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Hydrogen Production from Aluminum Waste using the Aluminum-Water Method with Potassium as Activator

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Abstract

The research on hydrogen production from aluminum waste using the aluminum-water method with potassium as an activator has been successfully conducted. This study aims to evaluate the performance of potassium as an activator in hydrogen production with water volume and potassium percentage variables. The method involves reacting aluminum waste-sized 60 mesh with potassium as an activator. The research results show that the optimum conditions are achieved with 1 gram of aluminum reaction by adding 1.5 mL of water and 7% w/w potassium, producing 553 mL of hydrogen gas at a 69 mL/min production rate. In conclusion, potassium as an activator effectively enhances hydrogen production from aluminum waste.

Keywords: Hydrogen, Potassium, Aluminum-water, Activator, aluminum-waste

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Abstrak (Indonesian)

Penelitian mengenai produksi hidrogen dari limbah aluminum dengan metode aluminum-air menggunakan kalium sebagai aktivator telah berhasil dilakukan. Penelitian ini bertujuan untuk mengevaluasi kinerja kalium sebagai aktivator dalam produksi hidrogen dengan variabel volume air dan persentase kalium. Metode yang digunakan melibatkan reaksi limbah aluminum berukuran 60 mesh dengan kalium sebagai aktivator. Hasil penelitian menunjukkan bahwa kondisi optimum dicapai pada reaksi 1 gram aluminum dengan penambahan 1.5 mL air dan 7% b/b massa kalium, menghasilkan produksi gas hidrogen sebesar 553 mL dengan laju produksi 69 mL/menit. Kesimpulannya, kalium sebagai aktivator efektif dalam meningkatkan produksi hidrogen dari limbah aluminum.

Kata Kunci: Hidrogen, Kalium, Aluminum-water, Aktivator, limbah alumunium

INTRODUCTION

In the modern era, human activities and operations heavily depend on energy. However, the current fuel predominantly used is fossil fuel, which produces carbon dioxide in the environment. Excess carbon dioxide in the atmosphere can have adverse effects and is a major contributor to the greenhouse effect and global warming, leading to extreme weather changes [1]. In addition to producing carbon dioxide emissions, the availability of fossil fuels in nature is also beginning to deplete and will reach its limit if used continuously (non-renewable energy) [2]. Research on alternative renewable energy is being conducted almost worldwide, seeking sustainable alternative energy sources to replace fossil fuels [3]. Developed countries have also started transitioning to low-carbon energy decarbonization [4].

Hydrogen-based fuel cells have become an attractive alternative to fossil fuels and can serve as decarbonization energy [5]. Hydrogen is a new energy source with abundant reserves, high combustion heat, and environmental friendliness because its combustion

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byproduct is only water [6]. The reaction between hydrogen and oxygen produces energy that can be used as a fuel source [7].

Hydrogen production can be carried out through several methods, such as steam reforming [8], electrolysis [9] [10], and the aluminum-water method [11]. The aluminum-water method is one of the techniques used to produce hydrogen by reacting the aluminum metal with water, with aluminum oxide as a byproduct [12]. The availability of aluminum metal is also abundant, including from food and beverage waste. Aluminum waste can be repurposed to produce hydrogen gas [13]. The aluminum-water method has several advantages, including a simple and safe operation system with low costs [14].

