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Development of a polymer electrolyte membrane fuel cell stack for an underwater vehicle

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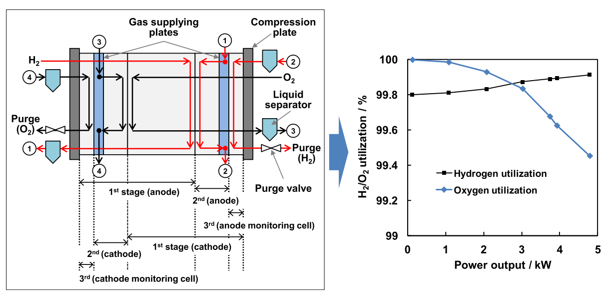
HIGHLIGHTS

- A cascade-type PEM fuel cell stack was developed for an underwater vehicle.
- The stack uses hydrogen and oxygen for the propulsion of the underwater vehicle.
- A high efficiency of 65% results in low reactant consumptions.
- High hydrogen and oxygen utilizations of 99.89% and 99.68%, respectively, were obtained.
- The durability of the stack was confirmed by a 3500-h performance test.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents a polymer electrolyte membrane (PEM) fuel cell stack that is specifically designed for the propulsion of an underwater vehicle (UV). The stack for a UV must be continuously operated in a closed space using hydrogen and pure oxygen; it should meet various performance requirements such as high hydrogen and oxygen utilizations, low hydrogen and oxygen consumptions, a high ramp-up rate, and a long lifetime. To this end, a cascade-type stack design is employed and the cell components, including the membrane electrode assembly and bipolar plate, are evaluated using long-term performance tests. The feasibility of a fabricated 4-kW-class stack was confirmed through various performance evaluations. The proposed cascade-type stack exhibited a high efficiency of 65% and high hydrogen and oxygen utilizations of 99.89% and 99.68%, respectively, resulting in significantly lesser purge-gas emissions to the outside of the stack. The load-following test was successfully performed at a high ramp-up rate. The lifetime of the stack was confirmed by a 3500-h performance test, from which the degradation rate of the cell voltage was obtained. The advantages of the cascade-type stack were also confirmed by comparing its performance with that of a single-stage stack operating in dead-end mode.

1. Introduction

PEM (polymer electrolyte membrane) fuel cells have been extensively developed for powering many types of commercial vehicles such as passenger cars, buses, forklifts, scooters, and boats because of their numerous advantages over the conventional internal

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combustion engine or secondary batteries. These advantages include relatively high efficiency, high power density, short startup times, low emission of pollutants, and low operating temperatures [1–3]. Over the last decade, PEM fuel cells have also been studied for UVs (underwater vehicles), including submarines, unmanned underwater vehicles (UUVs), and submersibles, because the aforementioned advantages are more useful when PEM fuel cells are used as power sources for UVs. For instance, the underwater endurance of a UUV had been significantly increased after its power source was changed from a Li-ion battery to a PEM fuel cell system [4,5]. Further, a PEM fuel cell system significantly improved the stealth capabilities of a submarine and helped increase the mission duration because it generated less noise, emitted less exhaust heat, and allowed for greater underwater endurance compared to conventional diesel/battery propulsion systems [6,7].

A considerable number of different PEM fuel cells, which use oxygen rather than air, have been developed for UVs over the last two or three decades. However, there is very little information on the performance and durability of PEM fuel cells in the literature. Ballard Power Systems was the first to develop a PEM fuel cell for powering a submersible in 1989. The fuel cell was designed to generate 3 kW for a two-person submersible called *PC-14*, which was manufactured by Perry Technologies [7,8]. ZSW supplied a PEM fuel cell system for the propulsion of an autonomous underwater vehicle (AUV), *DeepC*, in 2002 [7,9,10]; its fuel cell system, consisting of two stacks, was designed to generate 3.6 kW using hydrogen and pure oxygen supplied by 300-bar pressure vessels. The endurance of *DeepC* was increased to 40 h at a cruising speed of 4 knots (approximately 7.4 km h^{-1}) with the fuel cell system. Mitsubishi Heavy Industries (MHI) developed a 4-kW-class PEM fuel cell system as a power source for an AUV called *Urashima* [4,5,11]. The AUV was originally powered only by a Li-ion battery and had a cruising range of approximately 100 km. After upgrading the power system to a fuel cell, however, the cruising range considerably extended to approximately 300 km [4,5]. In the early 2000s, Siemens supplied a PEM fuel cell system for the propulsion of a Type 212 submarine that was manufactured by Howaldtswerke-Deutsche Werft (HDW) GmbH [12]. The fuel cell system consisted of nine 34-kW stacks and enabled the submarine to remain submerged for up to three weeks without snorkeling. After confirming the feasibility of the fuel-cell-powered submarine, Siemens scaled up the stack to generate 120 kW at an efficiency of 56% [7,8].

