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Novel hydrogen production and power generation system using metal hydride

Bokkyu Choi [a], Dhruba Panthi [a], Masateru Nakoji [b], Toshiki Kabutomori [b], Kaduo Tsutsumi [b], Atsushi Tsutsumi [a,*]

[a] Collaborative Research Center for Energy Engineering, Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan

[b] Exergy Power Systems, Inc., Komaba Open Laboratory 501, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan

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ABSTRACT

A novel electrochemical reactor for hydrogen production and power generation is proposed based on a fuel cell/battery system. The reactions (hydrogen evolution and oxidation) in the system occur at solid/liquid and solid/gas two-phase boundaries using a metal hydride negative electrode. This leads to high energy efficiency for both hydrogen production and power generation. We thus investigated electrochemical charge/discharge performance at various current densities by fabricating an experimental cell. This cell was composed of negative and positive electrodes with a 1:3 capacity ratio. Hydrogen gas was produced in a linear manner during the charge process and it was completely consumed during the discharge process. The energy conversion efficiencies of hydrogen production and of the complete hydrogen production/power generation process at a current density of 37.0 A/m^2 were 98.3% and 79.6%, respectively. These values are higher than those of conventional water electrolysis and/or power generation systems.

Introduction

Fossil fuels such as coal, oil, and natural gas are the main energy resources used globally. Energy consumption has increased continuously but fossil fuels are exhaustible resources. Additionally, carbon dioxide (CO_2) emission is considered to be a major factor in global warming and is a problem that arises from the use of fossil fuels. To resolve these problems, renewable energy (RE) sources such as wind, solar, and hydro power have attracted much attention because of their clean and sustainable properties [1]. RE sources are practically inexhaustible but are intermittent power sources because they are influenced by weather conditions. Therefore, energy storage systems (ESSs) are required to increase their energy utilization efficiency [2]. Secondary batteries such as lithium ion batteries, sodium sulfur batteries, and flow batteries are considered to be prospective ESSs [2]. Secondary batteries are suitable ESSs if they store and use energy at the installed location. However, the richness of RE depends on the region and the type of RE. Energy storage and the transfer of energy from a RE-rich to a RE-poor area are required [3]. With regard to energy-transfer systems, secondary batteries do not satisfy the requirements because of cost and weight. Furthermore, it is not possible to store all the

* *Corresponding author*. Tel.: +81 3 5452 6727; fax: +81 3 5452 6728.
E-mail address: a-tsu2mi@iis.u-tokyo.ac.jp (A. Tsutsumi).
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energy generated by RE sources in secondary batteries because of capacity limitations. This is determined by the amount of active material used during the synthesis of the electrodes [4,5]. Energy from RE sources may be stored by converting it to hydrogen gas. Hydrogen is the most abundant element in the universe and it covers approximately 70% of the earth's surface. Hydrogen is characterized by i) a high energy conversion efficiency, ii) diverse sources, and iii) no CO_2 emission during combustion or electrochemical reactions [6,7]. Various hydrogen production methods exist such as natural gas steam reforming, coal/biomass gasification, photolysis, and water electrolysis [7]. Among the hydrogen production methods, water electrolysis using electricity from solar and wind power is the best choice for hydrogen production because it is of very high purity (99.9%) and is technologically simple [7–12]. However, as shown in Fig. 1(a), water electrolysis reactions occur at gas (hydrogen, oxygen)/liquid (electrolyte)/solid (electrode) three-phase boundaries, which leads to a high over-potential and a low hydrogen production efficiency [11,12]. To overcome this problem, a new type of electrochemical reactor referred to as a fuel cell/battery (FCB) system was proposed in our previous research [13–19]. In the FCB system, fuel cell/water electrolysis reactions at the solid/liquid/gas three-phase boundary are split into reactions at the solid/gas and solid/liquid two-phase boundaries. This leads to a suppression of the over-potential because of an increase in the reactive area. For the negative electrode of the FCB system, especially, it was reported that metal hydride (MH) can be rapidly charged to approximately 70% of the theoretical capacity within 10 min by the highly-pressurized hydrogen gas and the charged MH can be electrochemically discharged [14]. This implies that the hydrogen oxidation reactions by MH can occur at the solid/gas and solid/liquid two-phase boundaries with a high reaction rate. In recent studies reported by Ouyang et al., metal hydrides such as Mg_3La, Mg_3Ce, Mg_3Pr, and Mg_3Mm hydrides were also studied for the hydrolysis systems [20–23]. They observed that hydrogenated Mg_3Mm had the fastest hydrolysis rate and produced 695 mL/g hydrogen in 5 min [20] and that the fully hydrogenated Mg_3La alloy could also generate 873.24 ml/g in 66 min [21]. These results indicate that the metal hydrides are promising materials for the hydrogen production systems.

