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Experimental investigation of solar assisted hydrogen production from water and aluminum

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ABSTRACT

Sustainable production of hydrogen at high capacities and low costs is one the main challenges of hydrogen as a future alternative fuel. In this paper, a new hydrogen production system is designed and fabricated to investigate hydrogen production using aluminum and solar energy. Numerous experiments are performed to evaluate the hydrogen production rate, quantitatively and qualitatively. Moreover, correlations between the total hydrogen production volume over time and other parameters are developed and the energy efficiency and conversion ratio of the system are determined. Also, a method is developed to obtain an optimal and stable hydrogen production rate based on system scale and consumed materials. It is observed that at low temperatures, the hydrogen production volume, efficiency and COP of the system increase at a higher sodium hydroxide molarity. In contrast, at high temperatures the results are vice versa. The maximum hydrogen production volume, hydrogen production rate, reactor COP and system efficiency using 0.5 M NaOH solution containing 3.33 g lit^{-1} aluminum at 30 °C are 6119 mL, 420 mL min^{-1}, 1261 mL H_2 per 1 g of Al, and 16%, respectively.

Introduction

Hydrogen is a potentially environmentally benign fuel with considerable heating value that has increasingly attracted attention as a promising alternative to fossil fuels in the near future. Successful transition to a future hydrogen economy requires development of better hydrogen production methods that are sustainable and economical [1]. Existing hydrogen production methods include biological, electrochemical and chemical processes [2]. Considering the relatively low efficiency of biological processes [3] and high cost of water electrolysis [4], chemical methods are increasingly a promising alternative due to their potentially lower costs.

Photo-electrochemical water splitting is one of the promising methods of hydrogen production, however it is still developing and far from commercialization [5]. Among various methods, hydrogen production based on light weight metals and their hydrides has the most potential to be realized in industrial applications. In this method, sodium borohydride, aluminum, manganese and other alloys are utilized as catalysts. Considering different parameters including cost, preparation, safety and applicability for vehicular

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applications, aluminum was reported to have more promising capabilities [6].

Soler et al. [7] studied hydrogen production using aluminum and its alloys in a 1 M KOH solution at 25 °C. Beside temperature and solution molarity, other parameters including aluminum morphology, initial concentration, aluminate ion concentration and also mixed conditions inside the reactor affect the hydrogen production rate. In case of using aluminum alloys, the composition of the alloy is a key factor in hydrogen production efficiency. Their results indicate that Al/Si and Al/Co alloys have the highest hydrogen production rate compared to other aluminum alloys. They achieved a hydrogen production rate of 26 $\frac{cm^3 H_2}{min\ gAl}$ and 139 $\frac{cm^3 H_2}{min\ gAl}$ using aluminum powder and foil, respectively.

Chen et al. investigated aluminum based hydrogen generation to identify the effects of reaction and preparation parameters [8]. Their results found that the reaction activity of aluminum can be improved by increasing the ball milling time because Al oxidation decreases. The use of CaO leads to generation of hydroxide ions by hydrolysis and activation of Al is promoted by adding NaCl. The hydrogen production is achieved in the presence of chloride ions and sulfate ions, but magnesium ions have an opposite effect due to their recombination potential with hydroxide ions. The maximum hydrogen yield is achieved in water at 30 °C.

Martinez et al. [9] investigated the effect of the molar ratio of NaOH to Al on the hydrogen production rate. They observed that using aluminum beverage cans and at a constant temperature of 23 °C and constant concentration of aluminum, the hydrogen generation rate rises with an increase of NaOH solution molarity. In another study, they integrated aluminum with a PEM fuel cell as a hydrogen system. They compared the performance of this system with a solar PEM electrolyzer and it was shown that aluminum is advantageous [10].

