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Investigate the Effect of Temperature and Voltage on the Production of Hydrogen from waste Aluminum

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Abstract
The objective of this work is to produce hydrogen using waste aluminum at different temperature and voltage. In order to prevent global warming and regulate climate change, hydrogen is in high demand as a future renewable green energy and an active study topic. To produce the hydrogen waste aluminum is used as electrodes in the experiments at various temperatures for same electrolyte (normal water). In terms of time, the creation of 5ml hydrogen was observed at 30 °C, 60 °C, and 80 °C. When electrolysis was performed at 30 °C, 60 °C, and 80 °C, the findings demonstrate that time and current consumption vary for 5ml hydrogen production at 20V, 25V, and 30V. The results reveal that as the voltage and temperature rise, so does the current consumption. The testing results reveal that the shortest time to create 5ml at 30V and 80 °C is 4.5 minutes, while the longest time for the same volume is 14.5 minutes at 20V and 30 °C. At a given point in travel, current consumption and hydrogen production at 80 °C are higher than at 30 °C and 60 °C. The electrolysis of waste aluminum preserved and control the gases emitted by recycling of aluminum. In addition, the oxides formation of aluminum can be used for different purposed in different field like medical, laboratory purposed, etc.

1. Introduction

Hydrogen is a renewable energy (RE) source, and in 2003, the United States produced 7.6 billion kilos of hydrogen through the thermal process. Steam methane reforming is the name for the thermal method of producing hydrogen (SMR). Hydrogen has a wide range of uses in industries such as chemicals, electronics, metals, fuels, food, and float glass [1]. Electrolysis is a chemical reaction that occurs when an electric current (direct current) is used to initiate it, and the disintegration of the reaction (individual water molecules breaking down into distinct hydrogen and oxygen molecules) is depicted in Eqn.1 as follows:

$$2H_2O(l) \rightarrow 2H_2(g) + O_2(g) \qquad \textbf{Eqn. 1}$$

According to equation (1), the optimal volume of oxygen and hydrogen gas is 1:2. Because electric current cannot conduct in pure water, water electrolysis requires the dissolution of an ionic material (acid/basic). The electrodes begin to create hydrogen gas at the negatively biased electrode and oxygen gas at the positively biased electrode at a voltage termed critical voltage. Eqn.2 and Eqn.3 show how hydrogen and oxygen are produced Eqn.3 [2]. Electrode with a positive connection to the power supply (anode):

$$4OH^- \leftrightarrow 2H_2O + O_2 + 4e^- \qquad \textbf{Eqn. 2}$$

Negatively connected electrode with power supply (cathode):

$$2H^+ (aq) + 2e^- \leftrightarrow H_2(g) \qquad \textbf{Eqn. 3}$$

The critical cell voltage for the start-up of electrolysis at standard conditions is obtained by using Eqn.4,

$$E^0_{cell} = \frac{\Delta G}{nF} \qquad \textbf{Eqn. 4}$$

Here, n is the number of electrons exchanged, and G^o is the change in Gibbs free energy under standard conditions. Helmholtz free energy (A^o) is utilized instead of Gibbs free energy in closed electrochemical cells, and it is computed using Eqn.5 and Eqn.6,

$$E^o_{cell} = -\frac{\Delta A^0}{nf} \qquad \textbf{Eqn. 5}$$

$$\Delta A^o = \Delta H^o - TR\Delta n - T\Delta S^o \qquad \textbf{Eqn. 6}$$

For the electrolysis of water, $\Delta H^o = 285.8\,\mathrm{kJ/mol}$, $\Delta n = 1.5, \Delta S^o\,(H_2) = 130.6, \Delta S^o(O_2) = 205.1, \Delta S^o(H_2O)(l) = 70\frac{J}{mol}K, \Delta S^0_{tot} = 163.14\mathrm{J/mol\,K}$, and $\Delta A^o = 233.1\mathrm{kJ/mol}$. Therefore, the critical is $E_{cell} = 1.21\ V$ [3].

