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Development of novel proton exchange membrane fuel cells using stamped metallic bipolar plates

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HIGHLIGHTS

- We present the development of novel proton exchange membrane fuel cells.
- A novel bipolar plate with straight channels is designed.
- The effects of temperature and pressure on stack performance are evaluated.
- The best performance is 1100 mA cm^{-2} at 0.646 V in this study.

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ABSTRACT

This study presents the development of novel proton exchange membrane fuel cells using stamped metallic bipolar plates. To achieve uniformly distributed and low pressure-drop flow fields within fuel cells, a novel bipolar plate with straight channels is designed and verification of a fuel-cell short stack using this bipolar plate is performed. In the experiments, low-temperature and low-humidity operations and high-temperature and high-humidity operations are adopted to evaluate effects of stack temperature and inlet relative humidity on performance at various outlet pressures. Experimental results show that under low-temperature and low-humidity operations, increasing the outlet pressure enhances stack performance and reduces performance differences between various stack temperatures. Under high-temperature and high-humidity operations, stack performance increases with increasing outlet pressures, while the extent of their increase becomes smaller. Compared to low-temperature and low-humidity operations, high-temperature and high-humidity operations have better electrochemical reactions and membrane hydration and, thus, better stack performance. In this study, the operation with a stack temperature of 80 °C and outlet pressure of 4 atm produces the best performance of 1100 mA cm^{-2} at 0.646 V.

1. Introduction

Proton exchange membrane (PEM) fuel cells possess high efficiency, produce low pollution, are quiet and require a low-temperature start-up, so many developed countries have invested manpower and resources in related research. To commercialize PEM fuel cells, the United States Department of Energy (DOE) has set technical targets [1] for portable, residential and transportation fuel cells. Because transportation fuel cells are used for automotive power, their high volume and weight power densities are especially emphasized. Automakers such as Honda, Toyota and General Motors have devoted time to developing transportation fuel cells for this purpose. To improve power densities of transportation fuel cells, most automakers use stamped metallic bipolar plates (BPs) instead of graphite BPs to greatly reduce the volume and weight of a fuel-cell stack. Therefore, PEM fuel cells using metallic BPs have become one of the most promising alternatives in future automotive power. Recently, the Industrial Technology Research Institute (ITRI), the leading Taiwanese research institute on PEM fuel cell research, obtained a breakthrough in fuel-cell technology using stamped metallic BPs. The purpose of this study is mainly to present the development of novel PEM fuel cells by the ITRI. To understand the design, fabrication and performance analysis of PEM fuel cells in previous research, especially for fuel cells using metallic BPs, related studies are reviewed as follows.

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Cho et al. [2] presented experimental research on a water-cooled PEM fuel-cell stack with 240 cm^2 of active area and 12 cells. They used Nafion 1135 membranes and TiN-coated 316L stainless steel BPs, and the reactant and coolant channels were formed by chemical etching, respectively, on both sides of the BP. Under operating conditions of fully humidified air and hydrogen, a constant temperature of 60 °C and normal pressure, this stack produced a current of 142.7 A (1027 W) at an overall voltage of 7.2 V. Furthermore, this stack was operated for 1028 h at a current of 48 A, and its degradation was approximately 11%. Sohn et al. [3] performed experimental and numerical analyses of an air-cooled PEM fuel-cell stack with 100 cm^2 of active area and 21 cells. Nafion 112 membranes, SGL gas diffusion layers (GDLs) and graphite BPs were used as components. Under operating conditions of highly humidified air and hydrogen, an average temperature of 60 °C and normal pressure, this stack produced a current density of 550 mA cm^{-2} (693 W) at an average voltage of 0.60 V. Air pressure drops and flow distributions were also simulated using computational fluid dynamics (CFD) in this study.

Scholta et al. [4] presented research on a water-cooled PEM fuel-cell stack with 100 cm^2 of active area and 24 cells in which membrane electrode assemblies (MEAs) of Gore Primea 5620, SGL 10BB GDLs and graphite BPs were used. The effects of reactant flow directions and geometries on cell performance were analyzed to obtain the optimum flow field that was suitable for the stack. Under operating conditions of low humidified air and hydrogen, a constant temperature of 55 °C and normal pressure, this stack produced an ultimate power density of 360 mW cm^{-2} (36 W $cell^{-1}$) at an average voltage of 0.60 V. Furthermore, the simulation of air flow distributions was performed to evaluate the feasibility of extending the present design to development of a stack with more than 150 cells. Weng et al. [5] experimentally investigated the performance of a water-cooled PEM fuel-cell stack with 100 cm^2 of active area and four cells. They used Gore Primea 5510 MEAs and graphite BPs, and both the reactant and coolant channels were serpentine. Under operating conditions of fully humidified air and hydrogen, a constant temperature of 70 °C and normal pressure, this stack produced an ultimate power density of 0.55 W cm^{-2} (220 W) at an average voltage of 0.50 V.

