Performance of Alkaline Water Electrolysis Cell in Generating Hydrogen-Oxygen Mixture Gas under Atmospheric Pressure

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***Abstract*— This paper focuses on evaluating the performance of an alkaline electrolysis cell. The work examined the effect of KOH concentration, applied voltage, electrode plate thickness, and electrode spacing. The results show that as the concentration of KOH increases from 1 g/L to 6 g/L, the efficiency increases from 47% to 57%. The results also show an optimal operating supply voltage of between 2.2 and 2.4 Volts. In addition, the results show that increasing the distance between the electrodes decreases both the efficiency and HHO generation.**

Keywords— Alkaline electrolysis cell, HHO generation, KOH concentration

I. INTRODUCTION

Since the industrial revolution till the present, the world use of fossil fuels as the primary source of energy has resulted in the production of vast quantities of pollutants that have led to global warming and a hazardous climate [1, 2]. In recent years, the energy sector started to move away from the dominant reliance on fossil fuels, such as oil and coal, to renewable sources such as wind, hydro-energy, and hydrogen. Hydrogen has been co-combusted with different fuel to reduce fuel consumption and improve the efficiency of internal combustion engines [3-6]. Hydrogen can be produced using multiple methods, with the majority being produced through the steam reforming process [1]. However, the steam reforming process harvests only 70% of the hydrogen present in steam, and it faces other problems such as the costliness and complexity of the process [7, 8]. Electrolysis is an alternative hydrogen production process that relies on using electric current to split water molecules into hydrogen gas and oxygen gas, a mixture of which is called hydroxy gas (HHO). A lot of research has been done to improve the efficiency of the electrolysis process. Some of the main factors that researchers have experimented with are the use of different catalysts such as alkaline compounds [9], varying power input and catalyst concentration [10], and the usage of surfactants to enhance the electrolysis process [11].

The usage of alkaline compounds as catalysts in the electrolysis process, known as alkaline Electrolysis, has been proven to increase the rate of HHO production [1]. An alkaline electrolysis cell consists of anodes and cathodes in the shape of metallic plates distanced from each other. The anodes and cathodes get direct current flowing through them which decomposes the Water-alkaline mixture into hydrogen gas at the cathodes and oxygen gas at the anodes. The equations representing the chemical reactions at the Anode and the Cathode are represented below in equations (1) and (2), respectively.

$$2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^-_{(l)} \quad (1)$$

$$2OH^-_{(l)} \rightarrow \frac{1}{2}O_{2(g)} + H_2O_{(l)} + 2e^- \quad (2)$$

At the cathode, hydrogen cations are reduced to hydrogen atoms with the help of electrons from the electrical source's negative terminal. The hydrogen atoms are unstable, so it reacts right away with another hydrogen atom to form $H_{2(g)}$. The direction of travel for H^+ ions is toward the cathode. Simultaneously, oxygen ions migrate to the anode, where they oxidize to form oxygen atoms and release electrons. The equation for the complete reaction accounting for the heat input is represented in equations (3) and (4). It has been shown that the diffusion of hydroxide ion has little impact alkaline water electrolysis cell because of the high flow rate of electrolyte [12].

At the cathode, hydrogen cations are reduced to hydrogen gas with the help of electrons from the negative terminal cathode. While the hydroxide anions migrate to the anode, where they oxidize to form oxygen atoms and release electrons. The equation for the complete reaction accounting for the electrical power and heat input is represented in equations (3) and (4).

$$\Delta G = \Delta H - T\Delta S \quad (3)$$

$$H_2O_{(l)} + 237.2\,\frac{\text{KJ}}{\text{Kmol}}(\text{Electricity}) + 48.6\,\frac{\text{KJ}}{\text{Kmol}}(\text{Heat}) \rightarrow H_{2(g)} + \frac{1}{2}O_{2(g)} \tag{4}$$

The process of alkaline electrolysis is advantageous due to the simplicity of the process, the abundance of water and alkaline salts, and the high purity of the produced hydrogen and oxygen [13]. The most prominent alkaline compounds used in alkaline electrolysis are potassium hydroxide (KOH) and sodium hydroxide (NaOH) due to their high values for conductivity compared to other alkaline salts[14-16].