Because the authors employ waste aluminum, the electrolysis of water and the creation of hydrogen in this study differs from previous studies. This is because waste aluminum is inexpensive to electrolyze, saves the environment and energy, and is freely accessible. The mass of aluminum is reduced to $Al(OH)_2$ and $Al(OH)_3$, which can be used directly for various purposes. The use of waste aluminum in electrolysis has two benefits: one is the generation of hydrogen, and the other is the formation of aluminum hydroxides. New, old, and internal scrap aluminum, according to the International Aluminium Institute, emit 0.5, 0.6 and 0.3 tons of CO_2 per tons of recycled aluminum, respectively.

Using discarded aluminum to make hydrogen reduces greenhouse gas emissions and helps to clean up the environment. The massive machinery that uses fossil fuels isn't the only source of pollution from recycling aluminum. When aluminum is melted, pollutants are released into the atmosphere. Furans, dioxides, hydrogen chloride, and particulate particles are released during the melting process. Furans are potentially one of the most hazardous contaminants in the atmosphere. They have been linked to a variety of human health issues, including liver damage, certain types of cancer, skin abnormalities, neurological issues, and immune system dysfunction.

In this research work, authors don't use any chemical catalyst to improve hydrogen production, hence the production of hydrogen is chemical-free. This also makes the work distinct from others because it is temperature-dependent and chemical-free. We are interested in temperature because temperatures range from zero to +45 °C in different places, it is vital to investigate the rate of hydrogen production with temperature. As a result, the research provides the best recommendations for selecting a natural hydrogen production site as well as a laboratory. The aluminum hydroxides produced by this process can be used for a variety of applications like relieving heartburn, acid indigestion, peptic ulcer, gastritis, esophagitis, hiatal hernia, or too much acid in the stomach, etc.

2. Literature Review

In 1789, Deiman and Troostwijk used an electrostatic generator to demonstrate water electrolysis for the first time. Later, Ritter took advantage of Volta's battery technology, allowing separation of the resultant gases and, in 1888, a commercial hydrogen synthesis method. In 1991, the first hydrogen-based device for storing renewable energy was developed, and by 1992, over 400 industrial water electrolyzes had been installed. In the Gemini Space Program [4], alkaline solutions were utilized as electrolytes, and the proton exchange membrane method was used to generate electricity. With a series of experiments, Cavendish investigated the properties of hydrogen-related to store hydrogen for the first time in 1766. Currently, compression or cryogenic liquefaction are the best methods for storing hydrogen. When compared to existing fuels, hydrogen has a high energy density by weight, but a low volumetric density [4].

The size and rate of expansion of generated flocs increase at high voltages, which has an impact on the efficient synthesis of hydrogen [6]. The number of oxidized aluminum increases when the electrical potential is increased during electrolysis [7]. Furthermore, as the electrical current is increased, the density of bubbles grows while their size decreases. In general, a 20V electrical potential is necessary to achieve the requisite hydrogen generation efficiency. The efficiency is also affected by electrical conductivity and the distance between electrodes [8]. To remove different ions and organic debris, electrochemical or electrocoagulation methods are also used. The system's efficiency was assessed at three different pHs, voltages, and time intervals, yielding a 95.6 percent efficiency for the electrocoagulation technique in hardness removal [9].

According to IRENA's Renewable Energy Roadmap (REmap) analysis, hydrogen will account for around 6% of total energy consumption by 2050 [10], whereas the Hydrogen Council estimates that it will account for roughly 18% by the same year [11]. Around 120 million tonnes of hydrogen are produced annually around the world, with only two-thirds of that being pure hydrogen and the remaining one-third being a mixture. Furthermore, natural gas and coal account for nearly 95% of all hydrogen production. Various countries and areas have hydrogen pipeline systems. Long-distance hydrogen transfer is similar. Hydrogen utilization is fairly limited outside of these traditional uses, which have been available for decades. New applications must drive hydrogen's role in the energy transition, and its supply must be decarbonized [12]. According to the International Energy Agency, there are more than 380 hydrogen refueling stations open to the public in 2019, and the stock of fuel cell electric vehicles (FCEVs) reached 11,200 units at the end of 2018, with sales of roughly 4,000 units. In addition, by 2025, the Hydrogen Council expects 3,000 refilling stations, enough to fuel about 2 million FCEVs reported by IEA 2021.

