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Hydrogen production by a low-cost electrolyzer developed through the combination of alkaline water electrolysis and solar energy use

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ABSTRACT

Electrolysis is a relatively simple process for obtaining hydrogen and can be combined with use of renewable energy sources, such as solar photovoltaic energy, for clean, sustainable gas production. This study designed a cylindrical electrolytic cell made of acrylic and 304 stainless steel electrodes to produce hydrogen. The electrolyte used was sodium hydroxide (NaOH 2–5 mol L^{-1}), and the direct current voltages applied were 2.0, 2.7, and 3.4 V. The maximum hydrogen production was achieved with 5.0 mol L^{-1} NaOH and 3.4 V electric voltage. The system was connected to a photovoltaic panel of 20 W and exposed to solar radiation from 10 a.m. to 2 p.m. Approximately 2 L of hydrogen was produced within a period, and an average irradiance of 800.0 W m^{-2} ± 60 W m^{-2} was achieved. The system was stable throughout the tests.

Introduction

The demand for energy increases as a consequence of global development and population increase. About 80% of energy demand comes from fossil fuels (oil, natural gas, and coal) [1] that produce greenhouse gases, such as carbon dioxide (CO_2) and methane (CH_4), which are directly related to the effects of global warming. In addition, pollution from fossil fuels harms the human health and various forms of life existing in the environment. The natural reserves of this resource are limited. In this regard, the need for renewable energy sources is growing [2].

Among renewable energy sources, hydrogen (H_2) is considered an alternative to fossil fuels in transport because of its minimal environmental impacts. Hydrogen is a clean fuel that produces water only after combustion and possesses higher calorific value (HHV) of 141.86 kJ g^{-1} at 25 °C and 1 atm than other fuels (e.g., gasoline exhibits HHV of 47.5 kJ g^{-1} under the same conditions) [3]. In nature, hydrogen is not found in its free form but in combination with other chemical elements, such as water and natural gas, thereby requiring chemical processing for its production. Currently, 48% of hydrogen is extracted from natural gas, 30% from the oil industry, 18% from coal gasification, 3.9% from electrolysis, and 0.1% from other processes [4].

Hydrogen production from non-renewable sources is economically viable, but production from renewable sources can significantly reduce adverse environmental impacts.

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Hydrogen can be produced from renewable sources in the form of biomass [5–8] and through processes utilizing water, such as electrolysis, thermal decomposition, and photocatalytic decomposition [9].

Electrolysis is a relatively simple process used to produce hydrogen, with a purity of 99.999% by volume after drying and removal of oxygen impurities [9]. One of the critical factors affecting hydrogen production is the source of electrical energy used to maintain the electrolytic reaction due to cost and environmental aspects. The power supply for electrolysis can come from renewable energy sources, such as hydraulics, wind, and solar photovoltaic cells [10–14]. Sunlight is an important source of clean energy; moreover, the amount of solar energy that reaches the Earth is greater than the energy needs of humans [15]. Thus, combining photovoltaic solar energy with water electrolysis is a sustainable way to obtain hydrogen.

Water electrolysis consists of separation of its molecules in hydrogen and oxygen gases by the passage of electric current. The current flows between two electrodes that are separated and immersed in an electrolyte. A diaphragm or a separator should be used to avoid mixing the generated gases in the electrodes. The electrodes, the diaphragm, and the electrolyte are elements that configure an electrolytic cell [9].

The efficiency of the electrolytic system can be improved through two methods: thermodynamically reducing the energy required for the reaction by raising the temperature or pressure; and minimizing energy losses in the electrolytic cell by reducing the dominant resistances via increasing the conductivity of the electrolyte [14].

Most studies on water electrolysis have focused on alkaline electrolysis [16–18] and proton exchange membranes (PEM) [19–25]. Alkaline water electrolysis has been used in large-scale industrial applications since 1920. This method possesses the advantages of low capital cost and lack of dependence on noble metals; however, low pressure and low current density negatively affect the size of the system and the production costs of hydrogen. PEM systems are less developed than alkaline technology and are commonly used in small-scale applications. Although these systems exhibit high energy density and efficiency, the materials used as catalysts and in the membrane are expensive and the system is complex due to high operating temperature and water purity requirements [26].

