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Effect of Compression on the Water Management of a Proton **Exchange Membrane Fuel Cell** With Different Gas Diffusion Layers

The gas diffusion layer (GDL) plays an important role in maintaining suitable water management in a proton exchange membrane fuel cell. The properties of the gas diffusion layer, such as its porosity, permeability, wettability, and thickness, are affected by the shoulders of the bipolar plates due to the compression applied in the assembly process. Compression therefore influences the water management inside fuel cells. A two-phase fuel cell model was used to study the water management problem in a proton exchange membrane fuel cell with interdigitated flow channels. The effect of the compression on the fuel cell performance was numerically investigated for a variety of GDL parameters. This paper focuses on studying the water management of fuel cells under compression for various types of gas diffusion layers. First, the deformation of a gas diffusion layer due to compression applied from the shoulders of the bipolar plates was modeled as a plainstrain problem and was determined using finite element analysis (FEA). The porosity and the permeability of the gas diffusion layer were then recalculated based on the deformation results. Next, the deformed domain from the FEA model was coupled with a fuel cell model, and the effects of the compression during the assembly process on the water management and fuel cell performance were studied for gas diffusion layers with different thicknesses, porosities, and compressive moduli. It was found that the deformation of the GDL results in a low oxygen concentration at the reaction site. The saturation level of liquid water increases along the flow direction, and is higher when the compression effect is considered in the simulation. [DOI: 10.1115/1.3177451]

1 Introduction

The gas diffusion layer (GDL) is an important component of proton exchange membrane (PEM) fuel cells. The GDL is typically made from porous materials such as carbon cloth or carbon paper. The main roles of the GDL are to provide mechanical support to the membrane and catalyst layer, and to conduct heat and electricity. Other key functions of the GDL are to evenly distribute reactants to the reaction site, and to provide a pathway to remove the water produced during the reaction. Therefore, GDL properties, such as its thickness, porosity, permeability, and wettability, influence the water transport inside the fuel cell. Some of these parameters, however, will change during the fuel cell assembly process. For example, when compression is introduced as a fuel cell is assembled, the thickness of the GDL decreases and therefore its porosity changes depending on the thickness of the gasket used and the degree to which the GDL is compressed [1]. The porosity also changes under different operating conditions, as does the permeability [2].

Experimental research has identified changes in the properties of a gas diffusion layer due to compression, and the subsequent effects on the overall performance of fuel cells. Bazylak et al. 3 inspected the microstructure of the gas diffusion layers using scanning electron microscope and visualized the ex situ water transport through the gas diffusion layer using fluorescence microscopy under various clamping pressures. The hydrophilic and hydrophobic regions of the GDL were found to change due to the breakage of fibers while under various compressions. Chang et al. [4] experimentally found that the porosity and permeability of the GDL changed under various clamping pressures. Lee et al. [5] and Ge et al. [6] tested the effects of compression on the performance of fuel cells in situ. Different types of gas diffusion layers were used in their tests and the effects of compression on the fuel cell performance were observed at high current density.

Numerous mathematical models have been developed aiming to precisely describe the transport phenomena in the GDL and to predict the cell performance. For simplicity, most of the numerical models usually assume the GDL to be a homogeneous material and to have a constant porosity [7,8]. To account for the nonuniform structure of the GDL, Gurau et al. [9] developed a onedimensional half cell analytical model, where the GDL was modeled as a series of parallel layers with different porosities. Chu et al. [10] further proposed four types of porosity distributions to simulate the nonuniformity of the porosity of the GDL. Roshandel et al. [11] developed a pseudo-2D model, where the porosity distribution considers the effects from both compression of the electrodes on the solid landing areas and the water generated at the cathode side of the GDL. Zhou et al. [12] investigated the effects of compression of the gas diffusion layer on the performance of a fuel cell with interdigitated flow channels. The interfacial contact resistance between the gas diffusion layer and the bipolar plate was considered and described by the model developed by Zhou et al. [13]. Zhou and Wu [14] further performed a similar study for a fuel cell with straight channels while ignoring the contact resistance

While the aforementioned numerical studies focused on the overall effects of the compression of gas diffusion layer on the

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Fig. 1 Two-dimensional fuel cell model geometry

performance of fuel cells, none investigated the details of water transport in the gas diffusion layer under compression, hence warranting further investigation. Furthermore, the effects of compression on a number of different types of gas diffusion layers have not been studied yet. The objective of this paper is to investigate how the compression by the shoulders of bipolar plates affects the performance of a PEM fuel cell. The emphasis is on studying the water management of fuel cells under compression for various types of gas diffusion layers. A two-dimensional mathematical model will be developed to couple the compression applied by the shoulders to the fuel cell performance. The local current density, oxygen distribution, water saturation level, and the polarization curve will be calculated for various types of gas diffusions layers under different compression pressures. This paper is organized as follows: First, the computational model and boundary conditions are described in Sec. 2, and the model is validated in Sec. 3, where the results are also presented and discussed; then Sec. 4 summarizes the major findings of this investigation and concludes this study.