3. Methodology

3.1 Experiment

As in traditional water-splitting technologies, inputs are water and electricity while the products are hydrogen and oxygen gases [13]. When current is applied to aluminum electrodes in electrolysis, they act as sacrificial electrodes, producing cations and anions. Metal hydroxide ions are formed by the hydrolysis of metal ions generated in the electrochemical cell according to reactions Eqn.7 to **Eqn.10** and at pH values between 6.0 and 7.0. The formation of gases during water electrolysis and metal dissolution allows the ensuing flocs to float **[14]**:

$$Al \rightarrow Al^{3+}(aq) + 3e^{-} \quad \textbf{Eqn. 7}$$

$$2H_2O + 3e^{-} \rightarrow \frac{3}{2}H_2(g) + 3OH^{-} \quad \textbf{Eqn. 8}$$

$$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^{+} \quad \textbf{Eqn. 9}$$

The final equation is obtained as

$$2Al + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2 \quad \textbf{Eqn. 10}$$

In comparison to other processes, the electrolysis process is one of the technological processes for producing environmentally beneficial hydrogen gas. Furthermore, if an acidic or basic hydrogen catalyst is utilized during electrolysis, the amount of hydrogen produced increases as the conductivity of the catalyst increases. Temperature, pressure, and electrolyte purity are all elements that influence water electrolysis. In the equation, the chemical reactions of electrodes in various media (neutral, acid, and base) are shown **Eqn.11** to **Eqn.13**:

$$3Al(s) + 8H_2O(l) \rightarrow Al(OH)_2(s) + 2Al(OH)_3 + 4H_2(g) \ (Neutral) \quad \textbf{Eqn. 11}$$

$$2Al(s) + 6H_2O(l) \rightarrow O_2(g) + 4H_2(g) + Al(OH)_2(s) \quad (Acid) \quad \textbf{Eqn. 12}$$

$$2Al(s) + 6H_2O \rightarrow 2Al(OH)_3(s) + 3H_2O \quad (Base) \quad \textbf{Eqn. 13}$$

Since $Al(OH)_3$ has a higher weight and density, it settles faster and has higher efficiency.

The experimental method is used to investigate hydrogen generation at various temperatures and voltages under standard air conditions. Electrodes, Beaker, Burette, DC Regulator (Power supply, 30V, 5A), Tap Water (Normal water), Magnetic Starrier, and other materials are necessary for the experiment. As electrodes, scrap aluminum sheets in a rectangular shape with dimensions of (1×1×0.05) cm^3 were constructed. The temperature of electrolyte in the experimental was controlled using temperature control present in magnetic starrier device. The size of aluminum electrode is predefined by authors because authors take an experiment to study the hydrogen production at different temperature and voltage. The electrodes has a 4cm gap between the positive and negative terminals. The electrode is placed within the inverted burette to measure the volume of hydrogen generation. Normal water has a pH value of 6.5. The experience arrangement is depicted in **Figure 1** below.

When a DC is passed between two electrodes submerged in an electrolyte, water electrolysis occurs. At the anode, oxygen is produced, whereas, at the cathode, hydrogen is produced. The main parameter of hydrogen production is the current traveling between any two electrodes. One of the most effective methods for bypassing electrical current through a water solution is electrical water analysis. It is simple and inexpensive to do, but it is not more efficient. The splitting of a water molecule with electricity to produce hydrogen and oxygen is known as electrolysis. The charge breaks the hydrogen-oxygen link, forming ions on both poles: the positively charged anode draws the oxygen, while the negatively charged cathode attracts the hydrogen.

4. Results and Discussion

4.1 Current variation with Voltage at different temperature

Figure 2 illustrates the current consumption for producing 5ml of hydrogen at 20V, 25V, and 30V. Each 5ml hydrogen production experiment was carried out at 30 °C, 50 °C, and 80 °C. The results reveal that the current consumption increases with voltage when the experiment is conducted at 30°C. When the experiment was conducted at 60 °C and 80 °C, a similar result was observed. Current consumption rose with temperature, for example, at the same voltage, current consumption increased from 80 ºC to 60 ºC to 30 ºC. Similarly, as illustrated in **Figure 2**, electric power usage rises as the temperature rises and consumption was high at high temperatures than at low temperatures. For example, at 30V with an experiment environment of 80 °C, 5ml hydrogen production takes 4.5 minutes, whereas, at 30V with an experiment environment of 30 °C, 5ml hydrogen production takes 7 minutes.