Aluminum metal waste cannot react directly with water due to a thin oxide layer covering the aluminum particle surfaces. This oxide layer prevents the interaction between aluminum and water, thus hindering the reaction from occurring spontaneously [15]. Therefore, a catalyst or activator needs to be added. Common catalysts used are basic solutions like NaOH or KOH [16]. Basic solutions such as NaOH or KOH are effective catalysts for increasing the reaction rate between aluminum and water as they can dissolve the oxide layer covering the aluminum surface. The more basic catalyst added, the more oxide layers dissolve, allowing the reaction to occur spontaneously and more rapidly, thus producing more hydrogen gas [14]. Activators that can be used for the aluminum-water reaction include Mg, Pt, K, Li, and other metals. Alkali metals are reactive for the aluminum-water reaction because their reactivity can break down the thin oxide layer that prevents the aluminum-water reaction. In this research, potassium alkali metal is used as the activator. Compared to alkali metals like lithium and sodium, potassium has higher reactivity. Tekade *et al.* (2018) revealed that alkalis are highly soluble in water, allowing their aqueous solutions to easily come into contact with aluminum metal. This is a key parameter for controlling the hydrogen production rate in water-splitting reactions. The high pH of the aqueous alkaline solution assists in the efficient distortion of the oxide layer on the aluminum surface [17], facilitating the formation of positive ions and subsequent reactions, ultimately increasing hydrogen production [16].

Kumar (2015) also researched hydrogen gas production using aluminum and water with Sodium as an activator. The experimental results indicated that the distortion of the oxide layer occurs rapidly in the presence of alkali, thereby resulting in a higher rate of hydrogen production [18].

According to research by Huang et al. (2013) [19], the size of aluminum particles can also affect the amount of hydrogen gas produced; the smaller the particle size used, the higher the hydrogen gas production. Previous research by Amelia (2021) [20] showed 20, 40, and 60 mesh particle size variations. The results of this study indicated that 60 mesh aluminum produced the most optimal hydrogen gas compared to 20 and 40 mesh aluminum. The novelty of our research is using aluminum waste for hydrogen production, using milling methods, and adding a potassium activator in the mechanical alloying method to mix the aluminum metal and activator. In this study, we tested the hydrogen gas production rate using 60 mesh aluminum with several variables, including the addition of water volume and the performance of the potassium activator.

MATERIALS AND METHODS

Materials

This study used 60 mesh aluminum powder from aluminum waste, potassium bulk Riedel de Haen 12621, and distilled water.

Preparation of Raw Aluminum Material

The aluminum samples used in this study were sourced from aluminum waste. The following steps were undertaken to obtain the 60-mesh aluminum powder: the aluminum waste was separated from coarse impurities and then cleaned of fine contaminants, such as dust, using mineral water. Subsequently, the cleaned aluminum was dried by exposure to open air. Once dry, the aluminum waste was pulverized using a short-duration mechanical alloying process. Finally, the milled product was sieved using a 60-mesh sieve [20].

Hydrogen gas production using the Aluminum-Water method with Potassium Activator

Effect of water volume

1 gram of 60 mesh aluminum was mixed with potassium powder at three wt.% of aluminum and then placed into the HEM (High Energy Milling) device. The metals were placed into a container with grinding balls at a 5:1 ball-to-powder ratio (BPR) and milled for 15 minutes, with 3 minutes of milling followed by 1 minute of rest. The resulting potassium-aluminum alloy (1 g) was then placed into a reactor inside a glove box flushed with nitrogen gas to prevent oxygen

presence. Water was added to the reactor in varying volumes (1, 1.5, 2, 2.5, and 3 mL) to determine the optimal water volume. This procedure was conducted at room temperature. The volume of hydrogen gas produced was recorded from the initial gas formation until 60 minutes, and the volume of hydrogen gas was measured based on the volume of water displaced from a measuring cylinder.

Effect of Potassium activator mass

1 gram of 60 mesh aluminum was mixed with potassium in varying composition masses of 3, 5, and 7 wt. % of the aluminum, then milled using ball milling for 15 minutes. One gram of the resulting potassium-aluminum alloy from each mass ratio was placed into a reactor inside a glove box flushed with nitrogen gas to prevent oxygen presence. In the optimal volume determined from previous procedures, water was added to the reactor at room temperature. The volume of hydrogen gas produced was recorded from the initial gas formation until 60 minutes, and the volume of hydrogen gas produced was measured based on the volume of water displaced from a measuring cylinder.

