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Corrugated mesh flow channel and novel microporous layers for reducing flooding and resistance in gas diffusion layer-less polymer electrolyte fuel cells

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HIGHLIGHTS

- Large flooding reduction was attained with corrugated mesh in a GDL-less fuel cell.
- Flow-channel patterns affect the contact resistance of corrugated mesh MPLs.
- MPL conductivity is the key to reducing HFR without GDLs.
- MPL rigidity can affect contact resistance with improved pressure distribution.

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ABSTRACT

Electrode flooding at the cathode impedes the increase in power density of polymer electrolyte fuel cells (PEFCs), limiting their use at high current densities. Liquid water can accumulate in the pores of the gas-diffusion layer (GDL), deteriorating performances significantly. This paper reports a novel fuel-cell structure for the reduction of electrode flooding utilizing corrugated mesh as gas-flow channels and gas diffusers placed directly onto the microporous layer (MPL) without a conventional GDL in between. The polarization curve of the corrugated-mesh fuel cell shows a lower flooding tendency at a high current density; however, the high-frequency resistance (HFR) of this fuel cell increases significantly as a result of fewer contact points between the corrugated mesh and MPL. In addition, MPL conductivity and rigidity are investigated in efforts to reduce the flow-channel pattern resistance. The rigidity of the MPL has a small effect on the reduction in HFR, which may be caused by an improved pressure distribution on the catalyst layer.

1. Introduction

Polymer electrolyte fuel cells (PEFCs), which convert the chemical energy of hydrogen directly into electrical energy, are regarded as a promising alternative technology and clean power source for automotive, stationary, and portable applications [1–5]. The utilization of fuel cells for powering automotive equipment requires a reduction in cost and size, as current automotive fuel cells are not profitable and are still too large, limiting the layout of the fuel-cell system [6].

Currently, most automotive fuel cells operate with a maximum current density of 1.0 A cm^{-2} [7–9]. This low current density requires a large active area in order to produce a vehicle power output of 70–120 kW, which consequently increases the number of polymer electrolyte membranes (e.g., Nafion, Acipex, and Dow membranes), catalyst layers with precious metals, and gas-diffusion layers (GDLs) required. The expense of these materials means that larger active areas significantly increase the cost of the fuel-cell stack. In addition, a GDL thickness of 90–200 μm for each electrode increases the length of the stacking direction, with the total volume of the GDL occupying about half of the fuel-cell stack. These considerations create limitations for conventional fuel-cell structures with regard to cost and size.

Solving these commercialization issues for automotive fuel cells requires a novel fuel-cell structure that enables high current density operation without a GDL. Increasing the current density of

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conventional fuel cells causes a sudden decrease in performance, known as cathode flooding. When current density increases, more water is generated in the electrochemical reaction ($O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$) at the cathode, and more water is transported from the anode to the cathode through the membrane via electro-osmotic drag [10–12]. The water at the cathode condenses and accumulates, blocking oxygen diffusion and causing a sudden decrease in the cell voltage. Simultaneously increasing the current density causes the membrane to dry out at the anode. The membrane is dehydrated by electro-osmotic drag from the anode to the cathode [13], in addition to the increased temperature from the electrochemical reaction and ohmic heat. The proton conductivity of the membrane is heavily dependent on its water content, meaning that dehydration of the membrane decreases proton conductivity, and thus, cell performance.

In a previous study, we achieved a performance of 0.55 V at 1.8 A cm^{-2} without a significant voltage drop, even at a relatively high current density of over 1 A cm^{-2}, utilizing tightly aligned microcoils in the flow channel without a GDL. We have also measured the performance of conventional flow fields with GDLs; the performance showed a severe voltage drop starting at a relatively low current density of 0.6 A cm^{-2} [14]. In general, GDLs work by distributing the gas from the flow channel to the land underneath in a conventional flow field [15]; however, when the GDLs and channel/land structure are combined, the water cannot be removed from underneath; this water accumulation results in a non-uniform blockage of gas supply to the catalyst layer, the well-known phenomenon of electrode flooding, which significantly decreases fuel-cell performance along with an accompanying increase in current density [16]. We have concluded that the microcoil flow channel can supply the reactant gas uniformly to the catalyst layer (in this work, no sign of flooding is visible up to 1.8 A cm^{-2} in the polarization curve). Nonetheless, the GDL-less microcoil flow channel shows a larger high-frequency resistance (HFR) than conventional flow fields with GDLs. Due to fewer contact points between the microcoils and microporous layer (MPL), electron conduction occurs in the in-plane direction of the MPL, which causes a larger HFR in the microcoils with higher contact and concentration resistance from the point-to-surface contact on the MPL.

