external meter. The nominal 1.8–2.2 V per cell corresponds to 10.8–13.2 V for a six-cell series string; 9–14 V was explored to show the low-voltage and over-voltage behavior.

The temperature was measured at 1-second intervals in the experiment using a TENMARS TM-747D model K-type thermocouple.

Figure 3(b) provides a full depiction of the functional experimental setup.

3. Results & Discussion

Heat is an unavoidable side effect of electron movement through the gasket-seated gap, and controlling that heat

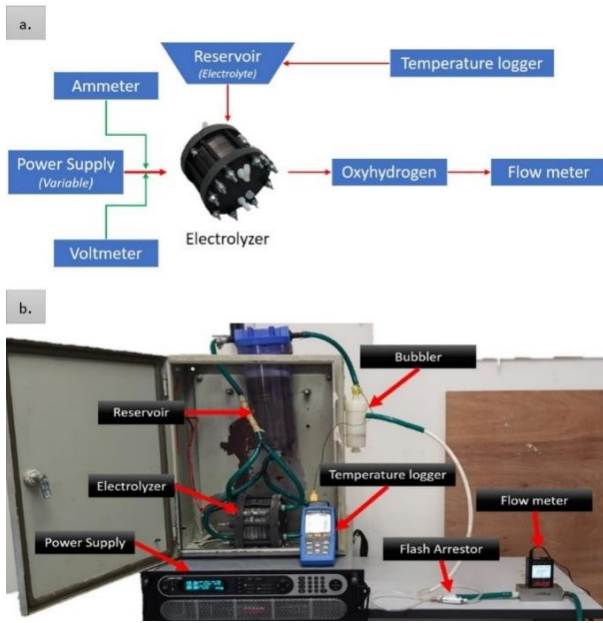


Fig. 3. (a) Schematic diagram of experimental setup; (b) Working experimental setup

is the real challenge in the control of the electrolyzer. Each square inch of plate surface can efficiently carry about 0.54 amps (as per the current density). This current is actually flowing into the water, and is most concentrated at the active surface area—the area bounded by the gasket—and is also most concentrated at the point of electron buildup and thus heating.

There's an inherent tradeoff here. Push the current density higher, and gas output rises, but so does heat generation. That's the practical ceiling on sustained oxyhydrogen output. If the available surface area can't adequately distribute the current, electrons end up bottlenecking at the nearest point of water contact, and that localized crowding is what drives excess heating. Beyond the optimal current density, efficiency would be lower, and energy would be wasted as heat.

As seen from Faraday's equation, a minimum of 1.24 V and a production rate of 0.01 L/min per ampere are required because this is the smallest amount of potential that can be put between two plates to split water with the least amount of heat loss. The higher the applied potential, the more heat is lost. Due to the loss caused by the resistance in the cell (as in Figure 4), it is not possible to conduct electrolysis exactly at 1.24V. These resistances include electrical, transport, and electrochemical reaction resistance (as given in equations 11–14). Electrical energy is directly responsible for heat energy, while resistance in the transfer of ions is created due to bubbles of hydrogen and oxygen that are generated on the surface of the electrode. To overcome the voltage drop due to these resistances, practically 1.8–2.2 volts per cell was applied to start the effective electrolysis.

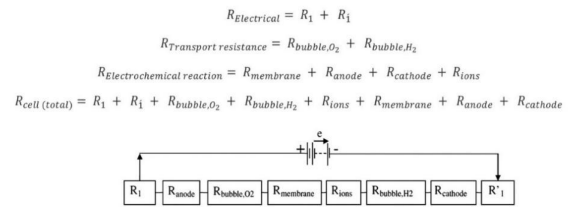


Fig. 4. The total resistance of an electrolyzer cell

$$R_{\text{cell(total)}} = R_{\text{electrical}} + R_{\text{Transport Resistance}} + R_{\text{electrochemical reaction}} \quad (11)$$

$$R_{\text{electrical}} = R_1 + R'_1 \quad (12)$$

$$R_{\text{Transport Resistance}} = R_{\text{O}_2, \text{bubble}} + R_{\text{H}_2, \text{bubble}} \quad (13)$$

$$R_{\text{electrochemical reaction}} = R_{\text{membrane}} + R_{\text{anode}} + R_{\text{cathode}} + R_{\text{ions}} \quad (14)$$

3.1 Influence of current on the production of HHO

The effect of the current on the production of HHO was tested on the given setup and noted in Table 1. For variation of the current at different values ranging from 6 to 24 Amps, an adjustable Sorensen SG Series power supply was used. During variation of the current, the voltage was kept constant at 12 volts per stack of electrolyzer.