Ilyukhina et al. [11] presented a methodology to activate alumina using Gallium. They studied the effects of kinetic parameters of the reaction between activated aluminum and water on the hydrogen production rate and efficiency. The parameters include gallium content of the alloy, alloy composition, particle size and reaction temperature. They concluded that at a reaction temperature of 25 °C, the composition of Ga-In-Sn-Zn(50:30:10:10) has the highest hydrogen production rate of 2150 mL min^{-1} per unit mass of the alloy compared with other alloys at an efficiency of 88%. Parmuzinaa et al. [12] performed experiments to activate alumina using a eutectic solution of Ga-In-Sn-Zn (60:25:10:5). Moreover, the rate of oxidation of activated aluminum was evaluated based on the composition of the eutectic solution, reaction temperature and size of aluminum powder. It is revealed that activated aluminum using a Ga-In-Sn-Zn solution has a higher aluminum consumption efficiency compared with a Ga-In solution. They achieved a hydrogen production rate of 44 mL min^{-1} and 15 mL min^{-1} using a Ga-In-Sn-Zn solution and Ga-In solution, respectively. Elitzur et al. [13] investigated a method for on-demand hydrogen generation using activated aluminum powder and water for aircraft applications. They concluded that the waste water available on-board can be used for hydrogen generation based on the reaction between aluminum and urine. They demonstrated the hydrogen production rate of about 200–600 ml/min/g Al at a yield of about 90%.

Chen et al. [14] investigated the effects of additional NaCl, ball milling time and Li content of Al-Li alloys on hydrogen generation. They reported a 100% hydrogen yield of Al–Li alloys under optimal preparation conditions. It was also found that the initial water temperature, even at 0 °C, has negligible effect on hydrogen production. Al-Li alloys with an Li content of less than 10% are capable of hydrogen production in water at different temperatures.

Gai et al. [15] performed a systematic investigation on the effect of trace species in water on the Al-water reaction. It is revealed that trace F^- ions and trace organic acids generated from the decay of animals have a significant role in the Al-water reaction compared to other cations and anions. Their results indicate that organic acids and trace F^- ions, as sacrificial agents, together with water can generate hydrogen from the Al–water reaction. Ho [16] evaluated the hydrolysis of waste aluminum foil to compare with traditional Al powder in an alkaline aqueous solution and associated additives. The method yields hydrogen generation rate of 30 ml s^{-1} g^{-1} using waste Al foil with Bi in low alkaline solution at 70 °C without mechanical ball-milling process.

Chai et al. [17] analyzed the effects of $CoCl_2$ and $NiCl_2$ on the Al-water reaction. The effects of increasing the reaction temperature and solution molarity are also investigated. Their results implied that an increase of temperature from 30 to 45 °C in 1 M $CoCl_2$ or $NiCl_2$ solution leads to higher hydrogen production, whereas an increase of temperature from 45 to 60 °C reduces the production rate, considerably.

Teng et al. [18] analyzed the effect of aluminum hydroxide on hydrogen generation during the aluminum and water reaction. They concluded that $Al(OH)_3$ with a higher surface area but lower degree of crystallinity leads to a rapid hydrogen generation rate. They explained this phenomenon based on the formation of boehmite from the reaction of Al_2O_3 and by-product β-$Al(OH)_3$. They reported a hydrogen yield of 70% using exothermic characteristics of the Al-water reaction in an aqueous solution containing fine aluminum hydroxide. Dudoladov et al. [19] performed various experiments on oxidation of aluminum in different anti-freeze solutions at low temperatures up to −40 °C. Usual granules of aluminum with an average diameter of about 5 mm and activated aluminum in gallium based eutectic solution were utilized. They analyzed oxidation of aluminum powder in *NaOH*, *KOH*, $ZnCl_2$ and $CuCl_2$ solutions. It was concluded that a KOH solution has the best oxidation performance in the water-aluminum reaction. The best result based on granulated non-activated aluminum was 2000 mL hydrogen using 2.5 g of aluminum in a hydrochloric acid solution and in the presence of $CuCl_2$.

Wang et al. [1] investigated the influence of solution volume on hydrogen production in an aqueous solution of *KOH* and *NaOH*. They concluded that an increase of solution volume from 3 to 15 mL in 1 M solution of *NaOH* leads to an increase of hydrogen production from 120 to 370 mL. Soler et al. [20] compared the performance of three aqueous solutions including *NaOH*, *KOH*and $CaOH_2$ on the hydrogen production rate. The results indicated that aluminum is consumed in the *NaOH* solution more rapidly. It is also revealed that the

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