Data analysis

The reaction rate for each procedure was determined using the following equation:

$$r = \frac{\Delta v}{\Delta t}$$

r = reaction rate (mL/min)
Δv = change in hydrogen gas volume (mL)
Δt = change in time (minutes)

The reactor contains a single channel in the form of a tube used to expel the hydrogen gas produced from the reaction between aluminum and water. This tube is connected to an inverted 250 mL graduated cylinder filled with water. The hydrogen gas produced will flow through the tube and displace the water, thus reducing the volume of water in the graduated cylinder. The time and the reduction in volume are recorded and processed to determine the rate of hydrogen gas production. Next, XRD characterization is performed to identify differences in compounds formed before and after the reaction. The differences in compounds formed in the samples can be determined by identifying the 2-theta peak angles and reference peaks from JCPDS.

RESULTS AND DISCUSSION

Hydrogen gas production using the potassium activator in this study was carried out with variations in water volume and activator mass. The use of potassium metal as an activator dissolves or breaks down the oxide layer covering the aluminum surface, allowing water to easily oxidize the aluminum metal to aluminum hydroxide as shown in the following equation:

$$2K + 2H_2O \rightarrow 2KOH + H_2 \quad (1)$$

$$Al_2O_3 + 2KOH + 3H_2O \rightarrow 2KAl(OH)_4 \quad (2)$$

$$KAl(OH)_4 \rightarrow KOH + Al(OH)_3 \quad (3)$$

Once the oxide layer on the aluminum surface is destroyed, the reaction between aluminum and water proceeds rapidly, forming hydrogen gas bubbles as shown in the following equation:

$$Al + 3H_2O \rightarrow Al(OH)_3 + \frac{3}{2}H_2 \quad (4)$$

Adding activator substances such as potassium metal effectively increases the reaction rate and the amount of hydrogen gas produced [21].

Effect of water volume

Adding water to the reactor containing the potassium-aluminum alloy will form aluminum hydroxide and hydrogen gas, as shown in **Figure** 1.

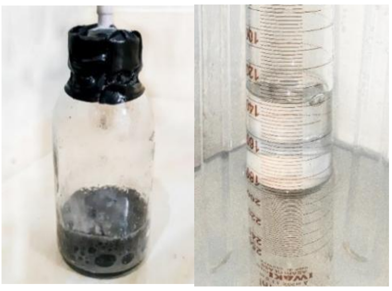

Figure 1. Formation of Hydrogen Gas

Figures 2 and 3 show the amount of hydrogen gas produced and the reaction rate of the potassium-aluminum alloy with various water volumes over 60 minutes.