Other methods of hydrogen production by water electrolysis include the use of anion exchange membranes [27] and solid oxide electrolyzers (SOE) [28,29]. However, these technologies are less developed compared with alkaline and PEM electrolysis.

Alkaline water electrolysis through solar energy has been studied by many researchers because of its simplicity, low cost, and purity of hydrogen produced; however, this method has challenges such as intermittency and optimization of photovoltaic panels for a better use of available solar energy. Alkaline water electrolysis combined with photovoltaic panels can be conducted with or without peripheral equipment. Two settings for a photovoltaic system and an electrolytic unit for hydrogen production were analyzed by Ref. [30]; in the first setting, they directly connected the photovoltaic system to the electrolytic unit; in the second, they used maximum power point tracking (MPPT). The authors concluded that using MPPT increased the hydrogen production rates for the same solar radiation levels. The system global efficiencies were 1.5% in the direct connection between the solar panel and the electrolytic cell and 2.3% in the system with MPPT.

Hydrogen obtained via water electrolysis can be used in fuel cells to produce energy. A complete system using hydrogen as energy vector in a pilot plant was developed by Ref. [31]. The electrolyzer had two concentric electrodes made of 316 stainless steel immersed in an aqueous solution of 30% w/w KOH. The electrolyzer was connected to a photovoltaic panel with dimension, short-circuit current, open-circuit voltage, and rate power of 0.107 m^2, 0.75 A, 21.7 V, and 12 W, respectively. This system generated up to 6 W a day and 5 L of hydrogen, with a peak of solar radiation of 460 W m^{-2} at around 1 p.m. The authors connected a 12-cell fuel battery to 120 LED bulbs, and the system could operate for 18 h with a 10 L stock of hydrogen without using any external power source.

The effects of KOH and NaOH electrolytes on alkaline hydrogen production with photovoltaic solar energy were evaluated by Ref. [32]. The system consisted of two electrolyzers connected in parallel; one of the electrolyzers was filled with 400 cm^3 3 M KOH solution, and the other one was filled with the same volume and concentration of NaOH. Nickel electrodes were used and connected directly to the photovoltaic panel. After 9 h of experiment, 5122 and 3279 cm^3 H_2 was produced with KOH and NaOH electrolytes, respectively. The authors attributed the higher volume of H_2 produced to the higher ionic conductivity and mobility of K^+ ions than those of Na^+ ions.

The effects of KOH electrolyte concentration, space between electrodes, and acrylic and polymer membrane separator on the amount of hydrogen produced and the efficiency of the system were studied by Ref. [33]. The electrolyzer consisted of an acrylic cell and stainless steel electrodes. A 225 W PV panel was used as a source of energy for the electrolytic reaction and coupled with a charge controller and a battery to store excess energy. The highest efficiency for the system was obtained using the polymer membrane, setting the distance between the electrodes to 5 mm, and employing 10% KOH. However, maximum efficiency did not correspond to the maximum gas productivity; as such, optimization would be required for a more economical use of the unit.

Common electrodes are made of different types of steel [31,34–36]. Scholars have also used electrodes made of other materials [30,37–39]. The production of hydrogen through water electrolysis and a photovoltaic module was investigated with electrodes made of different materials: copper, mild steel, stainless steel, bronze, graphite, aluminum, and lead [38]. The electrolyte used was a solution of sodium chloride (NaCl), and the system operated under environmental conditions (25 °C and atmospheric pressure). The optimal results were achieved using copper electrodes, followed by bronze, stainless steel, and graphite electrodes.

Most studies have used potassium hydroxide (KOH) as electrolyte in conventional electrolyzers at a concentration of 25%–30% by mass [14,30,40]. Sodium hydroxide (NaOH) and sodium chloride (NaCl) are also commonly used [34,38,39].