Figure 5 illustrates that oxyhydrogen production rose steadily as the current increased, though the relationship wasn't perfectly linear throughout. After a certain point, the HHO flow rate started to deviate from the predicted linear behavior, which was attributed to increasing current leakage, which subsequently affected the entire electrolyzer efficiency. In particular, an increase in applied current from 6 to 24A increased the flow rate from 0.3 l/min to 1.31 l/min. The faster the current, the more bubbles form on the surfaces of the electrodes. After the current reached about 16 A, this effect became severe enough to be a real problem: the growing amount of bubbles caused the electrodes to become unstable and began to disrupt the flow of current. Meanwhile, increases in current also increase the rate of exchange between the positive ions and the electrons, leading to increased electron transfer across the electrode gap and, in turn, a faster dissociation rate for water. The higher the current, the better the electrode conductance; the more ion collisions will occur, and the more effective they will be; and the more ions in the vicinity will lower the electrical resistance and increase the conductivity. The negative aspect is that this overcurrent scenario is the main reason for plates to overheat. That heat promotes evaporation of the water, which is a hindrance, not a help, to efficiency. This is why the efficiency pattern is observed: it was fairly flat at 65–66% up to approximately 14A, but took a sharp dip after that, falling to 58.3% at 24A. However, the higher flow rates did not yield cleaner gas, as the flow rate continued to increase (to 1.31 L/min at 24A). The introduction of a small amount of water vapor into the HHO stream by the bubble activity and evaporation of water also reduced the quality of the gas while increasing the volume of

Table 1

The flow rate of HHO gas for constant voltage

Current (A)	Flow Rate (l/min)	Energy Evolved (H ₂)	η
6	0.3	0.6633	66.33
8	0.4	0.8844	64.40
10	0.52	1.14972	65.08
12	0.63	1.39293	64.49
14	0.79	1.74669	65.09
16	0.87	1.92357	61.65
18	0.96	2.12256	59.46
20	1.07	2.36577	59.14
22	1.19	2.63109	58.82
24	1.31	2.89641	58.40

gas being produced.

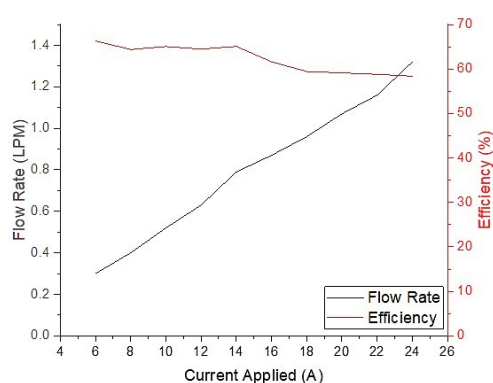


Fig. 5. Effect of constant voltage and applied current on HHO gas production in an electrolyzer (dry cell)

3.2 Influence of voltage on the production of HHO

The theoretical minimum potential required to electrolyse water is 1.23V, which is equal to the standard Gibbs free energy of the reaction. This value, however, is not actually enough in practice for gas evolution. This additional potential is known as over-potential and is influenced by a variety of factors such as the surface morphology of the electrodes, electrolyte concentration, inter-electrode gap, and gasket geometry in the electrolytic cell. In practical systems, therefore, electrolysis usually takes place at 1.8–2.2 V per cell. The present study experimented with an electrolyzer with SS316 stainless steel electrodes at ambient temperature with a concentrated electrolyte solution.

To assess the effect of applied voltage on HHO gas production, a series of six experiments was then performed, based on the results from the previous series of current optimization experiments, which showed that the optimum operating current was 14 A. A six-cell stack configuration was used; current was maintained at six different levels (14, 16, 18, 20, 22, and 24 A); and voltage was stepped up between 9 V and 13 V. A programmable power supply was used to control output, so in reality, the maximum voltage was reached only when the current was increased to the specified limit, and this is apparent in the limited voltage ranges seen

at the higher current settings. Results are presented in Figure 6. It is known that raising the applied voltage increases ion exchange at the electrode–electrolyte interface, increases uniformity of charge density on the electrode surface, and speeds up reaction kinetics, all of which are expected to increase HHO output. As seen in Figure 6(a), at this point (current limit 14 A), the flow rate followed a consistent increase with voltage through the entire range of operation (9–13 V), with an optimum efficiency of 65%. However, no increase in flow rate was detected beyond 12 V due to the fact that the current limit was reached at 12 V.