II. Experimental Setup

A schematic diagram the test setup are shown in Fig. 1. Figure 1 displays a schematic of the alkaline HHO cell that is composed of two identical stainless-steel plates acting as the cathode and anode of the cell. Hydrogen gas is produced at the cathode while oxygen gas is produced at the anode. The plates are separated by two 3 mm sticks of plastic separators to assure uniform spacing between the cathode and the anode. The HHO gas produced by the setup flows into a graduated cylinder which at the beginning is filled with the water-alkaline mixture. The cylinder is held by a retort stand. The gas mixture production rate is found by measuring the displaced volume over time. The time is measured by a stopwatch.

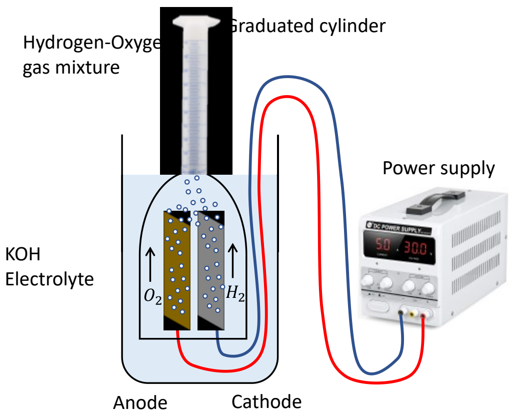

Fig.1. Schematic of the Test Setup

Hydrogen is formed on the cathode while oxygen is formed on the anode. The efficiency of the cell is calculated using the following equation:

$$\eta = \frac{\dot{m}_{HHO} HHV}{I\ V} \tag{5}$$

Where $\dot{m}_{H_2}$ and HHV are the produced mass flow rate and high heat value of hydrogen, respectively. I and V are applied current and voltage on the alkaline cell, respectively. The mass of hydrogen is calculated from hydrogen molar flow rate and molecular weight as shown below:

$$\dot{m}_{H_2} = \dot{N}_{H_2} M_{H_2} \tag{6}$$

Assuming that only hydrogen and oxygen are produced from the electrolysis process, the number of moles of H2 and O2 gas mixture is calculated by measuring the volumetric flow rate and ideal gas equation shown below. The volumetric flow rate is measured by a graduated cylinder and stopwatch.

$$\dot{N}_m = \frac{P\ \dot{\forall}_m}{R_u T} \tag{7}$$

Where $\dot{\forall}_m$, P and T are the volume flow rate, pressure, temperature of the mixture, respectively. R_u is the universal gas constant which equals 8.3145 kJ/(kmol.K). The molar flow rate of hydrogen-oxygen gas is calculated from the volumetric flow rate of the collected gas. The volumetric flow rate is measured by measuring the volume change over time. The electrical power is controlled by a variable power supply.

III. Results and Discussion

The performance of the alkaline electrolysis cell is examined under different conditions, namely, alkaline concentration, input voltage, plate thickness and plate spacing.

A. *The effect of alkaline concentration*

As alkaline concentration increases, one expects more ions to be available to carry the charges which in turn improves the gas formation. As shown in Figure 2, as alkaline concentration increases the current increases at a fixed voltage as well as the amount of HHO gas. As alkaline concentration increases, the electrolyte resistance decreases which improves electrolysis efficiency. In the given range and under 2.2 volts, the efficiency shows a linear relation with KOH concentration as shown in Figure 3.

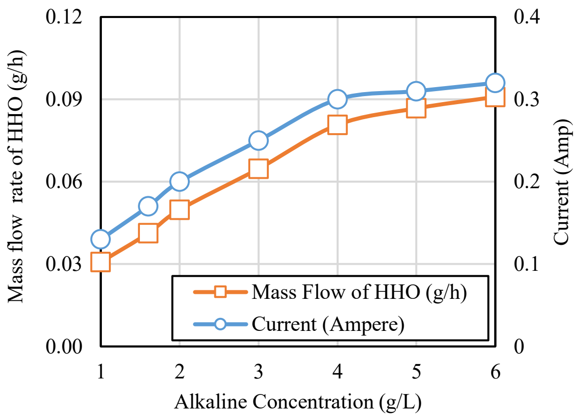

Fig. 2. The variation of HHO mass flow rate and current with alkaline concentration under voltage of 2.2 Volts, the plate thickness of 1 mm, and spacing between plates of 3 mm.

