KSOE

Journal of Ocean Engineering and Technology 39(1), 1-8, February, 2025 eISSN 2287-6715
https://doi.org/10.26748/KSOE.2024.072

Original Research Article

Performance Evaluation of PEMFC Single Cells under Constant Voltage and Constant Current Conditions

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KEYWORDS: Polymer electrolyte membrane fuel cell, Single cell, Constant voltage, Constant current, Degradation rate

ABSTRACT: *Operating conditions significantly affect the durability of polymer electrolyte membrane fuel cells (PEMFC) in marine applications. This study presents experimental results for the performance evaluation of PEMFC single cells under constant voltage and constant current conditions, simulating marine vessel operations. The cells were operated at constant voltages of 0.75 and 0.60 V and at a constant current of 6.64 A. Periodic polarization curve measurements were used to assess performance degradation. The degradation rate at 0.60 V was 13.5% higher than at 0.75 V, while the rate at 0.75 V was 21.0% higher than under constant current conditions at 6.64 A. The findings demonstrate that constant voltage operation accelerates PEMFC degradation more significantly than constant current operation, with the effect being more pronounced at lower voltages. These results provide foundational data for predicting lifespan and determining optimal operating conditions for PEMFCs in marine applications.*

1. Introduction

Globally, the transition to alternative energy sources is accelerating to combat climate change. The International Maritime Organization (IMO) has set a goal to achieve net-zero carbon emissions by 2050, as outlined during the 80th Marine Environment Protection Committee (MEPC) session, urging the maritime industry to adopt alternative energy solutions. In response, the feasibility of using hydrogen fuel cells in ships is actively being explored, particularly focusing on polymer electrolyte membrane fuel cells (PEMFC) (Elkafas et al., 2022; Welaya et al., 2011; Van Biert et al., 2016). Lee et al. (2022) demonstrated the viability of hydrogen-fueled PEMFCs through a life cycle assessment (LCA) comparing marine gas oil (MGO), liquefied natural gas (LNG), and hydrogen as environmentally friendly alternatives. PEMFCs generate electrical energy using hydrogen fuel, emitting only water, making them a promising clean energy source. With advantages such as high power density, low operating temperatures, and rapid start-up and shutdown capabilities, PEMFCs show significant potential for maritime applications. However, mechanical and chemical factors during operation cause performance degradation over time, reducing power efficiency and output (Wu et al., 2008; Ren et al., 2020; Jouin et al., 2016; Borup et al., 2007). Although the IMO emphasizes safety regulations covering essential issues like fire prevention and electrical equipment installation (IMO, 2022), research on performance degradation is critical to ensuring the reliable application of PEMFCs in ships.

PEMFC performance degradation is influenced by various operating conditions, including constant current, constant voltage, constant power, and dynamic load operations. Previous studies have examined performance degradation under these conditions. Cleghorn et al. (2006) operated PEMFCs at a constant current of 800 mA/cm² for 26,300 h, concluding that mass transport losses primarily governed the observed degradation. Chung et al. (2009) studied degradation in PEMFC single cells under constant current (80 mA/cm²) and open circuit voltage (OCV) conditions for up to 1,784 h, identifying rapid initial degradation due to catalyst particle growth during the first 40 h. Guilminot et al. (2007) reported degradation over 529 h of constant power operation, attributing it to factors such as platinum dissolution, carbon corrosion, and membrane degradation, which reduced the electrochemical surface area and altered catalyst layer structure. Lin et al. (2009) simulated dynamic load cycles reflecting vehicle driving

Received 30 August 2024, revised 22 October 2024, accepted 2 January 2025
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conditions over 370 h and found that increased electrolyte membrane resistance was a key factor in performance degradation. Similarly, Borup et al. (2006) analyzed performance degradation under US06 drive cycle tests, representative of rapid acceleration and high-speed conditions, identifying catalyst agglomeration and subsequent reductions in the electrochemical surface area as primary causes of degradation. Despite extensive research under constant current, power, and dynamic load conditions, studies on PEMFC performance degradation under constant voltage remain limited. Since ship power systems typically operate at constant voltage to ensure electrical stability and compatibility (International Electrotechnical Commission [IEC], 2016), this study aims to address this gap by analyzing PEMFC degradation under constant voltage conditions. By comparing these findings with those from constant current operation, the research evaluates PEMFC durability across different operating conditions.

