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The Design of ACE (Aluminum Corrosion and Electrolysis) Reactor and Its Performance to Produce Hydrogen from Beverage Cans

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Abstract

The reaction of aluminum (Al) with an alkaline solution in producing hydrogen gas has been known for a long time. This aluminum corrosion reaction has a major obstacle in the passivation phenomenon, a formation of aluminum oxide coating on the metal surface that prevents aluminum from collapsing. Integration of electric current to the potassium hydroxide solution could result in electrolysis of water which increases the production of hydrogen. This process was carried out continuously in an ACE (aluminum corrosion and electrolysis) reactor of water. This reactor design enabled to produce hydrogen and oxygen in separating chamber. The use of 10 g of cans, 0.02 M gallium, 12 VDC, and 0.8 M KOH obtained the maximum production rate of hydrogen 162.58 ml/s with a purity of 79.83%.

Keywords: *aluminum corrosion; hydrogen; water electrolysis*

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INTRODUCTION

Hydrogen is a promising alternative energy for carbon-based fuel substitution. The advantages of hydrogen fuel are free emissions of COx and SOx and its high heating value (HHV = 142 MJ/kg and LHV = 120.2 MJ/kg) or about three times higher than the heating value of gasoline. Gutbier and Hohne (1976) attempted to produce hydrogen through a reaction between magnesium-aluminum and seawater. Soler *et al.* (2005) reported the reaction of aluminum powder with sodium hydroxide solution (NaOH) produced an optimum yield of hydrogen at temperature of 70-90 ^{o}C. However, higher yield was obtained in reacting aluminum with sodium aluminate ($NaAlO_2$) than that of NaOH solution (Soler *et al.*, 2009).

Addition of nano-crystalline metal oxides such as TiO_2, Co_3O_4, and Cr_2O_3 further increase hydrogen gas production in the corrosion process of aluminum metal powder by water (Wang *et al.*, 2011). The rate of hydrogen production increased in combination method between electrolysis of water and aluminum corrosion. The method applied by placing the graphite carbon as the electrode in a closed chamber containing aluminum and electrolyte solution. It required less than 5A of power consumption and produced 500L of hydrogen in 25 min (Phillips, 2015).

The reaction between aluminum and water are as follows:

$$2Al_{(s)} + 2KOH_{(aq)} + 6H_2O_{(l)} \rightarrow 2KAl(OH)_{4\,(aq)} + 3H_{2(g)} \quad (1)$$

$$2KAl(OH)_{4\,(aq)} \rightarrow 2KOH_{(aq)} + 2Al(OH)_{3\,(s)} \quad (2)$$

$$2Al_{(s)} + 6H_2O_{(l)} \rightarrow 2Al(OH)_{3\,(s)} + 3H_{2(g)} \quad (3)$$

The rate of corrosion of aluminum metal in alkaline water was in line with a concentration of the solution and temperature (Deepa and Rao, 2013). Hydrogen gas and aluminium hydroxide can produce from aluminium with water (previous reaction). Hydrogen gas was potency as fuel. Aluminium hydroxide can be reacted with sulphuric acid and converted to alumnium sulphate. Aluminium sulphate is flocculant that applied as dust removal and as a clump of waste in the water purification (Ayundyahrini *et al.*, 2013).

The main obstacle in the production of hydrogen through this corrosion reaction is an easy auto-passivated of the aluminum surface. Passivation is a process to form a thin layer of metal oxide compounds on the metal surface to prevent further rusting processes. Aluminum which is exposed to oxygen from the air environment will quickly form a thin layer of aluminum oxide (Ramirez *et al.*, 2012). Nevertheless, surface passivation can be minimized by optimising some experimental parameters such as temperature, alkali solution concentration, and aluminum raw materials. The metal oxide coating which prevents aluminum damages can be prevented by gallium which acts as an inhibitor and controller in the aluminum oxidation process (Woodal *et al.*, 2008).

Since aluminum is a stable metal, it is used as a material in aluminum cans, aluminum foil, and other objects made from aluminum. However, these used objects are potentially polluting the environment (Sutresna, 2006). To reduce the aluminum pollution, it is necessary to recycle and reuse them into other products. The tin cans contain various aluminum level ranging from 1.41 to 16.04% (Manurung and Ayuningtyas, 2010). Aluminum alloys with other metals, such as gallium, rhenium, bismuth, calcium, and magnesium have higher reactivity than the pure aluminum, but they are not easily available (Wang *et al.*, 2012).