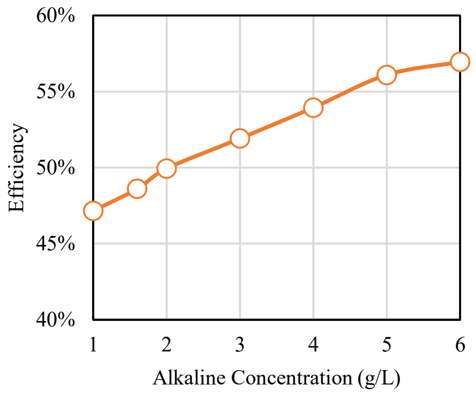

Fig. 3. The variation of efficiency with alkaline concentration under voltage of 2.2 Volts, the plate thickness of 1 mm and spacing between plates of 3 mm.

B. The effect of applied voltage

In order to determine the influence of applied voltages on electric current and HHO generation, the voltage applied to the cell was adjusted from 2.0 to 2.8 volts. Figure 4 shows that as the applied voltage increases, the current and the flow rate of HHO gas increase. This is expected since a higher voltage allows more electrons to pass through the cathode in a given period, increasing the reduction rate of hydrogen cation and therefore increases the production of HHO gas. However, the power increase due to voltage increase does not mean a more efficient process. A non-monotonic relation is observed between efficiency and voltage as shown in Figure 5. Obviously, when the KOH concentration in the solution is 4 g/L, the electrolysis cell performs best at a voltage between 2.2 and 2.4 volts. This is due to the cell's internal resistance, which turns excess input energy into heat, thereby warming the solution.

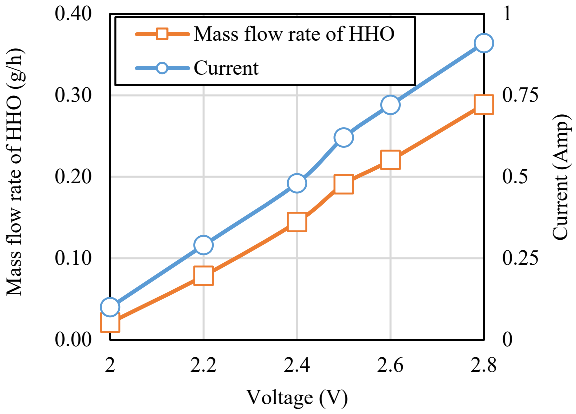

Fig. 4. The variation of HHO mass flow rate and current for different voltage inputs under a concentration of 4 g/L, plate thickness of 1 mm, and spacing between plates of 3 mm.

In general, the minimum voltage required to start the electrolysis process is known as the threshold voltage which depends on the properties of the electrolysis cell. Once the threshold voltage is exceeded, the rate of reaction increases with the increase in voltage, up to a certain maximum point known as the limiting voltage (See Figure 5). The limiting voltage is the voltage at which the electrolysis reaction reaches its maximum rate and beyond which further increases in voltage do not result in significant increases in reaction rate. In the contrary, the increase in applied voltages results in a higher energy consumption and heat generation, which leads to drop in efficiency.

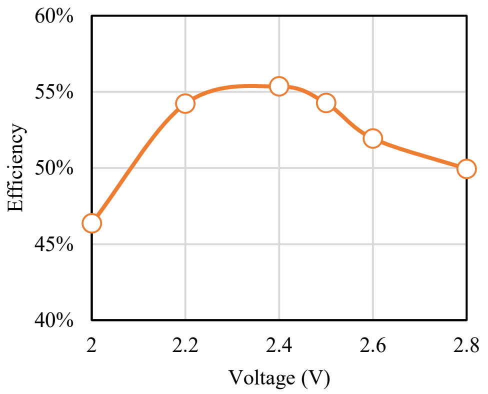

Fig. 5. The variation of efficiency for the different voltage inputs under a concentration of 4 g/L, plate thickness of 1 mm, and spacing between plates of 3 mm.

C. The effect of plate spacing

Figure 6 depicts the correlation between the plate spacing and the HHO mass flow rate. The x-axis represents plate spacing, whereas the y-axis represents HHO mass flow rate. The plate gap has a negative impact on the HHO mass flow. With wider gaps between the plates, HHO mass flow slows down. As the distance between electrodes increases, so does the electrical resistance, resulting in a slower hydrogen ion reduction rate.

The maximum HHO mass flow occurs at plate spacing of 3mm when the rate of production is 78.4 mg/h. As the distance between the plates grows, the amount of HHO flowing through them decreases. The mass flow rate decreases to 61.4 mg/h at a plate spacing of 6 mm, and around 25 41.3 mg/h at a plate spacing of 9 mm.