2. Experimental Setup and Conditions

2.1 Test Station and PEMFC Single Cell

The test station used in this study (Pureun Tech Energy) consisted of hydrogen and nitrogen cylinders, an air compressor, humidifiers, a mass flow controller (MFC), an electronic load, and a PC, as shown in Fig. 1. Hydrogen from the cylinder was supplied to the PEMFC single cell at a controlled flow rate via the MFC (Bronkhorst, EL-FLOW classic F-201CL) and a bubbler humidifier (Pureun Tech Energy). Air from the compressor was similarly humidified before being supplied to the single cell. To prevent water condensation in the humidified gas, line heaters capable of reaching temperatures up to 200 °C were installed along the gas supply lines. Residual gases were vented outside during experiments, and nitrogen lines were connected to both the fuel and air electrodes to purge hydrogen and air from the station

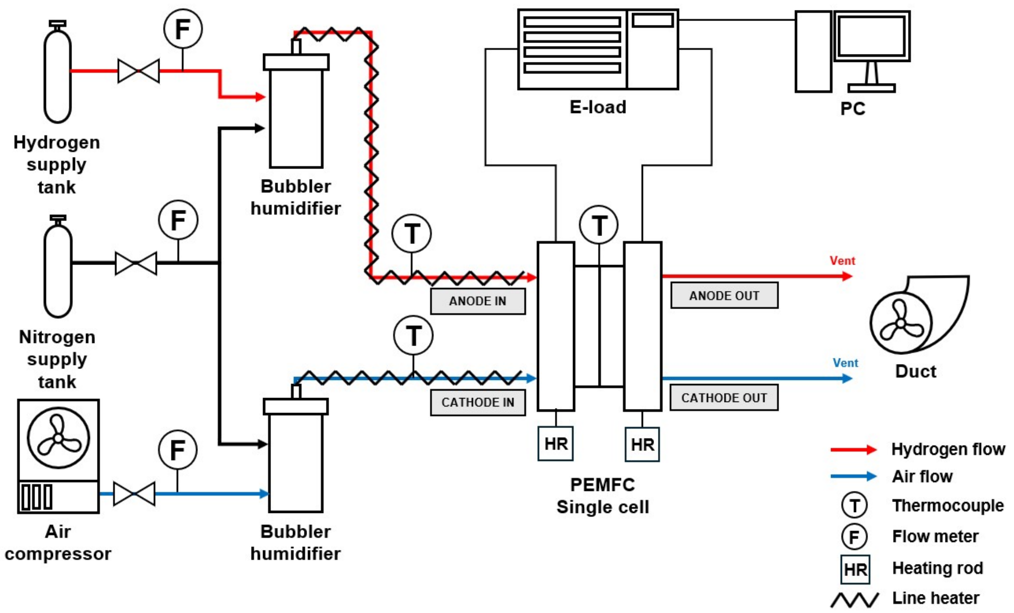

Fig. 1 Schematic of the PEMFC single cell test station

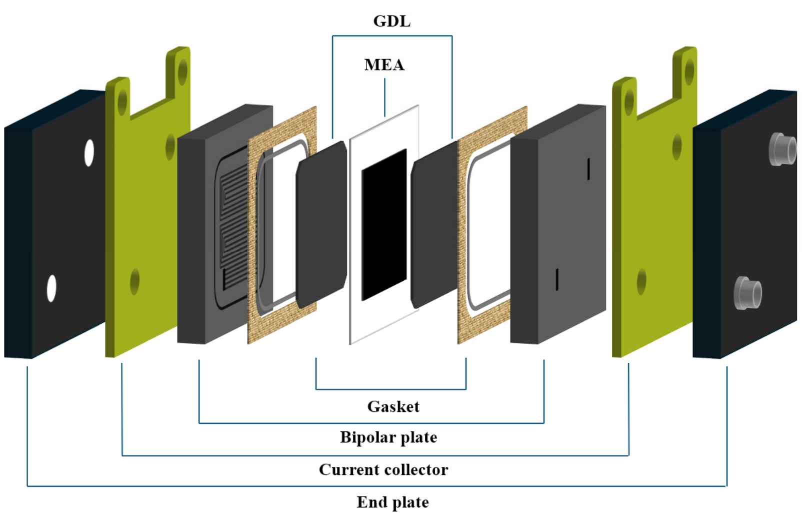

Fig. 2 Components of a PEMFC single cell

before and after each experiment. Since the reaction heat generated by the single cell was insufficient to maintain the operating temperature, heating rods were installed in the end plates for temperature control. Temperatures of the line heater and single cell were monitored using K-type thermocouples with a detection range of −200 to 1,250 °C. An electronic load (Kikusui, PLZ405W) connected to the anode and cathode of the single cell controlled and measured current and voltage at a frequency of 1 Hz. Data on temperature, flow rate, current, and voltage were recorded using a PC for analysis.

The PEMFC single cell used in the experiments was assembled as shown in Fig. 2, comprising gaskets (silicon, Teflon), bipolar plates (graphite), current collectors (gold-plated copper), and end plates (anodized aluminum). These unit cell parts (CNL Energy) were combined with a membrane electrode assembly (MEA) and a gas diffusion layer (GDL). The MEA included a polymer membrane (Gore, 15 μm) and a catalyst layer with a 25 cm^2 area, with a Pt loading of 0.4 mg/cm^2 on both the anode and cathode sides. The GDL was SGL Carbon's Sigracet 39BB, a carbon paper with a microporous layer (MPL).