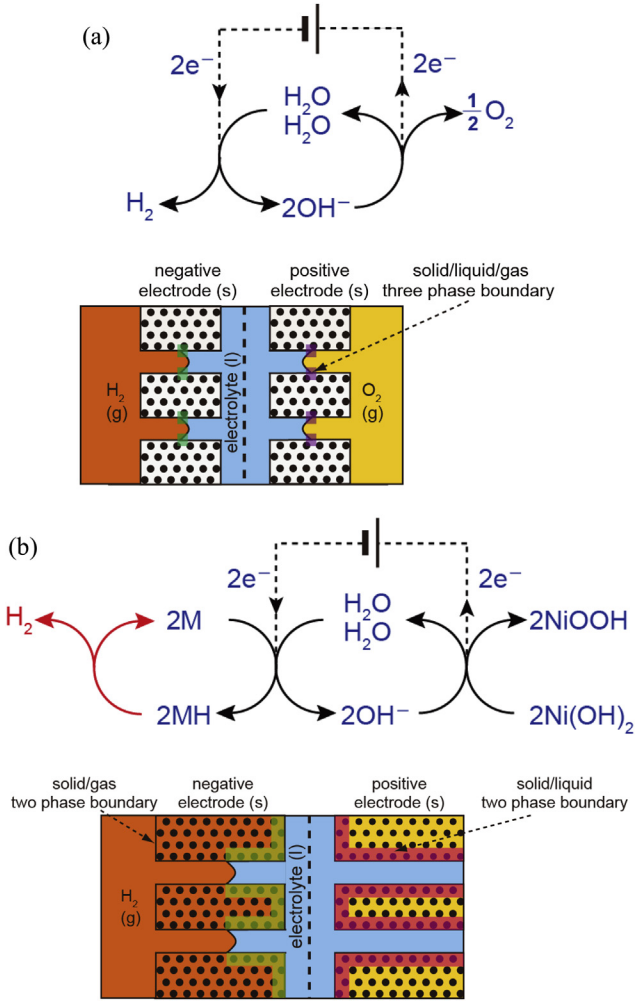

Fig. 1 – Schematic of the reaction mechanism and the cell configuration (a) for conventional water electrolysis and (b) for the novel water electrolysis system with Ni/MH.

With the reaction mechanism of the FCB system, in this paper, we suggest a novel water electrolyzer, as shown in Fig. 1(b). The electrolyzer is composed of MH and nickel hydroxide as negative and positive electrodes, respectively. This is based on nickel-metal hydride (NiMH) batteries but the amount of the negative electrode can be reduced significantly. This results in a low-cost system because the MH accounts for a large part of the NiMH battery cost [24]. When the cell is charged to the capacity of the positive electrode, hydrogen gas will be exclusively generated on the negative electrode as follows:

$$2M + 2H_2O + 2e^- \rightarrow 2MH + 2OH^- \quad (1)$$

$$2MH \rightarrow 2M + H_2 \quad (2)$$

The reactions shown in Eqs. (1) and (2) occur at the solid/liquid and soild/gas interfaces, respectively. Hydrogen gas can be used as a reactant during cell discharge and this occurs by the reverse of the reactions shown in Eqs. (1) and (2). Therefore, this novel electrochemical reactor can be expected to function both as a highly efficient hydrogen generator and as a high-capacity energy storage device. In this study, we investigated the electrochemical performance of the suggested electrolyzer and determined its energy conversion efficiency.

Analysis of the energy efficiency

The energy efficiencies were analyzed considering four different systems: i) conventional water electrolysis, ii) a fuel cell, iii) novel water electrolysis, and iv) the FCB system. Exergy, which is a quantitative measurement of useful energy, was used in the analysis. For thermal energy, exergy can be determined by the following relationship [25]:

$$\text{Exergy} = (H - H_0) - T_0(S - S_0), \quad (3)$$

where H, S, and T are the enthalpy (kJ), the entropy (kJ/K), and the temperature (K). Subscript 0 represents reference