2 Computational Model

The primary objective of this paper is to numerically investigate how the compression by the shoulders of bipolar plates affects the performance and water management of a PEM fuel cell. In this section, a two-dimensional isothermal two-phase model is developed to predict the performance of a PEM fuel cell (PEMFC) with an interdigitated flow field. Since water is produced on the cathode side of a PEM fuel cell, only the cathode electrode will be modeled in this work. The model is developed in a similar way as that of He et al. [15].

2.1 Model Geometry and Assumptions. Figure 1 shows a schematic of the modeling geometry, consisting of the cathode porous gas diffusion layer in contact with an interdigitated gas channel. The interface includes a gas channel inlet, a shoulder of the bipolar plate, and an outlet to the gas channel. The water is assumed to be produced in liquid form since the fuel cell is operating below 100° C at approximate ambient pressure. Darcy's law applies since both gas and liquid water are assumed to be continuous. The cathode catalyst layer is assumed to be an infinitely thin boundary between the GDL and membrane. The GDL is assumed to be a hydrophobic and isotropic material, where the strain and stress follow a linear relation.

2.2 Governing Equations. The steady-state two-phase iso-thermal PEMFC model includes the following conservation equations:

Continuity equation

$$\nabla \cdot (C^g v^g) + r_w = 0 \tag{1}$$

$$\nabla \cdot \left(\frac{\varepsilon_{0s\rho_w}}{M_w}v^l\right) - r_w = 0 \tag{2}$$

Momentum conservation

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$$v^g = -\frac{K_0(1-s)}{\mu^g} \nabla p^g \tag{3}$$

$$v^{l} = -\frac{K^{l}}{\mu^{l}} \nabla p^{l} \tag{4}$$

Species conservation

$$\nabla \cdot (C^{g} v^{g} y_{O_{2}} - C^{g} D^{e}_{O_{2}} \nabla y_{O_{2}}) = 0$$
(5)

$$\nabla \cdot (C^g v^g y_w - C^g D^e_w \nabla y_w) + r_w = 0 \tag{6}$$

where C^g is the molar concentration of the gas phase (mol/m³), v^g is the superficial velocity of the gas (m/s), p^g is the gas pressure (Pa), r_w is the interfacial mass transfer rate of water by condensation or evaporation (mol/m³ s), v^l is the velocity of liquid water (m/s), s is the liquid saturation, p^l is the liquid water pressure (Pa), y is the molar fraction of the species; K is the permeability of the GDL (m²), μ is the dynamic viscosity (Pa s), D_i are the diffusion coefficients (m² s⁻¹), and M is the molecular weight (kg/mol). The superscript "g" represents the gas phase, the superscript "l" represents the liquid phase, the subscript "w" represents the water vapor, and the subscript " O_2 " represents the oxygen. The interfacial mass transfer rate of water between liquid and vapor is

$$r_w = k_c \frac{\varepsilon^g y_w}{RT} (y_w P^g - P_w^{\text{sat}}) q + k_v \frac{\varepsilon_0 s \rho_w}{M_w} (y_w P^g - P_w^{\text{sat}}) (1 - q) \quad (7)$$

where q is the switch function defined as

$$q = \frac{1 + |y_w P^g - P_w^{\text{sat}}| / (y_w P^g - P_w^{\text{sat}})}{2}$$
(8)

The binary diffusivities D_i used in the species conservation Eqs. (5) and (6) are calculated from the empirical correlation given by

$$D_{i} = D_{i}^{0} \left(\frac{T}{T_{0}}\right)^{1.5}$$
(9)

where T is the fuel cell operating temperature, T_0 is the reference temperature, and D_i^0 is the reference binary diffusivity, and their values are given in Table 1. In order to consider the effects of porosity of the gas diffusion layer, an effective binary diffusivity is used. This effective binary diffusivity is modified by the Bruggeman correlation [16] and is given as

$$D_i^e = D_i(\varepsilon)^{1.5} \tag{10}$$

The gas and liquid pressures are related to each other by the capillary pressure, where $p^l = p^g - p_c$. Using Eq. (4), the velocity of the liquid water is given as