2.2 Single Cell Activation

Before operating the single cell, an activation process was performed. This process is essential for improving the initial performance of newly manufactured PEMFCs by hydrating the polymer membrane and optimizing the catalyst layer (Pei et al., 2022). Activation was conducted according to the method provided by the cell manufacturer (CNL Energy). Fig. 3 illustrates one cycle of the activation protocol used in this study. The single cell was operated in constant voltage (CV) mode, starting from OCV and decreasing to 0.40 V in 0.05 V increments, maintaining each voltage for 10 s. At 0.40 V, the cell was held for 1 min before increasing the voltage back to OCV in 0.05 V increments, holding each step for 10 s. During this process, the hydrogen flow rate was maintained at 0.7 LPM, and the air flow rate was kept at 3.0 LPM to ensure sufficient moisture and reactant supply. This protocol was repeated for 60 cycles. Activation was deemed complete when the current density deviation at 0.40 V measured during the last three cycles was within ±10 mA/cm^2, as specified in IEC 62282-7-1 (IEC, 2017).

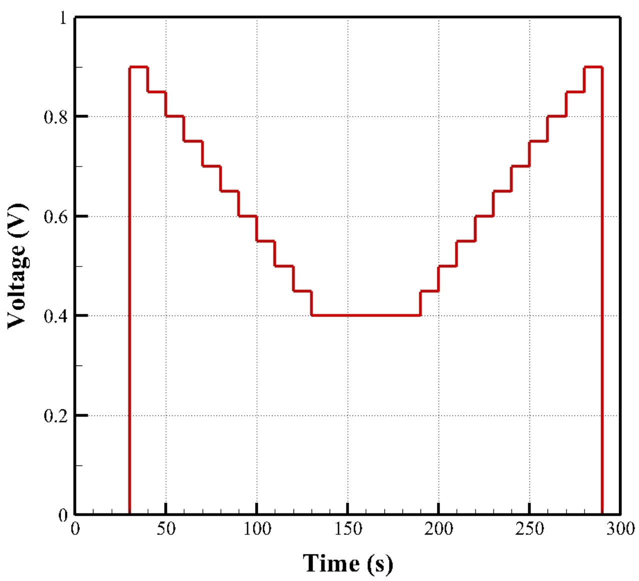

Fig. 3 Activation protocol in one cycle

2.3 Experimental Condition

To evaluate the impact of operating conditions on fuel cell performance, experiments were conducted under constant voltage and constant current operations. The cell temperature, relative humidity of the supplied gases, and stoichiometric ratios were kept constant across all experiments to isolate the effects of load conditions on the fuel cell. The experimental conditions were as follows: cell temperature of 70 °C, relative humidity of 100%, hydrogen stoichiometric ratio of 1.5, and air stoichiometric ratio of 2.0. The flow rates of hydrogen and air were determined using Eq. (1) (Malkow et al., 2010).

$$Q_{I,\lambda} = \frac{M \times I \times \lambda \times n}{z \times F \times \rho \times \phi} \quad (1)$$

In Eq. (1), Q (L/s) is the volumetric flow rate, M (g/mol) is the molar mass, I (A) is the current applied to the cell, λ is the stoichiometric ratio, n is the number of cells, z is the charge number, F (C/mol) is the Faraday constant, ρ (g/dm^3) is the density of the inlet gas, and ϕ is the mole fraction of the gas.