The flow rate increased steadily with applied voltage at 16 A, while the efficiency of the electrolyzer showed a declining trend, down to 61.6% at 12 V (Figure 6b). An even higher efficiency loss, to 58.9%, was seen at 12 V at 18 A (Figure 6c), for a still higher flow rate of 0.96 L/min. It was not possible to test a voltage higher than 12 V because of the current limits of the electrolyzer. As the voltage at 20 A decreased from 9 to 14 V, efficiency continued to decrease, reaching 58.17% at 13 V, and the flow rate increased to 1.07 L/min (Figure 6d). The flow rate further increased to 1.16 l/min at 22 A; however, this was accompanied by a corresponding decrease in efficiency to 56.86% (Figure 6e). When the current was set to the highest value tested (24 A), the efficiency measured 57.48%, and the maximum flow rate measured at 13 V (24 A) was 1.3 L/min (Fig. 6f). In general, the results showed that raising the voltage from 9 VDC to 12 VDC simultaneously improves the flow rate and the efficiency of the electrolyzer.

At higher currents, however, continued increases in voltage lead to a reduction in efficiency, but a continued increase in flow rate. This inverse relationship is due to the increase in ohmic losses and leakage of current at high current densities because of the overvoltage of the cell. Overvoltage also causes an increase in cell temperature, which may impact the volumetric efficiency and purity of the product gas (not measured), as higher amounts of water vapour have been observed to be entrained into the gas stream under these conditions. These results indicate that cell overvoltage could be used to increase gas flow rate, but at the expense of

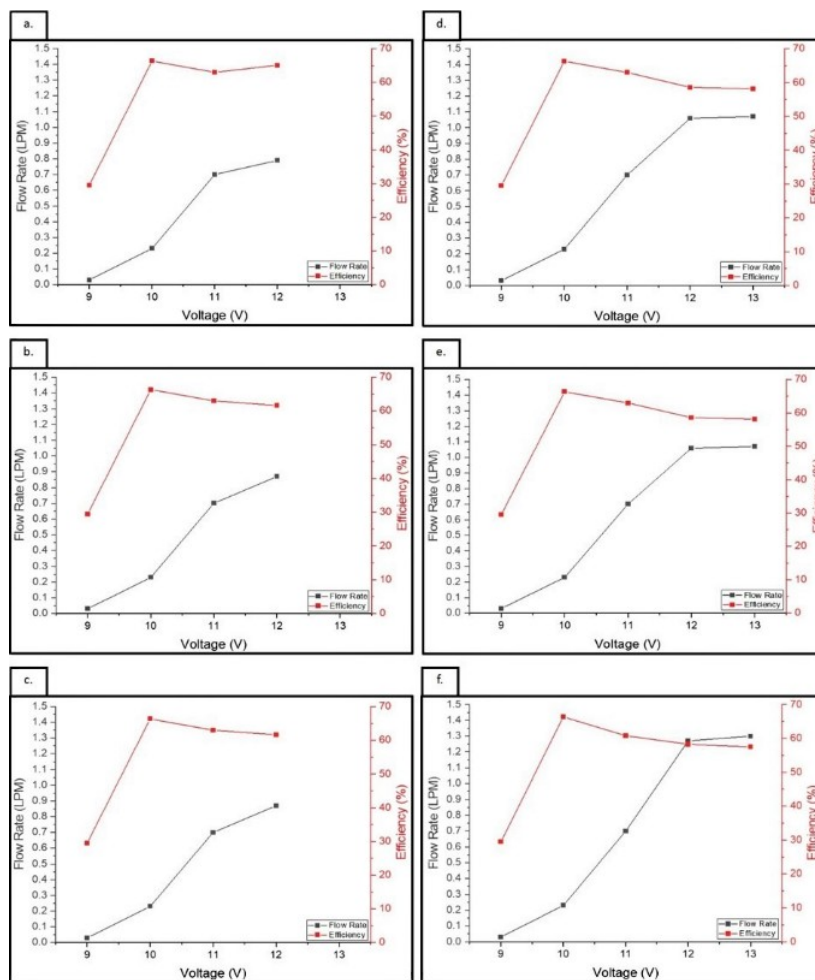


Fig. 6. Effect of current limitation with different applied voltage on electrolyzer (dry cell) for production of HHO gas: (a) 14 A, (b) 16 A, (c) 18 A, (d) 20 A, (e) 22 A, (f) 24 A

the overall electrolyzer efficiency, which needs to be taken into account in the design of an HHO-generating system.

