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Improving gas diffusivity with bi-porous flow-field in polymer electrolyte membrane fuel cells

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ABSTRACT

The performance of polymer electrolyte membrane (PEM) fuel cells highly depends on their mass transport property at high current density operation. To improve the mass transport property, various types of flow-fields have been developed, such as serpentine, straight, grid, and porous flow-fields. Because of the limits of thin land and channel width, the authors have developed a porous type flow-field with unique pore diameter distribution. Unlike general types of porous flow-fields, it has a double peak in the pore diameter distribution; in this paper, it is called a "bi-porous flow-field". The structure was intended to have organized flow paths for liquid water and gas. The paper investigates its performance and impedance characteristics compared with those of the conventional flow fields. The results of the analysis on the polarization and electrochemical impedance spectrometry revealed that the bi-porous flow-field exhibits the smallest gas diffusion resistance at a high current density operation regardless of humidity conditions. These results indicate that the bi-porous flow-field conducts water management well at high current density. In low humidity conditions, however, dry-out tends to occur and must be prevented.

Introduction

Fuel cells are a promising next-generation power source due to their characteristics of higher efficiency, lower pollutant emission, and higher flexibility for primary energy sources. Among various types of fuel cells, polymer electrolyte membrane (PEM) fuel cells have a good start-stop characteristics and relatively high power density, so that they are applied for automotive and portable power sources as well as CHP (combined heat and power). One of the major research topics for PEM fuel cells is increasing the power density further, because decreasing the number of stacking cells can effectively reduce cost.

A PEM fuel cell consists of electrode catalysts, PEMs, gas diffusion layers (GDLs), and bipolar plates. To achieve higher power density, efficiency of the electrode catalyst activity must be increased, electrical resistance of the cell decreased, and transport of reactant gases and produced water improved. Particularly, water transport must be controlled to increase the limiting current density while maintaining a smooth supply of reactant gases to the catalyst layers. When a fuel cell

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operates at high current density, more water is generated by the electrochemical reaction at the cathode, and this inhibits reactant gas diffusion. For good water management, the flow-field structure must be properly designed, as it directly influences the behavior of gas and liquid flow.

Various shapes have been proposed for the flow-field structure [1–5] to effectively supply a reactant gas to the electrode. In-situ visualizations of condensed water in a GDL and channels have been carried out [6] using an optical microscope [7–9], X-ray radiography [10,11], and neutron imaging [12,13] to understand the complex phenomena in a fuel cell. Two-phase flow analysis with the lattice Boltzmann method has also been conducted [14] to clarify the dynamics of liquid and gas flow in a micro scale porous medium. Investigations on a GDL to prevent water condensation have been reported [15–17]. As for the research on the gas flow-fields, porous media such as metal foams and fiber felt have been applied for gas channels. Most results show that the porous media work as effective gas distributers for high current density operation [2,18–23]. Kumar and Reddy developed a numerical mass transfer model for the phenomena in metal foam and reported that decreasing the permeability of gas flow-field improved performance [2]. Srouji et al. reported that the limitation at ultra-high current density was due to the dehydration at the anode, while reactant mass transport was kept well with a porous flow-field [21]. Some reports have pointed out the dehydration problems of the porous flow-field, and there has been a report on the lower heat removal capability in low humidity conditions [23].

The present research focuses on a structure of the porous flow-field for achieving novel flow distribution of the reactant gases in higher current density conditions. Conventional channel flow-fields have land and channel structures, and this makes the flow distribution of gas, liquid, electrons, and heat uneven. Thinner intervals between the channel and the land have been reported to effectively improve performance [24]. However, it is difficult to manufacture numbers of channels with thin intervals. A porous structure, on the other hand, can be fabricated more easily and be considered as the limited structure of the thinnest interval of the channels. The advantages of a porous flow-field are expected to be (1) an increase in reactant gas diffusivity, (2) uniform distribution of thermal and electron conductivity, and (3) uniform contact pressure and stress over the entire electrode under stacking. At the same time, the porous flow-field may have disadvantages such as increased pressure drop and lower thermal conductivity.

Most of the porous flow-field has pore diameter distribution with a single peak. In the present research, a porous medium with a double peak in the pore diameter distribution was produced and applied for the fuel cell. In this paper, the porous medium is called a “bi-porous flow-field”. This bi-porous flow-field was developed with the expectation of organizing the flow patterns of water and gases. The authors assumed that the water would flow in the smaller pores of hydrophilic metal whereas the reactant gases would flow in the larger pores in opposite directions. Additionally, the pore structure may contribute to preventing the dehydration problems, as the smaller pore structure may keep water in the pores to hydrate the membrane.

The paper investigates the performance characteristics of the bi-porous flow-field in comparison with those of conventional flow-fields. Other reports have intensively reviewed the relationship between flow-field designs and cell performance [25,26]. According to the findings in this paper, it is difficult to conclude which type of flow-fields is the best as the performance strongly depends on the specific geometry including width of the channels and operating conditions. With this in mind, this paper presents the performance characteristics of the bi-porous flow-field as useful information for fuel cell developers.

Experimental apparatus and procedure

To evaluate the difference in flow-field structure on power generation characteristics, five types of flow-field were examined. The experiments were conducted with a single PEM fuel cell with a 25 cm^2 (5 cm $\times$ 5 cm) active area. The cell components had the same configuration except for the flow-fields. It used commercially available MEAs (GORE PRIMEA®; 20-μm-thick membrane; Pt loadings are 0.1 mg cm^{-2} for anode and 0.4 mg cm^{-2} for cathode) with GDLs (CNW20B with microporous layer). The flow-field structure was the same for the anode and cathode sides.

Fig. 1(a) shows the flow-field pattern evaluated in this experiment. Three of them are channel flow-fields: serpentine, straight, and grid. The others are two types of porous flow-fields. Flow distribution control ribs were arranged between a manifold and flow-field for the straight, grid and porous flow-fileds. The specifications of the flow-fields are listed in Table 1. The aperture ratio indicates open area in the contact plane relative to the total area, and it was estimated from porosity in the case of the porous media. A 5-mm-thick resin impregnated carbon plate was used as a bipolar plate material. The channels were formed on the surface of the plate mechanically by cutting the channels. Note that the serpentine and straight types have different channel and rib widths.

For the porous flow-fields the concave space was also formed on the surface of the plate to insert the porous medium. Both porous media were made of 1.0-mm-thick 316L stainless steel. The mono-porous flow-field is a commercially available metal-medium (Mitsubishi Materials) made with a bubble-foaming method. The bi-porous flow-field is a porous medium specially designed for high power density PEM fuel cells. It was made using a sintering method by Hitachi Metals, Ltd. Au nanometer coating was placed on the surface of both porous media in anode and cathode to reduce the contact resistance and prevent corrosion.

Fig. 2 shows the secondary electron microscope image and pore size distribution of the porous media: (a) mono-porous, and (b) bi-porous. The images were observed from the planar direction. The metal pillar forms a skeleton for the mono-porous flow-field and has relatively large pores. On the other hand, metal powder-aggregate forms a skeleton for the bi-porous medium. These figures indicate that the manufacturing process realizes the unique structure. The porosity of the porous media and pore size distribution was measured by mercury intrusion porosimetry. In the