Journal of Power Sources 330 (2016) 273–284

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Numerical and experimental study of the effects of the electrical resistance and diffusivity under clamping pressure on the performance of a metallic gas-diffusion layer in polymer electrolyte fuel cells

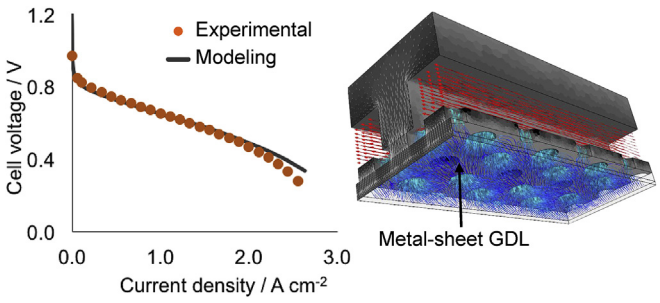
Shiro Tanaka [a, c, *], Warwick W. Bradfield [b], Cloe Legrand [a], Arnaud G. Malan [b]

[a] HySA/Catalysis, Department of Chemical Engineering, University of Cape Town, Private Bag X3, Rondebosch, Cape Town 7701, South Africa
[b] Industrial Computational Fluid Dynamics Research Group, Department of Mechanical Engineering, University of Cape Town, Private Bag X3, Rondebosch, Cape Town 7701, South Africa
[c] Department of Mechanical Engineering, Tokyo Metropolitan University, 1 Minamiosawa, Hachioji, Tokyo 192-0397, Japan

HIGHLIGHTS

- Using a metal-sheet GDL resulted in a lower ohmic resistance.
- A coupled model was developed and validated for fuel cells with a metal-sheet GDL.
- The porosity deformation in the MPL and CL under pressure was considered.
- The channel width of the metal-sheet GDL was the key for enhancing the performance.
- Pressure greatly affected the performance of the fuel cell with a metal-sheet GDL.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 May 2016
Received in revised form
25 July 2016
Accepted 29 August 2016

Keywords:
Polymer electrolyte fuel cell
Metal-sheet gas-diffusion layer
Flooding
Microporous layer
Contact resistance
Compression

ABSTRACT

The performance of a perforated metal-sheet gas-diffusion layer incorporated with a microporous layer in a fuel cell is evaluated with fine-pitch channel/land designs for the gas flow field on a bipolar plate. The combination of metal-sheet gas-diffusion layer and microporous layer exhibits significant performance without a large flooding effect. When comparing the performance with wider and narrower land cases, the land width affects the performance. To investigate the roles of the microporous layer, land width, etc. in the fuel cell with the metal-sheet gas-diffusion layer, a single-phase, isothermal, and multi-physics simulation is developed and coupled with electrical, mechanical, electrochemical and fluid dynamics factors. The simulated current–voltage performance is then compared to the experimentally measure performance. These are shown to be in good agreement apart for very high current-density cases i.e. greater than 1.5 A cm^{-2}. This is due the flooding effect predominantly appearing. It is further demonstrated that the microporous layer serves as the key component in facilitating gas diffusion and for preventing flooding. Furthermore, the pressure is found to have a strong impact on the performance, affecting the gas diffusion and electric resistance around the microporous layer.

* Corresponding author. HySA/Catalysis, Department of Chemical Engineering, University of Cape Town, Private Bag X3, Rondebosch, Cape Town 7701, South Africa.
E-mail address: shiro.tanaka@uct.ac.za (S. Tanaka).

http://dx.doi.org/10.1016/j.jpowsour.2016.08.121
0378-7753/

1. Introduction

Polymer electrolyte membrane fuel cells (PEMFCs), which convert the chemical energy of hydrogen directly into electrical energy, are regarded as promising alternatives and a clean power source for automotive, stationary, and portable applications [1–5]. The use of fuel cells for powering automotive devices requires reductions in cost, size, and weight, as the current automotive fuel cells are not profitable and are still large and heavy, which limits the layout of the fuel-cell system [6].

Generally, if the required power can be produced with a smaller active area having a higher current density, the fuel cell stack can be made smaller, lighter, and cheaper. Currently, most automotive fuel cells operate with a maximum current density of approximately 1.0–1.5 A cm^{-2} [7–9], which necessitates a large active area. This increases the size of catalyst-coated membranes (CCMs) (containing PEMs), catalyst layers (CL) (containing precious metals) and conventional gas-diffusion layers (C-GDLs) which are made with carbon fibers. . In addition, a C-GDL thickness of 90–300 μm for each electrode increases the length in the stacking direction, where the volume of the C-GDL occupies approximately half of the total volume of the fuel-cell stack. These factors negatively affect the cost and size of the fuel-cell structures. To remedy this in automotive fuel cells, higher current-density operation and a reduction in the C-GDL thickness are required.