3.3 Influence of temperature on the production of HHO

The HHO production system was continuously operated for 30 minutes at different current densities, and the flow rate and temperature of the flow were recorded during the operating process. The rate of gas production rose at the beginning of electrolysis, but leveled off after a certain operating time. This initial transient is believed to be due to the gradual slowdown of the operating conditions to a steady state where the pressure and temperature throughout the cell are in equilibrium, and the gas evolution rate is in steady state. At the same time, the degradation of the surface and the fouling of the electrode were seen to rise as the applied current increased and as the operating time of the electrode increased. Increasing the flow rate of the electrodes increased the molecular mobility of the hydrogen and oxygen species as well as the number of intermolecular collisions.

This is in line with the average molecular kinetic energy increasing, thereby causing higher levels of gas production. It was concluded that cell temperature is directly proportional to the applied potential. There was also additional heat generation under overpotential conditions, and this increased as operating time increased,

and the heat generation rate and HHO production rate increased throughout the single test period of 30 minutes. This was linked to higher electron mobility and better heat transfer at longer operating durations, which were concurrent with the progressive fouling and degradation of the electrodes. The gas production results obtained from varying the electrolyte (KOH solution) temperature, at fixed current conditions of 1, 2, 3, and 4 A and at 12 V, are shown in Figure 7. For the first trial, the electrolyzer was run for 30 minutes at 20A. The initial temperature was 34.2°C, and the flow rate was 1.06 L/min (Figure 7a). The flow rate was slightly raised to 1.1 L/min, but the gas outlet emitted visible mist at 20 A (qualitative observation; gas humidity and purity were not measured).

This vapor entrainment was found to be a source of decrease in gas purity, although the flow rate was increased. The operating temperature of the electrolyzer should not be higher than 70°C, as reported in the literature, and it was decided that 20 A is too high a current for this operating range of the electrolyzer.

The experiment was subsequently repeated at 14 A (Figure 7b). Flow rate increased marginally from 0.8 to 0.83 L/min over the 30 minutes, while temperature remained within an acceptable range, reaching only 45.2°C. A third trial was conducted at 10 A (Figure 7c), yielding a flow rate that increased only slightly, from 0.51 to 0.52 L/min, with a corresponding temperature rise of just 4°C, reaching 40.8°C by the end of the test.