Before starting operations, the initial polarization curve was measured, and subsequent polarization curves were recorded periodically to ensure accurate performance analysis. Constant voltage experiments were performed at two operating voltages, 0.60 and 0.75 V, to analyze performance degradation differences. The 0.60 V condition represents typical automotive fuel cell operation (Wang et al., 2021), while 0.75 V corresponds to stationary fuel cell operation (Lee et al., 2010). For constant current operation, a current of 6.64 A was maintained, equivalent to the current at 0.75 V on the initial polarization curve, to facilitate comparisons.

3. Results and Discussion

3.1 Performance Under Constant Voltage Condition

Fig. 4 illustrates the polarization and power curves of the single cell, measured before and after constant voltage operation. Fig. 4(a) shows the results for 0.60 V operation, while Fig. 4(b) presents those for 0.75 V. Based on the shape of the polarization curve, the major loss trends in the fuel cell can be identified (Bezmalinovic et al., 2015). The range of 0.40–1.00 A/cm^2, where voltage decreases linearly with current density, is dominated by Ohmic losses (O'hayer et al., 2016; Bagherabadi et al., 2022). The slope in this region reveals the trend of Ohmic losses. For 0.60 V operation, the slope increased from an initial value of 0.240 to 0.268 $\Omega \cdot cm^2$. For 0.75 V operation, it increased from 0.226 to 0.242 $\Omega \cdot cm^2$. The power curve, derived as the product of voltage and current, demonstrates the output across current densities.

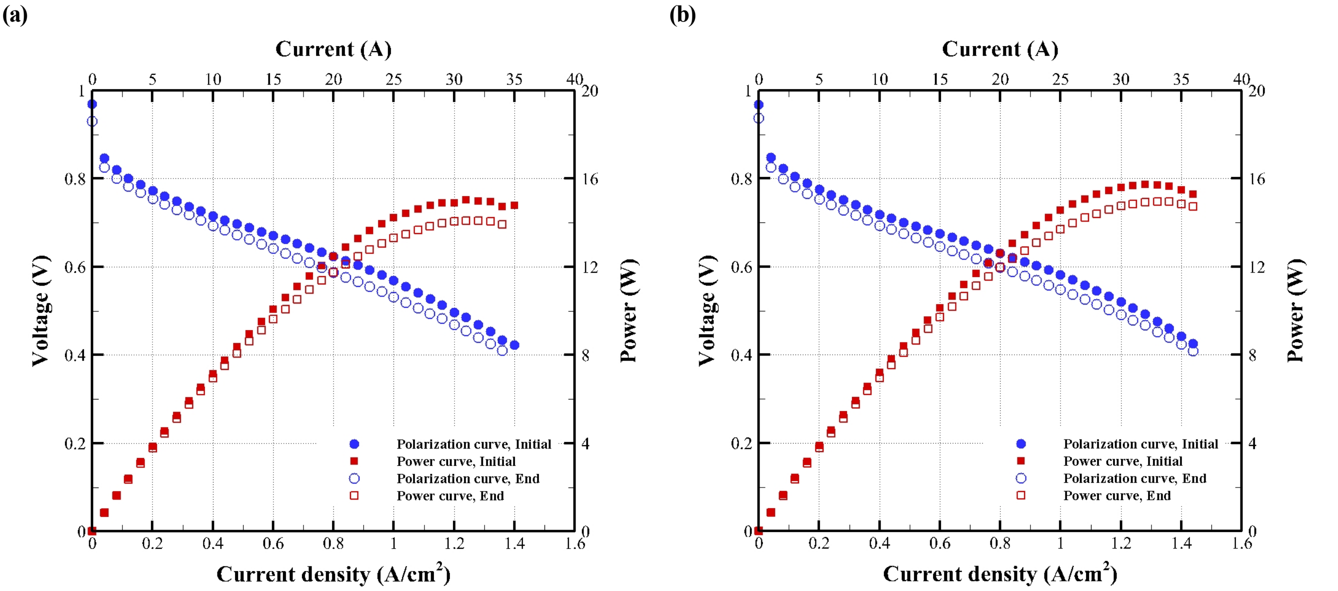

Fig. 4 Polarization curve and power curve at initial and end of degradation test under constant voltage operation at (a) 0.60 V and (b) 0.75 V