Unfortunately, higher current densities come with undesirable side effects. Firstly, an increase in the current density of the fuel cells may cause a sudden decrease in performance, which is known as cathode flooding. As the current density escalate, more water is generated via the oxygen reduction 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 in the GDL [10], thereby blocking oxygen diffusion and restricting a uniform distribution in the catalyst layer. This in turn causes a sudden decrease in the cell voltage. In general, a gas flow field is created on a bipolar plate (BPP) with grooved flow-channel and land structures, and the GDLs work is to distribute the gas from the flow channel to the land underneath [13]. However, water cannot be removed from the land when the GDLs and channel/land structures are combined; thus water accumulation results in a non-uniform blockage of the gas supply to the catalyst layer—the well-known phenomenon of electrode flooding. This significantly decreases the fuel-cell performance along with an accompanying increase in the current density [14].

Secondly, even in the case of no water accumulation in the GDL, the oxygen concentration in the cathode air has a broad distribution along the in-plane direction of the GDL, especially under the land region, due to the balance between the rates of oxygen consumption and diffusion. This is referred to as air management in the fuel cell [15]. Actually, a narrower land width can supply gases more efficiently and uniformly and exhibits slightly better performance [16]. This design, however, increases the electrical resistance because there is less contact area between the GDL and the BPP, resulting in a higher contact resistance and longer electron pathway through the GDL from the CL to the BPP. This also negatively impacts on overall performance.

Finally, an increase in the current density causes a higher prevalence of membrane dry-out at the anode. The membrane is dehydrated by the electro-osmotic drag from the anode to the cathode [17] in addition to the increased temperature from the electrochemical reaction and ohmic heat. The proton conductivity of the membrane heavily depends on its water content, and dehydration of the membrane causes decreases in the proton conductivity and cell performance.

In previous studies, we investigated several designs aimed at reducing the effects of flooding, air management, drying out, and the electrical resistance [18,19]. It was found that a corrugated mesh flow field could significantly reduce the effects of flooding and air management due it effecting a point-to-surface contact between the flow field and the GDL and thereby expediting water removal and a uniform air distribution. As for reducing the contact resistance with the lower contact area of the point-to-surface contact, a highly conductive perforated metal sheet (M-GDL) [20–22] was placed between the corrugated mesh and the CL. The gold-plated surfaces of the corrugated mesh and M-GDL had a negligible contact resistance, even with the small contact area [23], and the highly conductive metal thereby reduced the ohmic resistance due the longer pathway through the M-GDL. In addition, according to our previous modeling study [24], the high Young's modulus of the M-GDL could induce a uniform contact pressure on the CL to reduce the contact resistance of the M-GDL|CL interface drastically. However, the performance of the M-GDL was lower than that of the C-GDL. This lead to the conclusion that the M-GDL does not have enough capability to distribute the gas widely to the whole region of the CL, especially the region under the solid area of the M-GDL, when the M-GDL is directly placed on the CL. This is as gas could only diffuse vertically through the perforated holes; thus, the reaction tended to occur only in the region under the holes of the M-GDL. In addition, the hydrophilic surface of the M-GDL resulted in water accumulation on the surface, leading to flooding particularly in the holes.

In this study, we developed microporous layers (MPLs) that can cover the top surface and fill the holes of the M-GDL. This is to enhance the gas diffusion from the holes horizontally to the region underneath the solid area of the M-GDL through the MPL, thereby preventing flooding on the hydrophilic surface in the holes of the M-GDL. The current–voltage (I–V) performance of the M-GDL/MPL was evaluated for two different channel/land designs as the gas flow fields on the BPPs. A combined experimental-numerical approach was followed. To investigate the role of the MPL and the effects of the flow field design, especially on gas diffusion and electron contact resistance under compression, a single-phase isothermal model was considered which accounted for coupled electrical, mechanical, electrochemical, and fluid-dynamics factors.

2. Experimental model

Single fuel cells with a BPP and CCM were prepared to evaluate the M-GDL and MPL using the same procedures and conditions used in our previous studies [18,19,24]. A schematic is shown in Fig. 1. BPPs were made of 316L stainless steel (SS) with grooved gas channels by a chemical etching technique with 1-μm-thick gold plating afterward (TOYO PRECISION PARTS MFG. Nara, Japan). The active areas had a rectangular shape that was 6 cm long and 3 cm wide, and the two different channel designs were straight grooves which were aligned parallel to the length of this rectangle: (1) a land width of 0.1 mm, channel width of 0.2 mm, and channel depth of 0.1 mm; and (2) a land width of 0.03 mm, channel width of 0.27 mm, and channel depth of 0.1 mm. The CCM was manufactured similar to our previous study [24]. It consisted of Nafion NRE211-XL as a PEM (Ion Power, Delaware, USA), platinum deposited onto carbon (Pt/C) as a catalyst (TEC10E50E, TKK, Tokyo, Japan), a catalyst loading of 0.3 mg cm^{-2} for the anode and cathode, and an ionomer/carbon weight ratio (I/C) of 1.0. The M-GDL was made of a 30-μm-thick SS sheet with perforated through-holes created by a chemical etching technique. The latter was finally plated with 1-μm-thick gold layer (TOYO PRECISION PARTS MFG. Nara, Japan). The perforated through-hole design in the M-GDL was circular with a diameter of 60 μm, and the solid space