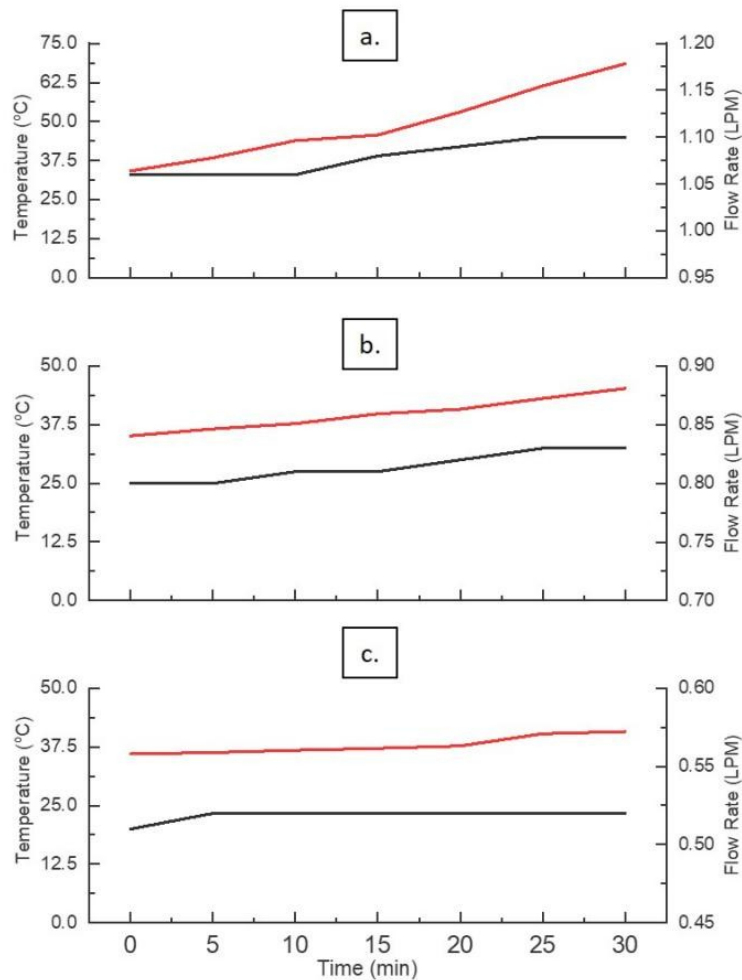


Fig. 7. Effect of temperature on electrolyzer at different currents (Red: Temperature; Black: Flow Rate), (a) 20A, (b) 14 A, (c) 10 A

Neither flow rate nor temperature exhibited substantial change under this condition. No active cooling was applied to the electrolyzer during any of these 30-minute test runs; the temperature values reported above reflect passive heat accumulation within the cell and electrolyte under natural convective heat loss to the surrounding environment.

These results are consistent with the expectation that increased electrolyte and electrode resistance generates additional heat within the cell. Elevated temperature promotes increased molecular collision frequency between ionic species, which, per Faraday's law, corresponds to higher HHO yield. However, excessive temperature rise also increases electrolyte concentration through water evaporation; under these conditions, although apparent gas yield may increase, gas quality is compromised due to water vapor contamination. Based on this, it was concluded that 14 A was the optimal current for the electrolyzer under testing, which resulted in a favorable flow rate with an acceptable working temperature. For interpretation of the time-dependent behaviour of the electrolyzer under sustained operation, the voltage-dependent trends mentioned in the previous section are helpful. The next section investigates the effects that voltage and the duration of operation have on the flow rate and thermal effects with increasing current from the optimum, while the latter has been investigated in the previous section with constant voltage. More than potential was found to be a significant

cause of excess heating, and thus operating duration is another important variable to consider; excess heat is cumulative over the operating time of the electrolyzer. The electrolyzer was then operated at different currents for 30 minutes, while keeping track of the flow rate and temperature to determine the interactive effect of current and time on system performance.

3.4 Influence of KOH Concentration in the electrolyte for the production of HHO

The effect of electrolyte concentration on the HHO gas production was studied by changing the concentration of potassium hydroxide (KOH) in distilled water. The electrolyzer was run at a constant current of 14 A, and the voltage was adjusted from 10 V to 13 V for each concentration tested. The results from Figure 8 indicate that the concentration of KOH had a positive effect on the production rate of gas. This is believed to be due to the improved electrical conductivity provided by the high concentration of KOH, which allows for higher current flow through the electrolyte solution. The production of oxyhydrogen gas increases with the increase of current flow, following Faraday's law of electrolysis. Table 2 shows that the maximum HHO produced was 0.88 L/min, at 30% KOH concentration. Higher amounts of KOH beyond this concentration did not significantly increase the gas production rate. From these results, it was concluded that the optimum electrolyte strength for the maximum output of oxyhydrogen gas

under the operating conditions discussed in this study is 30% KOH concentration.

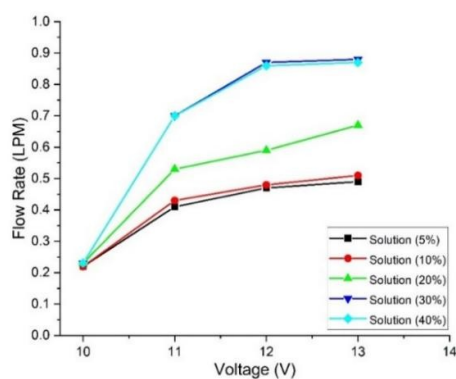


Fig. 8. Effect of concentration of electrolyte solution on electrolyzer for gas production