Shimpalee et al. [6] performed experimental and numerical analyses of an air-cooled PEM fuel-cell stack with 30.87 cm^2 of active area and six cells. They used Gore Primea 5510 MEAs and graphite BPs, and the reactant and coolant channels were serpentine and straight, respectively. Under operating conditions of low humidified air and hydrogen, an average temperature of 63 °C and normal pressure, this stack produced a current of 30 A (85 W) at an overall voltage of 2.8 V. Furthermore, the effects of oxygen concentrations, current densities and temperatures on the performance were analyzed using three-dimensional CFD. Squadrito et al. [7] experimentally investigated the performance of a water-cooled PEM fuel-cell stack with 200 cm^2 of active area and 70 cells. Gore Primea 5621 MEAs, SGL GDLs and graphite BPs were used as components, and both the reactant and coolant channels were serpentine. Under operating conditions of fully humidified air and hydrogen, a constant temperature of 60 °C and normal pressure, this stack produced 6.2 kW (170 A) of power at an overall voltage of 36 V.

Yi et al. [8] experimentally investigated the performance of a water-cooled PEM fuel-cell stack with 40 cm^2 of active area and three cells. They used commercial MEAs and carbon-coated BPs, which were manufactured by stamping 304 stainless steel sheets. Under operating conditions of low humidified air and hydrogen, a constant temperature of 60 °C and high pressure, this stack produced a current of 58.1 A (105 W) at an overall voltage of 1.8 V, and it was operated for 48 h to verify stability. Yan et al. [9] experimentally investigated the performance of a single PEM fuel cell with 256 cm^2 of active area. They used Gore Primea 56 and 57 MEAs and graphite BPs with serpentine reactant channels. Under operating conditions of humidified air or hydrogen, the performance using Gore Primea 57 MEAs was better than when using Gore Primea 56 MEAs at the specified cell and humidified temperatures. Compared with Gore Primea 56 MEAs, Gore Primea 57 MEAs can be applied to more low humidified operations. Ren et al. [10] experimentally investigated the performance of a PEM fuel-cell short stack with 50 cm^2 of active area. Nafion 211 membranes and stamped stainless steel BPs with TiN-coated film were used as components, and the reactant channels were parallel or serpentine. Under operating conditions of a stack temperature of 65 °C and normal pressure, this stack produced a current density of 800 mA cm^{-2} at an average voltage of 0.49 V and corresponding weight power density of 1353 W kg^{-1}.

From the above review of the literature, most studies have been focused on fuel cells using graphite BPs, while there are only two studies about fuel cells using stamped metallic BPs. When further reviewing the literature on stamped metallic BPs of PEM fuel cells, the related studies are mainly involved in BP design and manufacture. These include the effects of BP shape and coated film on electronic resistance [11–14] and the effects of the BP manufacture and channel geometry on its formability [15–17]. Therefore, studies on the performance verification of PEM fuel cells using stamped metallic BPs are extremely rare. Automakers devoted to developing PEM fuel cells have published a large number of patents for stamped metallic BPs. To understand fuel-cell technologies developed by automakers, we illustrated disclosed stamped-BP designs according to which related patents could be roughly classified.

Figs. 1–3 show three types of disclosed stamped-BP designs, which have straight, serpentine and zigzag reactant channels, respectively. In Figs. 1 and 2, oxidant-inlet and oxidant-outlet manifolds are diagonally laid on the top and bottom, respectively, and so are fuel-inlet and fuel-outlet manifolds. Coolant-inlet and coolant-outlet manifolds are symmetrically laid on the top and bottom, respectively. In Fig. 1, the reactant-path length along each straight channel is nearly equal, while the coolant-path length along each straight channel increases from the middle toward the left and right. This leads to a uniform reactant distribution but less-uniform coolant distribution. For this phenomenon of less-uniform coolant distributions, Maharudrayya et al. [18] have performed analyses by using numerical simulations. Their research showed that there is a large bypass of the flow through the central channel and this causes serious non-uniformity of flow. Furthermore, because the straight channel is short and not tortuous, both the reactant and coolant pressure drops are very small. Representative patents of the stamped-BP design with straight reactant channels are mainly published by Honda [19,20] and General Motors [21,22].

In Fig. 2, the reactant-path length along each serpentine channel is nearly equal, and so is the coolant-path length that is formed in a randomly flowing manner. Therefore, both of the reactant and coolant distributions are uniform. However, the serpentine channel is longer and more tortuous than the straight channel, so it produces larger pressure drops. Representative patents of the stamped-BP design with serpentine reactant channels are mainly published by General Motors [23–25]. In Fig. 3, oxidant-inlet and oxidant-outlet manifolds are diagonally laid on the top and bottom, respectively, and so are fuel-inlet and fuel-outlet manifolds. Coolant-inlet and coolant-outlet manifolds are symmetrically laid on the left and right of the BP-coolant side, respectively. The reactant-path length along each zigzag channel is nearly equal, and so is the coolant-path length along the direction normal to the zigzag channels. Therefore, both the reactant and coolant