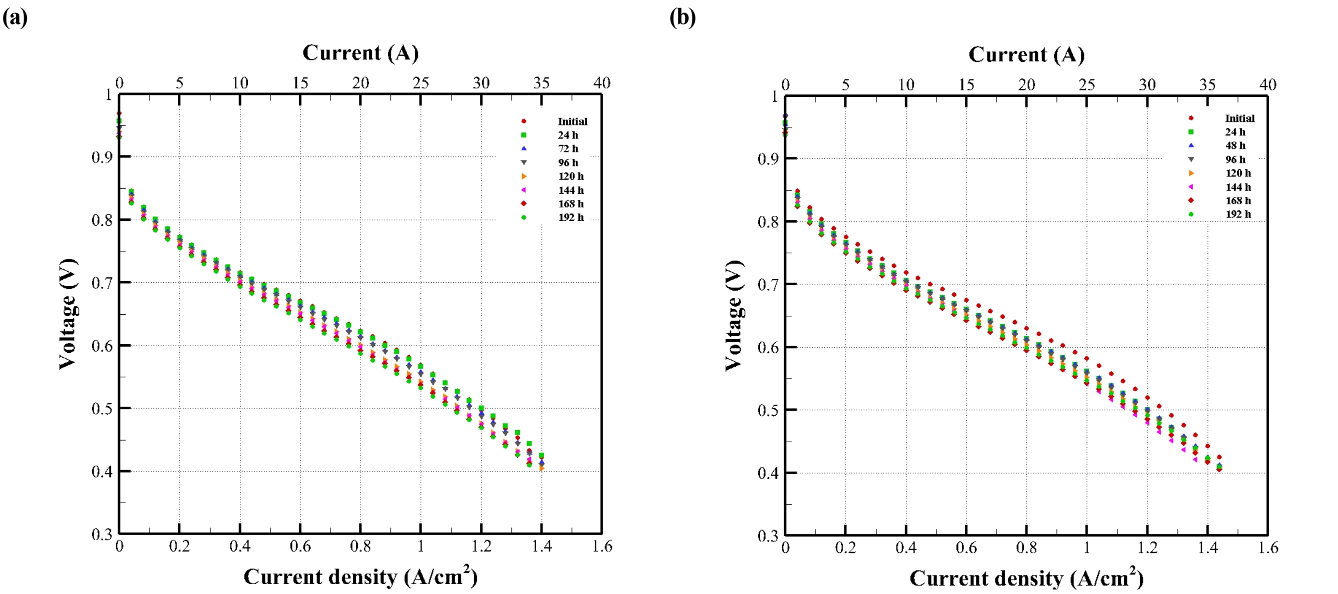

Fig. 5 Polarization curves of operated cell in constant voltage condition operation at (a) 0.60 V and (b) 0.75 V

Fig. 5 shows the polarization curves measured at different time intervals during constant voltage operation. Fig. 5(a) represents 0.60 V operation, while Fig. 5(b) represents 0.75 V operation. At all operating voltages, the voltage at each current density gradually declined with time, indicating progressive performance degradation during constant voltage operation. These results indicate that the performance degradation of PEMFCs under constant voltage operation occurs gradually over time.

To examine changes in unit cell voltage over time, the voltage data from Fig. 5 were reorganized similarly to Fig. 6. Fig. 6 represents time-dependent voltage changes measured at representative current densities (0.20, 0.40, 0.60, 0.80, and 1.00 A/cm²) and the OCV extracted from the polarization curves shown in Fig. 5. Fig. 6(a) corresponds to 0.60 V operation, while Fig. 6(b) corresponds to 0.75 V. At each current density, voltage decreased linearly over time, and degradation rates, defined as the rate of voltage decline per unit time, were calculated using linear regression. Higher current densities were associated with higher degradation rates.