The reason for this plateau, beyond 30% KOH concentration, is related to the electrolyte viscosity and the mobility of ions. At lower concentrations, conductivity increases in a regular fashion with the amount of KOH used, because the higher the concentration of KOH in the solution, the more charge carriers (K^+ and OH^- ions) will be available. However, when KOH was added beyond a certain concentration, the viscosity of the electrolyte solution increased, and thus the mobility of the ions was reduced. The decrease in the mobility of the ions is counterbalanced by the increase in the number of charge carriers, and this leads to a decrease in conductivity and, hence, gas production rate. Also, ion pairing and an increase in solution density with increasing concentration can further hinder the effective transport of ions between the electrodes. This behavior is in line with the known electrolyte theory; generally, the conductivity will peak at a certain intermediate concentration and then drop or level off because of mobility due to viscosity.

3.5 Efficiency assessment

The results from the foregoing sections (3.1–3.4) can then be used to assess the efficiency of the electrolyzer as a function of voltage, current, temperature, and electrolyte concentration. The operating parameters of the electrolyzer under test were optimized based on the results obtained as follows: operating conditions of 12 V, 14 A, an electrolyte concentration of 30% KOH, and below 30°C were optimized, for which the highest efficiency was achieved. Of these parameters, voltage turned out to be the most influential one for the efficiency of the electrolyzer. In particular, there was a significant decrease in the efficiency of electrolysis when the overvoltage conditions (defined herein as conditions of voltage above about 2.0 V per cell) were reached. In addition, this effect was compounded by a corresponding increase in cell temperature, with two main adverse implications being noted: degradation of HHO gas quality due to the presence of water vapour in the gas stream was observed, and accelerated deterioration of rubber gasket components was noted, thus

reducing the overall electrolyzer service life. These results highlight the need for voltage regulation as a key design and operating parameter for electrolyzers—both in terms of the quality of the generated gas and system longevity.

4. Conclusion

In this research, the effects of current, voltage, operating time, temperature, and electrolyte concentration were examined and evaluated systematically on an SS316 stainless steel electrolyzer for HHO gas production. The interdependence of these parameters and the synergistic effect on gas flow rate, efficiency, and gas quality were determined through a series of controlled tests. The results show that the efficiency of the electrolyzer is mainly affected by voltage among the parameters tested. With the 9 to 12 VDC increase, the flow rate and efficiency increased, but at higher currents, further increases in voltage led to the onset of overvoltage conditions, which started to reduce efficiency even though flow rate increased. This was due to the ohmic losses and current leakage at high current densities. The long operating time exacerbated the impacts, as increased current for longer periods of electrolysis resulted in a progressive increase in electrode fouling, gasket degradation, and system temperature, which contributed to loss of system life and gas quality. In particular, the operation at 20 A resulted in a temperature above 68°C in less than 30 minutes and led to water vapor contamination in a significant amount in the gas stream, while operation at 14 A kept the temperature in an acceptable range and maintained the required flow rate. The concentration of the electrolyte was also determined to be important, and the amount of HHO produced was seen to be proportional to the amount of KOH used up to 30%, where further increases had no significant effect on the production of HHO gas. The effects of this plateau were suggested to be a balance between increased viscosity of the electrolyte and counteracting ion mobility effects with increasing concentration. These results show that the electrolyzer operated under 12 V, 14 A, 30°C, and 30% KOH electrolyte concentration yielded maximum efficiency, whereas cell temperature stayed below the limits reported in the literature. It was found that overvoltage was the main cause of inefficiency and caused direct electrochemical losses and indirect thermal losses due to degradation of components and/or diminishing gas purity. The results give useful feedback for designing and operating stainless steel HHO electrolyzers, especially the balance between the flow rate and maintaining efficiency, the quality of the gas produced, and the life of the equipment. The study of the influence of the surface of the electrodes, electrolyte composition, and active thermal management strategies on the stable operating range of the electrolyzer, along with the long-term durability of gasket materials under continuous overvoltage operation, should be explored in the future.

Conflicts of Interest: The authors declare no conflict

Table 2

The flow rate of HHO gas at different KOH concentration levels in electrolyte solution

Voltage	Flow Rate (Liters per Minute)				
	(5%)	(10%)	(20%)	(30%)	(40%)
10	0.22	0.22	0.23	0.23	0.23
11	0.41	0.43	0.53	0.7	0.7
12	0.47	0.48	0.59	0.87	0.86
13	0.49	0.51	0.67	0.88	0.87

of interest.

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