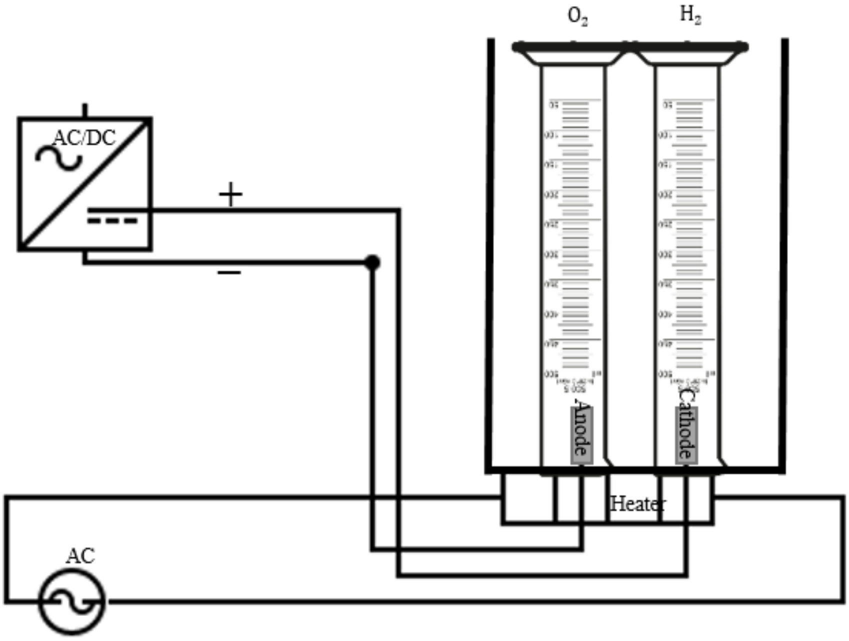


Figure 1: Electrolysis of water using waste Al electrode

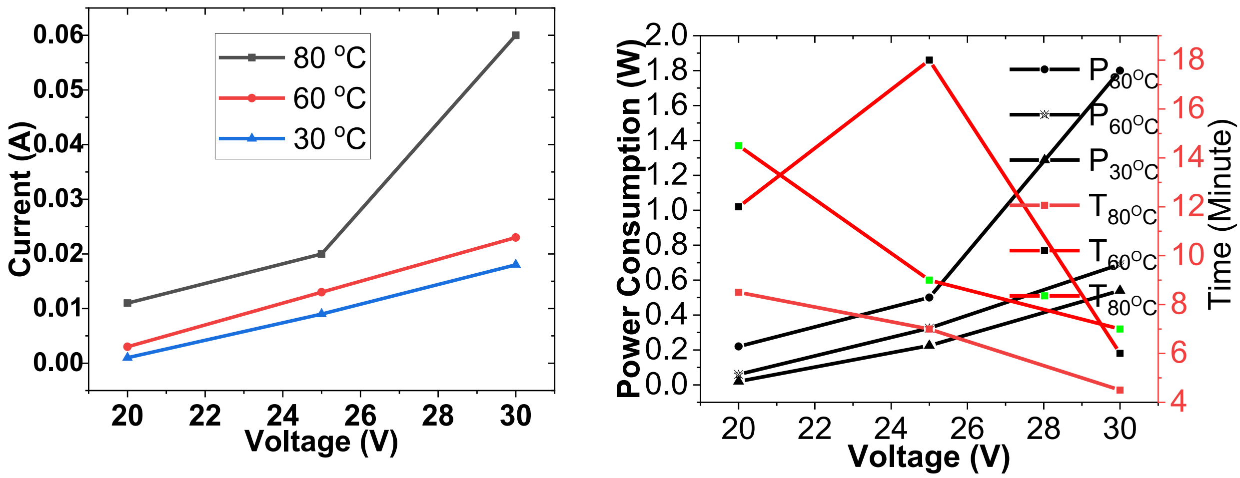


Figure 2: Voltage vs Current drawn at different temperatures

Porciuncula et al. (2012) electrolyzed water with KOH and NaOH catalysts at temperatures ranging from 295 to 345 K using aluminum (0.02×0.51mm) and discovered that at the same catalyst concentration, hydrogen generated by NaOH is larger than KOH [15]. The hydrogen production increase with voltage because the bonding energy of hydrogen and oxygen is less then applies voltage. Since we have relation of change in enthalpy $\Delta H = \Delta G + T\Delta S$, here T is directly related to temperature therefore increasing the temperature the enthalpy of the system increase and larger number of molecules get high energy as voltage and temperature increase therefore the production of hydrogen with temperature and voltage are directly proportional. The providing temperature to electrolyte causes the molecules to stretch the OH bands and the interaction between OH less and less amount of energy needed to break the OH for hydrogen production.

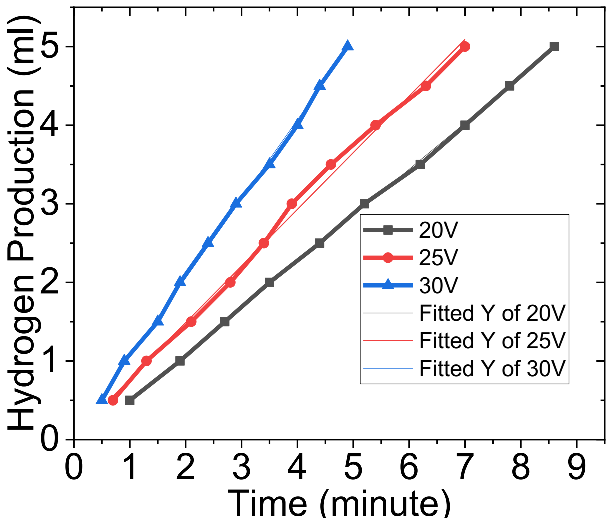