Fig. 7 illustrates the degradation rates as a function of current density for different operating voltages. As shown, lower operating voltages were associated with significantly higher degradation rates across all current densities. The average degradation rate across the full current density range (0.00–1.20 A/cm²) was 0.156 mV/h for 0.60 V operation and 0.138 mV/h for 0.75 V operation. The degradation rate at 0.60 V was 13.5% higher than at 0.75 V. These findings indicate that operating voltage significantly influences cell voltage degradation,

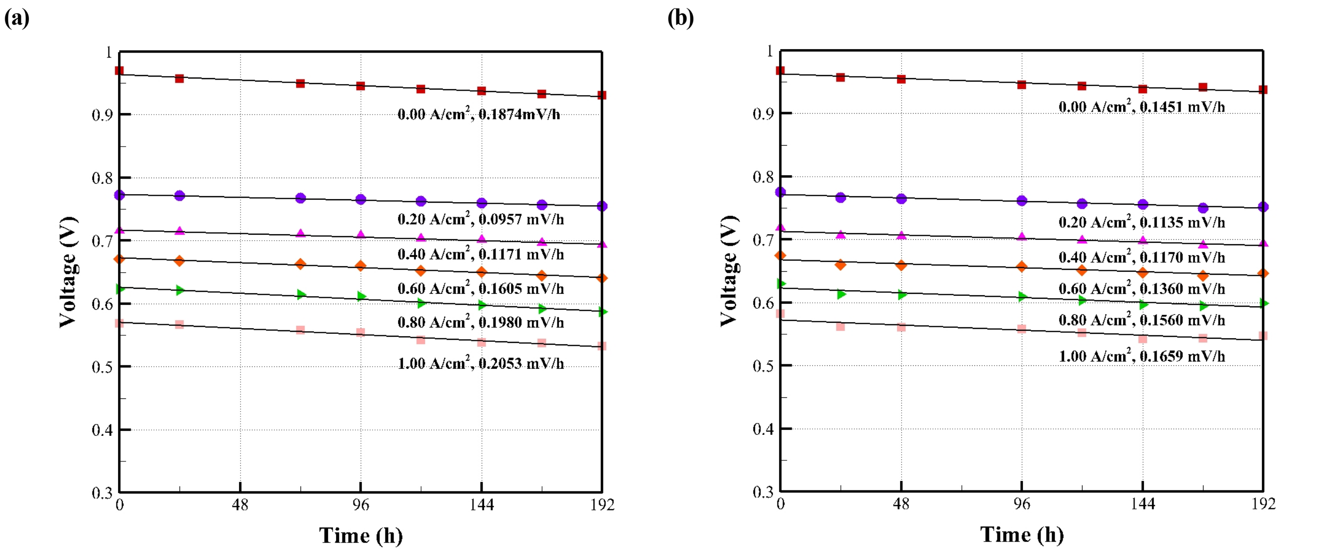

Fig. 6 Voltage drop at each current density in polarization curves vs. operation time under constant voltage operation at (a) 0.60 V and (b) 0.75 V

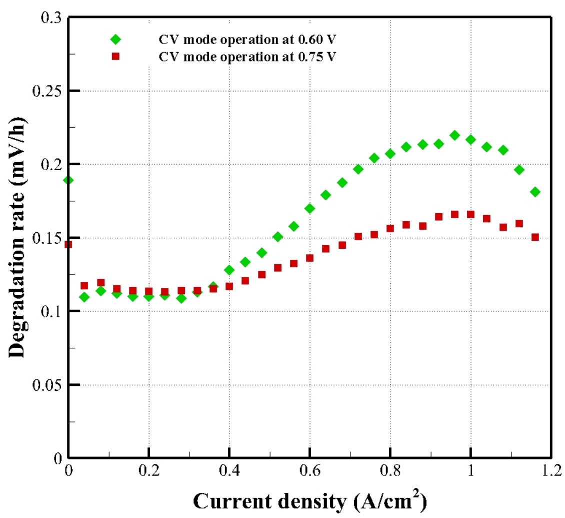

Fig. 7 Comparison of voltage degradation rate variations in constant voltage condition

with lower operating voltages accelerating this process. Under low-voltage conditions, increased electrochemical reaction rates generate more water (Shan et al., 2016). Excess water accumulation within the cell can clog flow channels and gas diffusion layers (GDL), restrict reactant transport, and exacerbate contamination and corrosion, thereby accelerating performance degradation (Schmittinger and Vahidi, 2008).

