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All-in-one portable electric power plant using proton exchange membrane fuel cells for mobile applications

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A portable electric power plant is developed using a $NaBH_4$ (sodium borohydride)-based proton exchange membrane fuel cell stack. The power plant consists of a $NaBH_4$-based hydrogen generator, a fuel cell stack, a DC-DC converter, a micro-processed controller and a data monitoring device. The hydrogen generator can produce 5.9 L/min pure hydrogen gas using catalytic hydrolysis of 20 wt% $NaBH_4$ to feed a 500-W scale fuel cell stack. Thus, the Co/γ-Al_2O_3 and Co-P/Ni foam catalysts in the hydrogen generator play significant roles in promoting hydrogen production rates that are as fast as necessary by enhancing the slow response that is intrinsic to using only Co-P/Ni foam catalysts. Moreover, different hydrogen production rates can easily be achieved during the operation by controlling $NaBH_4$ solution rates using a fuel pump so that the hydrogen storage efficiency can be improved by supplying required hydrogen gas in accordance with load demands. The specific energy density of the electric power plant was measured 211 Wh/kg. Therefore, the power plant described here can be a power source for mobile applications, such as cars and UAVs, as well as a stationary power supplier when electric energy is required.

Introduction

The increasing demand for clean energy that is occurring in response to pollution by fossil fuels has imposed great challenges on many research groups because different types of emissions from fossil fuel-based ground and aerial vehicles have been contributing to environmental pollution [1]. As green technologies develop, eco-friendly or low-emission fuels, such as a hydrogen-based energy, has been considered to be a promising alternative to fossil fuels [2] because it has no or low emissions when it is burned as a fuel [3]. In addition, hydrogen can release a high energy density (142 MJ kg^{-1}) compared to liquid hydrocarbons (47 MJ kg^{-1}) [4]. When hydrogen energy is consumed in the fuel cell system, which has very good efficiency, it can provide energy storage up to 33,300 Wh/kg, whereas that of new lithium-ion batteries are limited to approximately 270 Wh/kg [5]. However, with regard to hydrogen and fuel cell implementation, four main obstacles exist: hydrogen production, hydrogen storage, hydrogen

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distribution, and the high cost of fuel cells [6]. Additionally, pure hydrogen gas is not naturally produced and the finished products are more costly than the costs of petroleum production, which can hinder the integration of hydrogen fuel into high-energy-consumption industries [7].

There are currently two popular types of hydrogen-supplying technologies, including compressed hydrogen and chemical hydrides, for mobile applications. Compressed hydrogen is a physical storage method that requires high volume and pressure, and its mass storage efficiency (%H_2/kg) at 700 bars is 4.8% [8]. The gravimetric hydrogen storage of compressed hydrogen will increase as the fabrication technologies for the storage tanks develop. However, expensive hydrogen charging stations are only available on-site for filling a hydrogen tank, and high charging pressures remain problematic, making it an unsuitable storage method for small mobile applications [9]. Thus, an economic and safe method are the most significant issues for enhancing mobile hydrogen storage.

To meet the storage requirements for the portable power plant discussed herein, we adopted a chemical hydride, $NaBH_4$ (sodium borohydride), as a hydrogen-storage medium. The rationale behind this decision is that $NaBH_4$ has a relatively high volumetric and gravimetric hydrogen density. It is also safe. Furthermore, hydrogen production rates can be controlled in the presence of an appropriate catalyst at room temperature. The hydrolysis reaction of $NaBH_4$ is expressed in Eq. (1).