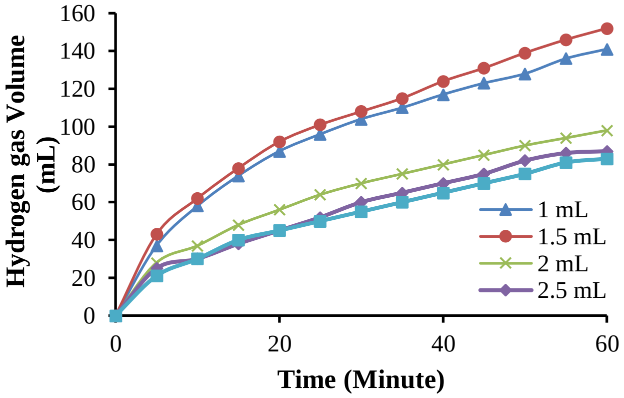

Figure 2. Hydrogen Gas Production at Various Water Volumes

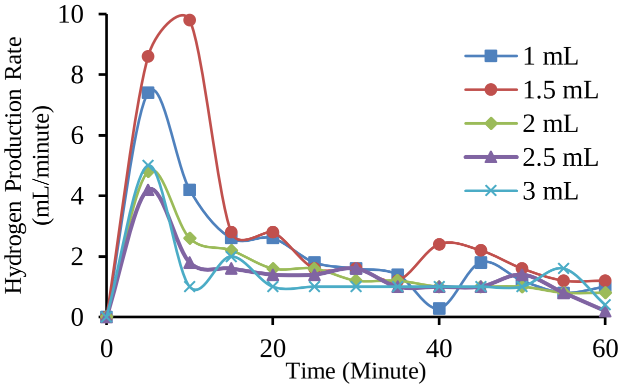

Figure 3. Reaction Rate of Hydrogen Gas Production at Various Water Volumes

It can be observed from **Figures** 2 and 3 that the volume of water added significantly influences the amount of hydrogen gas produced and the reaction rate. Based on the graph in **Figure** 5, hydrogen gas production increases with the addition of water from 1 to 1.5 mL. However, when the water volume is increased from 2 to 3 mL, the hydrogen gas production decreases. This is consistent with the stoichiometric equilibrium. According to the reaction stoichiometry, 1 mole of aluminum reacts optimally with 3 moles of water; theoretically, 1 gram of aluminum (0.037 mol) can react optimally with 0.1 mol of water, approximately 1.8 mL. In this study, the optimal hydrogen gas production was achieved by adding 1.5 mL of water, producing 152 mL of hydrogen gas at a rate of 8.6 mL/min. Hydrogen gas production decreased when the water volume was increased to 2 to 3 mL. This is because the added water volume exceeded the stoichiometric equilibrium, preventing the production of a higher volume of hydrogen gas. Excessive water volume can disrupt the exothermic nature of the reaction, causing the reaction temperature to decrease, which hinders the activator's ability to break down the oxide layer on the aluminum surface [21].

Effect of activator mass

The mass of the potassium activator can affect the production of hydrogen gas and the reaction rate. **Figures** 4 and 5 show the effect of the potassium activator mass (in % w/w) on the produced hydrogen gas. The graph in **Figure** 4 shows that hydrogen gas production increases with the addition of higher mass percentages of the potassium activator. Furthermore, as shown in **Figure** 5, the reaction rate of hydrogen gas production accelerates with the increase in activator mass. A 7% w/w potassium addition achieved optimal hydrogen gas production, producing 477 mL of hydrogen gas at 60.6 mL/min.

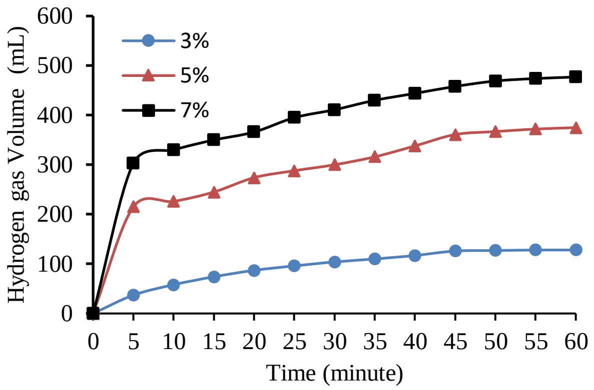

Figure 4. Hydrogen Gas Production at Various Potassium Activator Mass Percentages

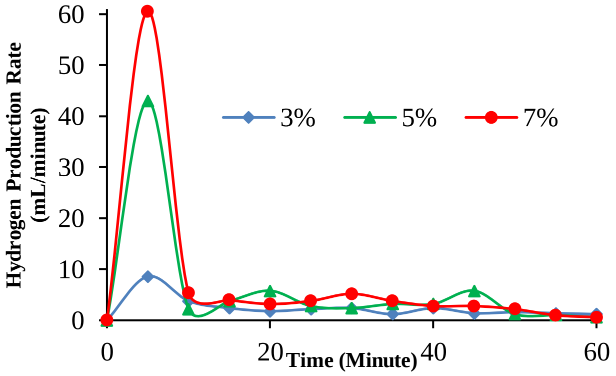

Figure 5. Reaction Rate of Hydrogen Gas Production at Various Potassium Activator Mass Percentages

The potassium-aluminum alloy formed from the milling process was then placed into the reactor and mixed with water at the optimal volume, resulting in the potassium activator reacting with water to form the reaction facilitated by the potassium activator breaks down the oxide layer on the aluminum, allowing water to oxidize the aluminum efficiently. The formation of potassium hydroxide lowers the activation energy and breaks down the oxide layer on the aluminum surface. As the mass percentage of the potassium activator increases, the oxide layer on the aluminum surface is more easily destroyed, resulting in the opening of pores on the aluminum surface. The open pores on the aluminum surface facilitate a faster reaction between aluminum and water, making the process more effective for hydrogen gas production and increasing the reaction rate [21].