The main purpose of this research was to design a reactor which produces hydrogen gas by reacted aluminum metal with electrolyzed water. Used can is one of potential aluminum source from domestic household waste. This undecomposable waste could contaminate soil and water. In this work, potential corrosion of aluminum from used beverage cans was observed at various acidity solutions. In addition, the impact of electric current and the addition of gallium (Ga) in increasing the hydrogen flow rate was also studied. Performance of reactor was determined by evaluating gas production of hydrogen and oxygen in the outlets.

RESEARCH METHODS

Materials

A borosilicate glass Hofmann voltammeter (Figure 1), a water electrolysis apparatus developed by August Wilhelm von Hofmann, was used to obtain an optimal process conditions. The Voltmeter is composed of 3 (three) parts: a filling tube, and 2 (two) reverse burette tubes arranged in vertical parallel and interconnected. Carbon rod electrodes that utilise the voltmeter proceed the water electrolysis.

The main raw material in this research was the chips of removed-paint layer Coca-cola cans (± 0.5 cm), potassium hydroxide, and aquadest. The cans contain 10.33% aluminum (Manurung and Ayuningtyas, 2010). The addition of 99.99% g Ga liquid metal and electric current were observed in driving the rate of hydrogen production.

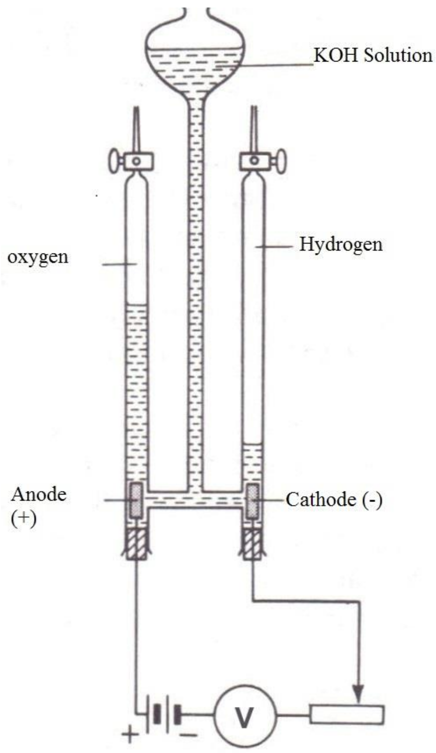

Figure 1. Voltameter Hofmann

Procedure

The chips (1 g) were inserted into the tube, followed by a 0.2 M KOH solution. When was in the filling process, both valves were in open position to release air. They were closed once the solution in the both tubes was in the same level. The filing period was recorded until no more bubble gas produced in the cathode. The data collection was repeated for other variables, e.g. KOH solution concentration (0.4-1.0 M), electric current (6, 12, 24 VDC) and gallium concentration (0 and 0.02 M. gallium).

The obtained hydrogen was determined by a pop test. The burette valve was opened while the inverted tube was closed by the thumb to hold the gas which then burned.

Reactor Design

The ACE reactor (Figure 2) for producing this pure hydrogen gas is composed of eleven parts. There were (1) the vessel in which the aluminum corrosion reaction occurs, (2) the reactor cap, (3) the gas gasket, (4 and 5) the electrode, (6) the ionization zone separator, (7 and 8) the zoning hole, (9) the hydrogen outlet, (10) the oxygen outlet, and (11) the connecting holes for hydrogen which produced by both methods.