The relationship between the plate spacing and the current is also seen in Figure 8. The distance between the plates has an inverse correlation with the current. The maximum current is 290 mA when the plate spacing is 3 mm. Due to the increased distance between the plates, the current drops to 230 and 160 mA at 6- and 9-mm plate spacing, respectively.

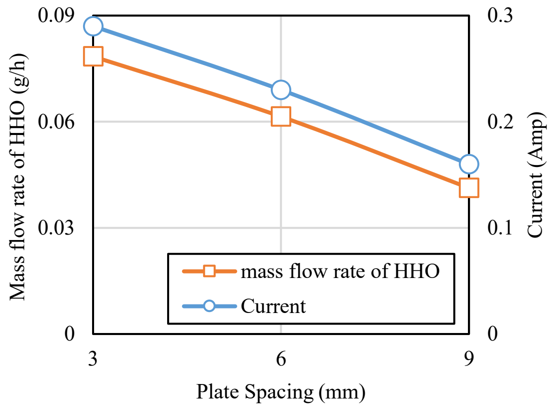

Fig. 6. The variation of the mass flow rate of HHO for the different spacing between the plates of 3, 6, and 9 mm for 1mm thick plates.

The relationship between plate spacing and electrolytic cell efficiency is demonstrated in Figure 9. The results show. The plate spacing has an adverse correlation with the efficiency of the system. At a plate spacing of 3 mm, the electrolytic cell operates at an efficiency of 57%. When the plate spacing is increased to 6- or 9-mm, respectively, the electrolytic cell's efficiency drops to 56% and 54%.

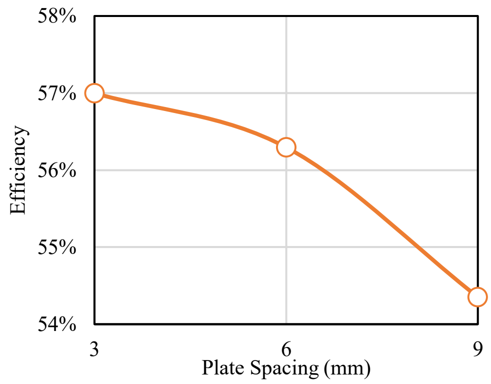

Fig. 7. The variation of the efficiency of the electrolytic cell for the different spacing between the plates of 3, 6, and 9 mm for 1mm thick plates.

It is not easy to determine the exact transport distance because the liquid electrolyte contains an abundance of hydroxide, which prevents it from being equal to the distance between the electrodes [17]. It is clear that the distance between electrodes can impact the performance of the electrolysis process in several ways. First, the resistance of the electrolyte solution is influenced by the distance between the electrodes. The resistance of the solution increases as electrode spacing increasing which raises the voltage drop across the electrolyte. Hence, to maintain the same current density with this higher voltage drop, a higher input voltage is needed, which may lead to increased energy consumption and decreased efficiency. Second, the mass transfer of the reactants and products to and from the electrode surfaces is influenced by the distance between the electrodes. A slower mass transport rate results from a greater space between the electrodes which cause slower reaction times and lower efficiency. Lastly, the separation between the electrodes have an impact on how the current density is distributed across the electrode surfaces. The distribution of current density may be more uneven with a greater gap between the electrodes, with higher current densities occurring close to the electrode surfaces. Reduced electrode lifetimes and decreased efficiency may be the results of this uneven distribution, which may also cause localized heating and gas evolution.

Overall, a number of variables, such as the characteristics of the electrolyte solution, the current density applied, and the electrode materials and geometry, affect the ideal distance between electrodes in water alkaline electrolysis. In industrial-scale electrolysis systems, practical considerations and electrode durability must be balanced against the general preference for a closer spacing between electrodes for higher efficiency and less energy consumption.

IV. Conclusion

This experimental evaluation of an alkaline water electrolysis cell examined how three different parameters affect the performance of the cell in HHO production. the following conclusion could be made from the data collected:

- The increase in alkaline concentration decreases electrolyte resistance which improves the efficiency of the cell.
- Higher power will be forced into the electrolysis cell when the voltage supply increases which increases the production of HHO gas.
- The optimal supply voltage for the cell for a concentration of 4 g/L is between 2.2 and 2.4 volts.

Larger spacing between electrodes decreases both production of HHO and the efficiency of the cell.

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