$$NaBH_4 + 2H_2O \rightarrow NaBO_2 + 4H_2 + 217\ kJ \tag{1}$$

From this equation, the $NaBH_4$ concentration is an important factor that if its concentration is increased to hold more hydrogen gas, the amount of water to dissolve the $NaBH_4$ is decreased. In consequence, the formation of sodium metaborate ($NaBO_2 \cdot xH_2O$) occurs readily at lower water solubility with higher $NaBH_4$ concentrations. If the system weight is not a critical factor, it is possible to adopt the lower concentrations of sodium borohydride as a hydrogen storage, which results in the minimized byproduct precipitation. However, the system weight is an important factor in designing mobile systems, especially UAVs. Moreover, one of the difficult challenges in using $NaBH_4$ as a hydrogen storage medium is the decrease in gravimetric efficiency that is associated with the hydration of reaction byproducts, sodium metaborate which is the highly viscous solution so that it can lower reaction yield by clogging the reactor [10] and may damage the fuel cell stack if it is supplied with hydrogen gas. Thus, the byproduct must be removed during the hydrolysis of $NaBH_4$. To eliminate $NaBO_2$, we equipped the liquid-gas separator with a purging pump that periodically pumped $NaBO_2$ out of the fuel cell system by the control logic during the operation. In this way, the negative effects of $NaBO_2$-hydration during the catalytic reaction process were eradicated, which resulted in system weight reduction as operational time elapsed. Therefore, after separating $NaBO_2$, pure hydrogen gas could be fed into the proton exchange membrane fuel cell stack (PEMFCS) to generate stable power. Moreover, the separated $NaBO_2$ after the operation of the PEMFCS was collected in the chemical container and sent to the special chemical factory for the wasting process.

To produce hydrogen gas at required rates, the addition of catalysts is necessary. Therefore, numerous catalysts based on metal-alloys have been investigated. Among them, noble metals such as ruthenium and platinum show high activity in the sodium borohydride hydrolysis [11] however, their high cost and availability may cause the system price to increase. Thus, Co and Ni borides are considered as good candidates for catalyzed hydrolysis reaction of $NaBH_4$ owing to their good catalytic activity and low cost [12,13]. In our previous research we also proved that Co-P/Ni foam catalysts was capable of increasing the catalytic activities of sodium borohydride [8]. Thus, we adopted the synthesis of mixed Co/γ-Al_2O_3 and Co-P/Ni foam catalysts to enhance the catalytic activity.

Then, the $NaBH_4$-based hydrogen system was integrated into the 500-W scale proton exchange membrane fuel cell stack because it has high power density and low operating temperature. With this integration, the fuel cell system could constitute a small and portable electric power plant with other devices such as a controller and DC-DC converter. Thus, the PEM fuel cells with its associated hydrogen production system could be developed for transportation applications as well as for stationary and portable applications [14].

To effectively control components in our portable electric power plant (such as a fuel pump, purging pump, and cooling fan in the hydrogen generator as well as a purge valve and oxygen-supplier fan in the stack), the micro-processed controller was built based on the systematic control logic. The controller allowed the $NaBH_4$ solution rate to be adjusted using a fuel pump in accordance with the load variations, thereby extending the operational time because of higher fuel efficiency. Therefore, our portable electric power plant could generate a maximum of 500-W power with the consumption of 5.9 L/min hydrogen gas that is supplied by the $NaBH_4$-hydrogen generator, and this electric power source could be utilized for mobile applications such as cars and small UAVs as well as a mobile power stations where electric energy is required.

Development of the portable electric power plant

Description of the hydrogen generator and the fuel cell system

The fuel cell system includes a fuel tank, fuel pump, purge pump, hydrogen generator, liquid-gas separator and two consecutive containers and a 500-W scale fuel cell stack. The hydrogen generator can supply 5.9 L/min hydrogen gas to the PEM stack from the catalytic hydrolysis of 20 wt% $NaBH_4$ using two different types of catalysts, including the Co/γ-Al_2O_3 and Co-P/Ni foam catalysts. These catalysts were embedded in the catalyst bed of hydrogen generator to promote the hydrolysis of $NaBH_4$. As such, the catalysts played important roles in increasing hydrogen production rates to be as fast as required for the operation of the fuel cell stack. However, when the $NaBH_4$ solution started to flow into the hydrogen generator with the fuel pump, not only was a required volume of

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