The hydrogen production at same voltage is higher at 80 °C than 30 °C because the energy gain by electrolyte molecules at high temperature faster and high than low at same voltage. At low temperature the production

4.2 Hydrogen Production with time at 80 °C

Figure 3 shows the increase of hydrogen production with time at 20V, 25V, and 30V at 80 °C. When hydrogen generation was measured for 5ml at 20V, it took 8.5 minutes, 7 minutes at 25V, and 4.5 minutes at 30V. This demonstrates that producing 5ml hydrogen at 30V takes less time than at 25V or 20V. At 80 °C, the electrolysis consumes 0.011A at 20V, 0.06A at 25V, and 0.013A at 30V. In addition, the amount of energy required to break the OH bond for reversible reaction is 1.23V which is minimum and ideal. But for our experiment we consider the applied voltage greater than 20V because the sized of electrodes are small and authors are try to use the wastage aluminum which has random sized but small.

4.3 Hydrogen Production with time at 60 °C

Figure 4 depicts the increase in hydrogen production with time at 20V, 25V, and 30V, as well as at 60 °C. When hydrogen production was measured for 5ml at 20V, it took 12 minutes, 8 minutes at 25V, and 6 minutes at 30V. This demonstrates that producing 5ml hydrogen at 30V takes less time than at 25V or 20V. At 60 °C, the electrolysis consumes 0.003A at 20V, 0.013A at 25V, and 0.023A at 30V.