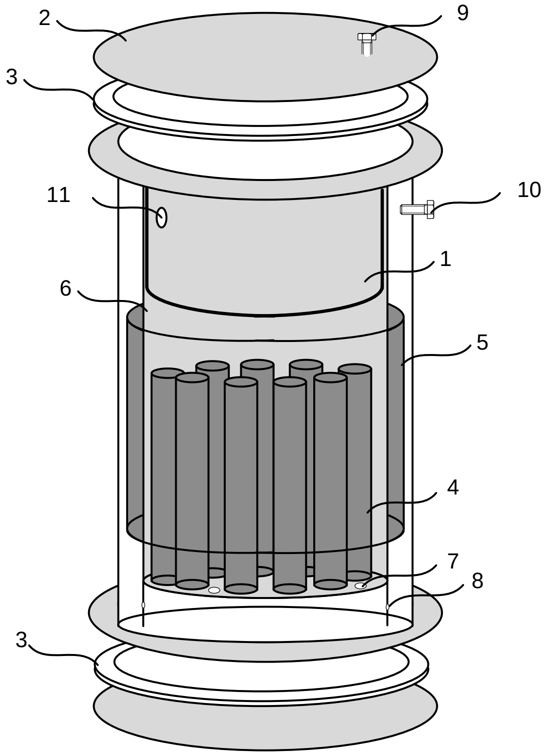

Figure 2. Design of an ACE reactor (aluminum corrosion and electrolysis)

The aluminum content of beverage cans has the potential to be a raw material for renewable energy production of hydrogen. The cans was cleaned and chipped before placing to the vessel (1). The potassium hydroxide solution was introduced into the reactor and then closed (2). A gasket was placed between the reactor body and the cap to avoid gas leakage during the reaction. The electrode was connected with an electric current (12 and 24 VDC). Material SS 310 was used as a cathode (1 ¼ inch) (4) and anode (10 inch) (5). The cathode and anode were separated by an insulating acrylic material (6) and only connected through holes 7 and 8. The gas results were taken from different output, hydrogen (9) and oxygen (10). A hole (11) connected the hydrogen from the corrosion and the one from electrolysis reaction.

RESULTS AND DISCUSSION

In this study, hydrogen gas was generated from corrosion reactions of aluminum can chips in potassium hydroxide solution (Eq. 1). This reaction was exothermic and only water was consumed (Eq. 3). The gas bubble and the decline of the surface of the solution in the Hoffman's voltmeter cathode tube determined the ionization water during the hydrogen production. The hydrogen vapor that filled the cathode tube will be increased the pressure until higher than the hydrostatic pressure of the solution.

The rate of hydrogen production was higher in smaller chips due to increasing the contact surface area. Figure 3 shows higher rate of hydrogen was produced in higher concentration of KOH. This led to produce more hydrogen from 1 g of can. The high concentration of alkaline solution as well as increasing reaction temperature (max 65^{o}C) resulted in faster rate of aluminum corrosion. Hence, the spontaneous reaction of aluminum in this alkaline solution did not require external heating during the process. This high concentration and temperature facilitated the formation of aluminum oxide (Al_2O_3) layers that allows further corrosion of aluminum metal (Porciúncula *et al.*, 2012).

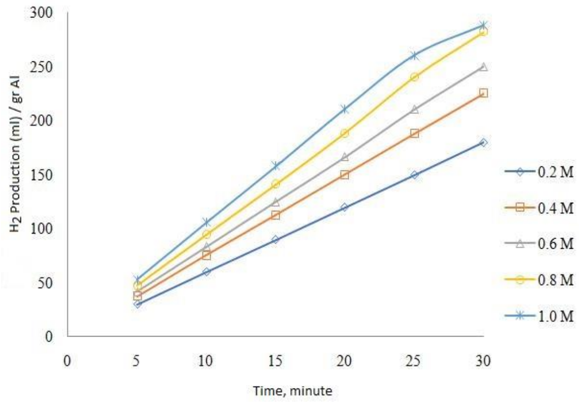

Figure 3. Effect of KOH solution concentration on H_2 gas production

High concentration of solution permited visible turbulence thus facilitated dissolved oxygen in solution as well as ionized oxygen from water molecules to contact and react with aluminum. This led to rapid stagnation of hydrogen flow rate (0.15-0.16 ml/s) at 0.6 M (Figure 4).

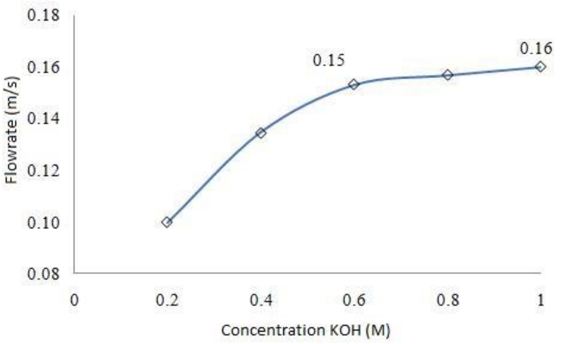

Figure 4. Effect of KOH concentration on flow rate of H_2/g Al

Introducing a direct current electricity lead to increase flow rate of hydrogen gas of this aluminum corrosion reaction. Theoretically, decomposition/ ionization of water molecules into hydrogen and oxygen ions is in accordance with Faraday's Law. Figure 5 shows a production of hydrogen gas (0.19 ml/s) with 24 VDC electricity at 0.6 M KOH solution.