Reaction between Aluminum and water for Hydrogen gas production without activators

They are testing the reaction between aluminum and water without using catalysts or activators to compare hydrogen gas production with and without these additives. Based on the conducted tests, no hydrogen gas bubbles formed, indicating that the reaction does not proceed spontaneously at room temperature and pressure. This is due to the oxide layer covering the aluminum particles, which prevents the reaction between aluminum and water at room temperature and pressure without the addition of activators [11]. The reaction between aluminum and water without activators can occur at 1250 °C over 90 to 120 minutes, making it inefficient for hydrogen gas production [22].

X-Ray Diffraction (XRD) characterization analysis

The XRD characterization analysis conducted in this study aimed to identify the presence of aluminum hydroxide ($Al(OH)_3$) compounds formed from the aluminum-water reaction by examining the diffractogram peaks. The formation of aluminum hydroxide compounds indicates that adding activator substances breaks down the oxide layer on the aluminum waste surface. The researchers observed differences in the diffractogram based on analysing aluminum waste and the products after the aluminum-water reaction under optimal conditions. The diffractogram data before and after the reaction are shown in **Figure** 6.

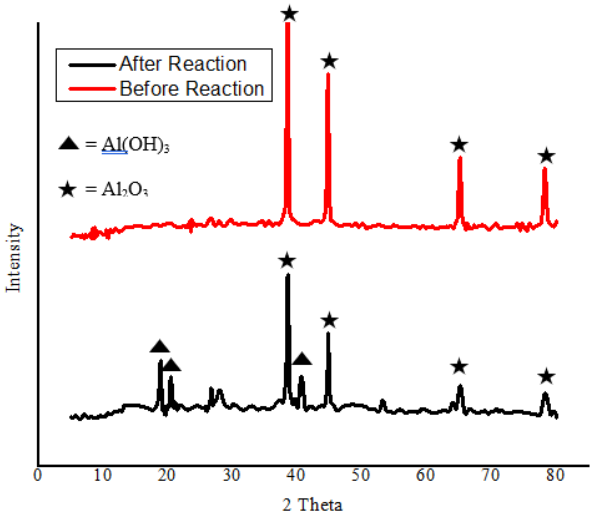

Figure 6. XRD Diffractogram of Aluminum Waste Before and After Reaction

Based on the XRD characterisation analysis shown in **Figure** 6, it can be observed that there are diffraction angles for aluminum hydroxide ($Al(OH)_3$) and alumina (Al_2O_3). The diffraction angle for alumina is found at 2θ = 38.475°, 44.645°, and 65.06°. These results are consistent with JCPDS 50-0741, corresponding to diffraction angles of 35.5°, 45.7°, and 66.6° (Obada et al., 2016). After the aluminum waste reacted with the activator and water, the diffraction angle for aluminum hydroxide was observed at 2θ = 18.919°, 20.37°, and 40.62°. These diffraction angles align with the standard JCPDS 00-0120-457, which has diffraction angles of 18.78°, 20.35°, and 40.798° [23]. Based on the XRD characterization analysis conducted, it is evident that the aluminum waste did not fully react with the activator and water, as peaks of alumina (Al_2O_3) compounds are still present in the XRD characterization results after the reaction.

CONCLUSION

Hydrogen gas production with 1 gram of aluminum using a potassium activator is optimal at a water volume of 1.5 mL and a potassium activator mass of 7% w/w. Meanwhile, XRD analysis results indicate that the aluminum-water reaction has occurred, leading to the formation of aluminum hydroxide, as observed in the diffraction patterns of the reacted samples.

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