3.2 Comparison of Performance Under Constant Voltage and Constant Current Conditions

To analyze the degradation characteristics of single-cell performance under different operating conditions, experiments with constant current operation were conducted and compared with the results from constant voltage operation. Fig. 8 shows the polarization and power curves measured before and after the constant current operation at 6.64 A. In the linear range of current density from 0.40 to 1.00 A/cm², the slope of the voltage increased from an initial value of 0.246 to 0.248 Ω·cm². This increase was 90% smaller than the corresponding increase observed during the 0.75 V constant voltage operation.

Fig. 9 depicts the polarization curve measured periodically during the 6.64 A constant current operation experiment. Similar to constant voltage operation, the voltage decreased progressively with increasing operating time, indicating that performance degradation in PEMFCs occurs gradually over time under constant current conditions.

Fig. 10 presents the decline in voltage over time for the OCV and selected current densities based on the periodic polarization curve measurements. The degradation rates during constant current

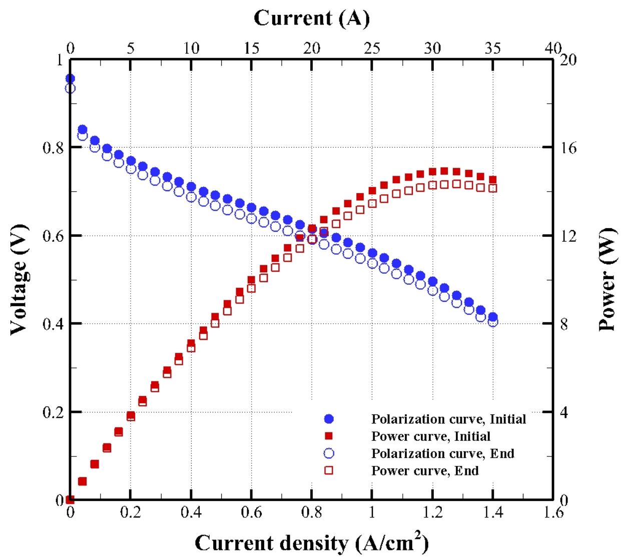

Fig. 8 Polarization curve and power curve at the initial and the end of degradation test under constant current condition (6.64 A, 190 h)

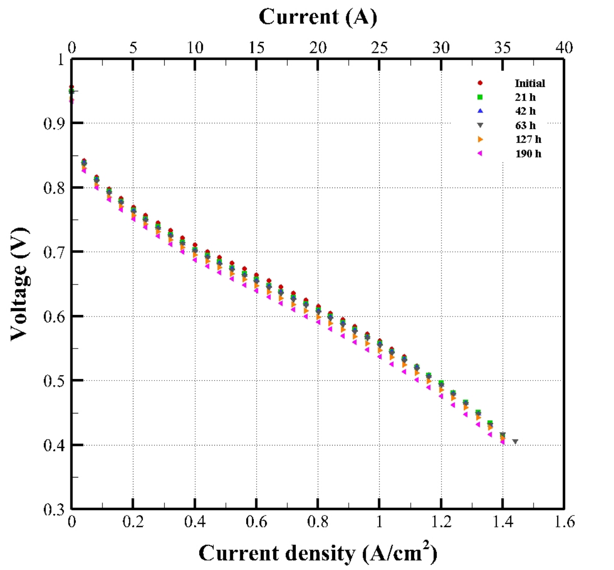

Fig. 9 Polarization curves of operated cell in constant current operation at 6.64 A (190 h)