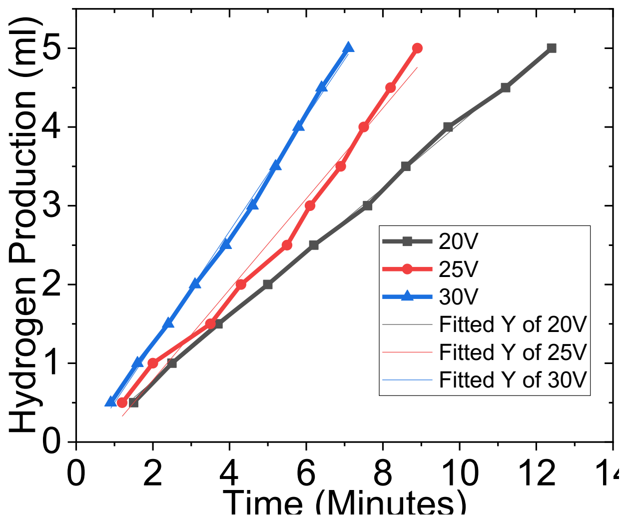


Figure 3: Hydrogen production with time at 80 °C **Figure 4:** Hydrogen production with time at 60 °C

The hydrogen production is for 30V is higher because the energy required to break the bond of electrolyte molecules is high in compare to other. That is at high voltage large number of electrolytic molecules gain energy therefore the beak of OH bond is high and hence large number of hydrogen production at same time. For low voltage, the energy supply to electrolytic molecules is lower that is low number of molecules gain energy and hence the production is low at same in compare to low voltage.

4.4 Hydrogen Production with time at 30 °C

Figure 5 depicts the growth of hydrogen generation with time at 20V, 25V, and 30V, as well as at 30 °C. When hydrogen production was measured for 5ml at 20V, it took 14.5 minutes, 9 minutes at 25V, and 7 minutes at 30V. This demonstrates that producing 5ml hydrogen at 30V takes less time than at 25V or 20V. At 30 °C, electrolysis consumes 0.001amps at 20 volts, 0.009 amps at 25 volts, and 0.018 amps at 30 volts.

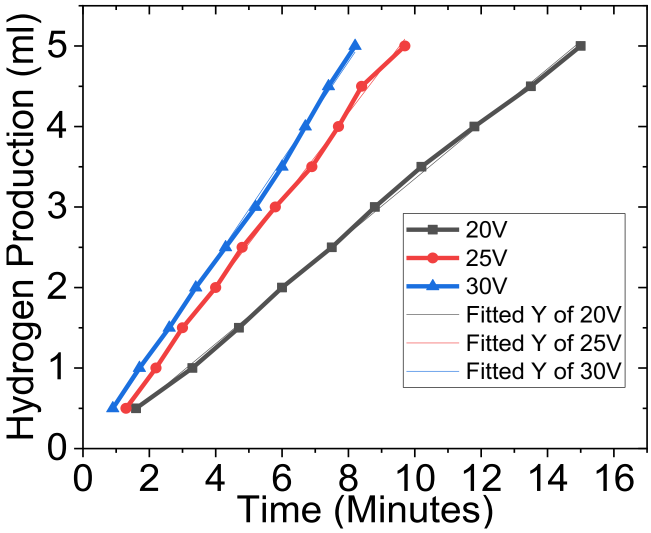


Figure 5: Hydrogen production with time at 30 °C

The production nature of hydrogen with time at consider temperature and voltage are linear. That means with increasing in the temperature and voltage the production of hydrogen is increasing with the aluminium electrode.

On comparing the hydrogen production with voltage and temerpature, it was found that the hydrogen production for high voltage (30V) was faster than other lower voltage (20V and 25V) at any temperature 30 °C, 60 °C and 80 °C for same dimension of electrodes. Also for high temperature the rate of hydrogen production is high at same voltage.

5 Conclusion

The experimental result shows with increasing the temperatures the hydrogen production and current consumption increase. If we compare the time of 5ml hydrogen production at same temperature for different voltage it is observed that time taken for 5ml production at high voltage (30V) is less than other 20V and 25V. Similarly, the time taken to produce 5ml hydrogen at high temperature (80 °C) less than low temperature at different voltage. The hydrogen production at 30V and 80 °C is higher in compare to another consider voltage and temperature. In this work authors limit the temperature up to 80 °C and voltage 30V for fixed a single dimension of aluminum. One can studies the hydrogen production by changing electrodes materials, catalyst, voltage and temperature to increase the hydrogen production. This is because hydrogen is assume as future energy and used as zero emission for different automobiles, vehicles, portable and non-portable devices as well as engines.

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