In addition to the PEM fuel cell constraints considered for land vehicles, there are some constraints that must be considered when developing a fuel cell system for UVs [13,14]. Under water, a fuel cell system cannot be supplied with air from the environment because it must be operated in a closed space (e.g., inside a submarine or UUV) where a sufficient supply of air is not usually available. Therefore, air-independent operation is essential; consequently, UVs must carry both oxygen and hydrogen onboard. In this case, pure oxygen stored either in liquid form or as a high-pressure gas would be beneficial for achieving a higher energy density. However, there are disadvantages in terms of water management and durability of the PEM fuel cell when operated with pure oxygen. In a PEM fuel cell operating with an oxidant of a lower stoichiometry, water flooding may occur more easily with pure oxygen than with air because the amount of residual gas remaining after the electro–chemical reactions would not be sufficient for removing liquid water; on the other hand, nitrogen gas in the air is present throughout the fuel cell to generate sufficient force to remove the liquid water [15,16]. In addition, fuel cell components such as membrane electrode assemblies (MEAs), gas diffusion layers (GDLs), and bipolar plates are exposed to unfavorable environments (i.e., higher oxygen concentrations or higher liquid water content), which can reduce their durability [17–20]. It is known that the degradation rates of the membranes in MEAs increase as the partial pressure of the oxygen increases in PEM fuel cells [21–23]. Thus, the lifetime of a PEM fuel cell is significantly reduced if one uses the same fuel cell components for pure oxygen as those developed for air. Typically, fuel cell systems discharge purge gas to the surroundings to reduce the impurities or mitigate water flooding in the stack [24–26]. In a UV, however, the amount of purge gas emitted to the surroundings should be minimized to reduce the visibility of the UV and increase the underwater endurance, i.e., to increase the stealth capabilities of the UV. Hydrogen and oxygen consumptions should be as low as possible to maximize the underwater endurance because, depending on their purpose, UVs are required to be in operation for several hours (up to several months) using a limited amount of reactants. Thus, the particular features mentioned above must be considered when designing the fuel cell to meet the performance requirements for a UV.

In this paper, we present the stack design and cell components specifically developed for hydrogen and pure oxygen operation and for fulfilling various performance requirements for a UV application. The suitability of the stack for UV applications was confirmed through various performance evaluations, including a 3500-h performance test.

2. Stack design

2.1. Performance requirements and development scheme

A PEM fuel cell stack must satisfy many performance requirements in order to be used as a power source for a UV; these requirements include air-independent operation, higher hydrogen and oxygen utilizations (i.e., lesser purge-gas emissions), a higher efficiency, higher ramp-up rates, and a longer lifetime. Fig. 1 summarizes the development schemes that correspond to these performance requirements. For air-independent operation, both hydrogen and oxygen must be carried onboard. Therefore, in this study, the stack was designed to use pure hydrogen from high-pressure vessels as the fuel and pure oxygen stored in liquid form as the oxidant.

The emission of purge gases from the stack to the outside of the stack must be minimized to increase the efficiency of the fuel cell system. The amount of purge gases discharged from the stack can be defined in terms of the hydrogen (U_{H2}) and oxygen (U_{O2}) utilizations, as follows:

$$U_{H2} = 1 - \frac{\hat{m}_{H2,purge}}{\hat{m}_{H2,usage}} = 1 - \frac{P\hat{v}_{H2,purge}}{60RT} \cdot \frac{2V_{avg}F}{1000W} \quad (1)$$

$$U_{O2} = 1 - \frac{\hat{m}_{O2,purge}}{\hat{m}_{O2,usage}} = 1 - \frac{P\hat{v}_{O2,purge}}{60RT} \cdot \frac{4V_{avg}F}{1000W} \quad (2)$$

If the hydrogen and oxygen utilizations are 100%, the hydrogen and oxygen supplied to the stack are completely consumed by the electro–chemical reactions to generate power; in this case, no purge gases are discharged. However, hydrogen and oxygen utilizations are typically much less than 100% because of water flooding and impurity accumulations in the fuel cells. Nevertheless, the utilizations should be greater than 99% to allow a catalytic combustor to burn off the purge gases in the UV. To maximize both hydrogen and oxygen utilizations, we employed a cascade-type stack design; in this design, the cells in the stack are divided into several blocks that are physically and electrically connected in series, and through which hydrogen and oxygen can flow in a cascaded manner. A detailed explanation of the cascade-type stack design is provided in Section 2.2.