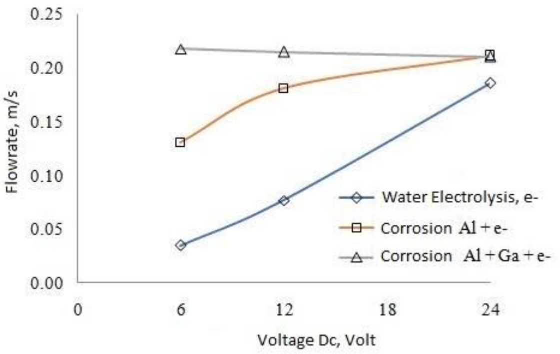

Figure 5. Effect of electric current and gallium at KOH concentration of 0.8 M

Since aluminum was placed in the area of hydrogen gas formation (cathode), it protected a direct contact between aluminum and oxygen from the electrolysis. Hence, the possibility of passivated aluminum metal for the corrosion reaction can be suppressed. The challenge in combining these two methods was imperfect separation (brown gas or HHO) between ionized hydrogen and oxygen due to more dissolved oxygen in the solution.

The presence of 0.02 M gallium liquid metal in decomposition of 1 g of the cans significantly affected the hydrogen rate production in various VDC voltage. Under these conditions, gallium becomes its aluminum-migrated inhibitor so that the corrosion and electrolysis hydrogen flow rate can increase by 0.1 ml/s. Galium is a critical component that inhibits the formation of aluminum oxide layer on the aluminum surface. Using the same method, other metals such as Bi, Sn, and In can also be used as Al alloys in producing the expected hydrogen gas (Wang *et al.*, 2011). In addition, introducing an electric current on Al-Ga solution increases the rate of hydrogen formation (Flamini *et al.*, 2006).

The working principle of the Hofmann voltammeter was then applied in designing the reactor. The formation of hydrogen and oxygen in separate zones was a key success in the design. Thus, the hydrogen gas can be used further as fuel. The prototype performance of ACE reactor was tested using several process variables including concentration of KOH solution, VDC voltage, and addition of gallium solution in reaction.

Figure 6. Prototype of ACE reactor (aluminum corrosion and electrolysis)

The performance of reactor prototype was tested using 10 g of cans chips. Table 1 shows the optimum flow rate of hydrogen production (162.58 ml/s) was achieved using a 0.8 M KOH solution and 0.02 M gallium at 65^{o}C.

The obtained hydrogen was tested through a pop test using a test tube. The burette valve was opened and the inverted reaction tube was quickly-closed with the thumb to hold the trapped gas. The hydrogen was then burned. The results showed an audible pop sound and light flashes of fire was produced when the hydrogen was determined by pop test and tube burned test, respectively. The pop sound would be louder when the hydrogen mixed with oxygen. Hence, the level of loudness during burning indicated the purity. The purity of the hydrogen produced from this ACE reactor using gas chromatography analysis was 79.83% vol. with heating value of GHV = 765 BTU / cuft.

CONCLUSION

This work showed an additional value of used aluminum beverage cans as raw material in producing alternative energy of hydrogen gas. The ACE reactor was successfully designed to produce hydrogen gas from the corrosion reaction of aluminum metal and water electrolysis. The performance test of ACE reactor

Table 1. ACE Reactor Prototype Performance Test

Concentration KOH (M)	Voltage (VDC)	Concentration Ga (M)	Time (minute)	Volume H_2 (lt)	Flow Gas (ml/s)
0,8	12	0	29,53	229,24	129,39
		0,02	49,31	481,01	162,58
		0,06	43,57	262,23	100,31
		0,1	52,13	182,18	58,25

using 10 grams of cans, 0.8 M KOH solution, 12 VDC, and Ga 0.02 M resulted an optimum flow rate of hydrogen production was 162,58 ml/s with hydrogen purity 79,83% vol.

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