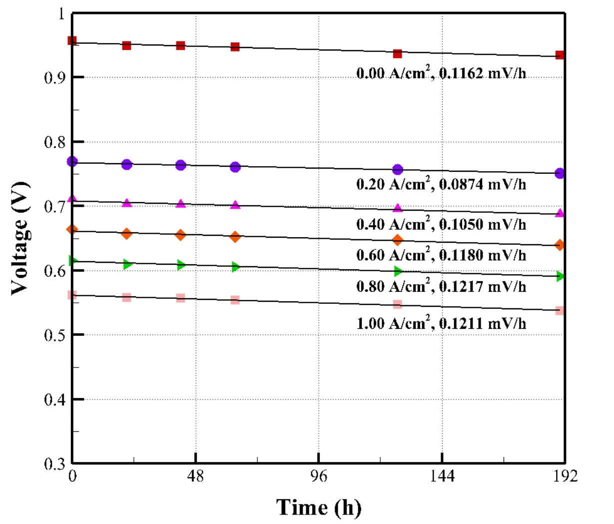

Fig. 10 Voltage drop at each current density in polarization curves vs. operation time under constant current operation at 6.64 A

operation were calculated through linear regression for each current density. Fig. 11 compares the degradation rates for each current density between the constant voltage operation at an initial voltage of 0.75 V (Fig. 5(b)) and the constant current operation (Fig. 9). Across all current densities, the constant voltage operation exhibited accelerated degradation rates compared to the constant current operation. The average degradation rate across the full current density range was 0.109 mV/h for constant current operation, which was 21.0% lower than the 0.138 mV/h observed for constant voltage operation. These results indicate that constant voltage operation accelerates single-cell degradation compared to constant current operation. Therefore, from the perspective of maintaining fuel cell longevity, constant current operation is more advantageous when

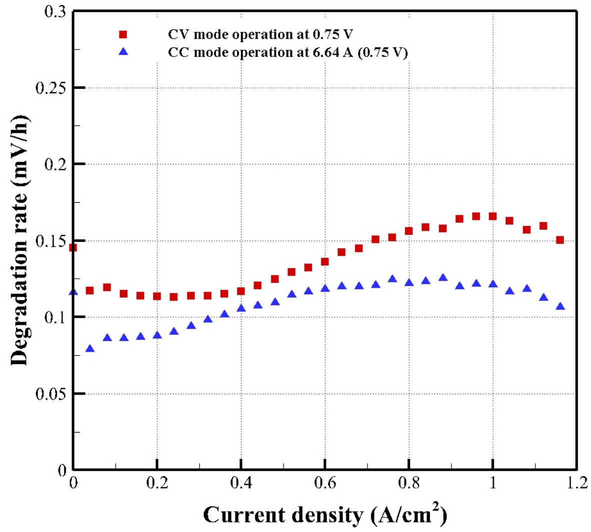

Fig. 11 Comparison of voltage degradation rate variation by operation mode

applying fuel cells in marine environments. To meet the dual requirements of maintaining fuel cell lifespan and ensuring the constant voltage conditions required by ship power systems, it is deemed necessary to develop an effective power management strategy.

The performance degradation analysis under constant voltage and constant current conditions serves as foundational information for predicting the lifespan of fuel cells applied to ships. However, since power generation output in actual maritime operations can be controlled depending on sea conditions (Wu et al., 2020), further studies on performance degradation under constant power operation are needed to more accurately reflect real-world conditions.

4. Conclusions

This study evaluated the durability of fuel cells for maritime applications through performance degradation experiments conducted under constant voltage and constant current conditions using single cells. Analysis of polarization curves identified voltage drop characteristics and degradation rates across different current densities. The average degradation rate during constant voltage operation was 0.156 mV/h at 0.60 V and 0.138 mV/h at 0.75 V. Degradation rates increased at lower operating voltages, indicating faster deterioration under these conditions. In constant current operation, the average degradation rate was 0.109 mV/h, 21.0% lower than under constant voltage operation at the same voltage level (0.75 V). These findings highlight the accelerated performance degradation during constant voltage operation, especially at lower voltages. Consequently, constant voltage operation has a greater negative impact on fuel cell lifespan compared to constant current operation. However, in real-world ship operations, power output is adjusted based on speed and sea conditions. Future research will focus on performance degradation analysis under varying load conditions that better reflect actual maritime operating environments.

Conflict of Interest

The authors declare that they have no conflicts of interest.

Funding

This work was supported by the Regional Innovation Strategy (RIS) through the National Research Foundation of Korea (NRF), funded by the Ministry of Education (MOE) (2023RIS-007), and the Global Advanced Engineer Education Program for Future Ocean Structures (P0012646), funded by the Ministry of Trade, Industry, and Energy.

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