There is little information published in the literature pertaining to electron resistance in GDL-less PEFC stacks. Seyfang et al. reported the performance of GDL-less stacks utilizing micro-patterned glassy carbon flow fields and a catalyst-coated membrane (CCM) [17]. They found that the GDL-less stack had a higher ohmic loss than the GDL-containing stack due to the reduction of electron travel pathways through the thin catalyst layer in the GDL-less case. They also evaluated the ohmic loss for several channel geometries to verify the electron path through the catalyst layer, obtaining a linear correlation between the channel width and HFR of the fuel cell. They used the catalyst layer as the electron conductor and collector; however, problems with high ohmic loss and low gas diffusion were experienced directly under the land of the bipolar plate, especially at the cathode.

Other than the larger HFR for microcoil flow channels in GDL-less stacks, the high cost of microcoils must also be considered, especially if being mass-produced. Furthermore, tightly setting a number of microcoils onto the bipolar plate is quite time consuming. Therefore, we have prepared a corrugated stainless-steel mesh as the gas-flow channel with the expectation that the corrugated mesh may play a similar role as microcoil flow channels in order to reduce flooding. Here, we report the preparation, performance, and HFR of a corrugated mesh applied to GDL-less fuel cells, and the effect of MPL conductivity on the HFR using the equivalent circuit model to extract the MPL contribution for the HFR.

2. Experimental

2.1. Preparation of a corrugated mesh flow channel

The corrugated mesh flow channel was prepared with a stainless-steel mesh and corrugating roll. The stainless-steel mesh (nets101 Co., Ltd, Shimizu, Japan) was a twill weave-type SS316L material of 300-mesh with a fiber diameter of 50 μm. The cross-section shape of the corrugated mesh was triangular with a height of 0.3 mm and length of 0.3 mm. To corrugate the mesh, a customized corrugating roll was fabricated (MIKI SEISAKUSYO CO. LTD., Osaka, Japan) as shown in Fig. 1. The template grooves were first machined on the surface of the roll along the direction of the circumference, the plain mesh was inserted between the two rolls, and the fluted shape was finally transferred to the mesh under a certain compression pressure. Fig. 2 shows an optical microscope image of a cross-section of the corrugated mesh. Two different flow-channel patterns were formed in the gas-flow direction, namely a straight pattern (straight corrugated mesh) and meandering pattern (meandering corrugated mesh). The straight corrugated mesh had a high electrical resistance on both sides; therefore, the meandering corrugated mesh was made as a solution as described in Section 3.2. The meandering pattern adopted the shape of a sine curve with a length of 0.6 mm and amplitude of 0.2 mm in the same triangular cross-section using a similar corrugating roll template method.

2.2. Preparation of MPLs

MPLs were used in the anode and cathode catalyst layers to control fuel-cell water management [18]. Generally, the MPL is coated on the GDL; however, in the present study of GDL-less fuel cells, a free-standing MPL was required for use between the catalyst layers and corrugated mesh flow channels. The electron-conducting pathway from the catalyst to the bipolar plate in the present fuel cells is thought to be different from conventional fuel cells that utilize GDLs. The electron is first transferred vertically to the MPL and then moved horizontally within the MPL to the corrugated mesh contact point. To observe this effect, four different MPLs were fabricated having different conductivities using four

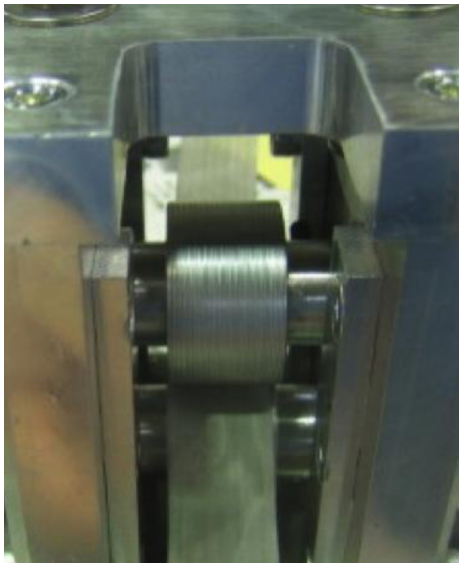

Fig. 1. Image of the roll corrugator used for production of corrugated mesh.