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| Table 1 Base case model p | arameters |
|---------------------------|-----------|
|---------------------------|-----------|

| Parameter name | Value | Unit | Source |
|-------------------------------------|-----------------------|----------------|-----------|
| Geometry dimensions | | | |
| Gas inlet width (half) | 0.5 | mm | [15] |
| Gas outlet width (half) | 0.5 | mm | [15] |
| Shoulder width | 1 | mm | [15] |
| GDL thickness | 0.25 | mm | [15] |
| Base case operating conditions | | | |
| Inlet gas pressure | 1.007 | atm | [15] |
| Inlet mole fraction of oxygen | 0.21 | 1 | [15] |
| Inlet mole fraction of nitrogen | 0.79 | 1 | [15] |
| Inlet mole fraction of water | 0 | 1 | [15] |
| Temperature | 60 | °C | [15] |
| Other properties and coefficients | | | |
| Gas viscosity at 60°C | 2.03×10^{-5} | Pa s | [15] |
| Exchange current density | 1×10^{-2} | A/cm^2 | [15] |
| Transfer coefficient of the | 0.5 | 1 | [15] |
| oxygen reduction reaction | | | |
| Electrode permeability | 1.2×10^{-12} | m ² | [15] |
| Electrode porosity | 0.4 | 1 | Estimated |
| Surface tension | 0.0625 | N/m | [17] |
| Contact angle | 110 | deg | Estimated |
| FEA analysis properties of carbon p | aper based GDL | -10BA | |
| Commenced on modulus of the CDI | 1 50 | MDa | [20] |

| Compression modulus of the GDL | 4.59 | MPa | [20] |
|--------------------------------------|------|-----|-----------|
| Poisson ratio | 0.09 | 1 | [12] |
| Compression pressure on the shoulder | 1 | MPa | Estimated |

$$v^{l} = -\frac{K^{l}}{\mu^{l}} \nabla p^{l} = -\frac{K^{l}}{\mu^{l}} \nabla (p^{g} - p_{c}) = \left(-\frac{K^{l}}{\mu^{l}}\right) \nabla p^{g} - \left(-\frac{K^{l}}{\mu^{l}}\frac{\partial p_{c}}{\partial s}\right) \nabla s$$
$$= \left(-\frac{K^{l}}{\mu^{l}}\right) \nabla p^{g} - D_{c} \nabla s \tag{11}$$

where the capillary diffusion coefficient D_c is defined as $D_c = -(K^l/\mu^l)(dp_c/ds)$.

The aforementioned governing equations are similar to the twophase 2D fuel cell model of He et al. [15]. The difference between the current model and that of He et al. [15] is how to determine the capillary diffusion coefficient D_c in Eq. (11). He et al. [15] assumed the capillary diffusion coefficient to be a constant when saturation is less than 0.1, which, however, needs further experimental verification. The capillary diffusion coefficient in the present work is calculated using the Leverett function [17] instead of assuming it constant and is given as

$$D_{c} = -\frac{K^{l}}{\mu^{l}} \sigma \left(\frac{\varepsilon}{K_{0}}\right)^{1/2} \cos \theta \cdot -1.417 + 4.240(1-s) - 3.789(1-s)^{2}, \quad \theta_{c} \le 90 \text{ deg hydrophilic}$$
$$D_{c} = -\frac{K^{l}}{\mu^{l}} \sigma \left(\frac{\varepsilon}{K_{0}}\right)^{1/2} \cos \theta \cdot 1.417 + 4.240(1-s) - 3.789(1-s)^{2}, \quad \theta_{c} \ge 90 \text{ deg hydrophobic}$$
(12)

2.3 Boundary Conditions. A constant pressure and a constant reactant concentration are assumed at the flow inlet interface between the GDL and the flow channel. At the flow outlet, the backpressure is given and the gradient of the concentration of each species is assumed to be zero. The shoulder of the bipolar plates is assumed to be impermeable, resulting in a no-flux condition for the species equation (e.g., Eqs. (5) and (6)). Symmetrical boundary conditions are adopted at the boundaries on both the left and right sides of the modeling domain. At the membrane-GDL interface, the catalyst layer is assumed to be an infinitely thin layer, where the superficial velocity in the direction perpen-

dicular to the surface is zero since the membrane is impermeable to gases. The fluxes of the oxygen and liquid water are functions of the local current density, and are given as follows. For oxygen,

$$-C^{g}D^{e}_{O_{2}}\nabla y_{O_{2}} = \frac{I}{4F}$$
(13)

For liquid water,

$$\frac{\varepsilon s \rho_w}{M_w} v^l = -\left(0.5 + \alpha\right) \frac{I}{F} \tag{14}$$

The Tafel equation is used to predict the distribution of the current density along the catalyst layer [15]

$$I = I_0 (1 - s) \frac{C^g y_{O_2}}{C_{O_2, \text{ref}}} \exp\left(\frac{\alpha F}{RT} \eta_c\right)$$
(15)

where I_0 is the exchange current density (A/cm²), η_c is the overpotential on the cathode side (V), α is the cathodic transfer coefficient, *F* is the Faraday constant, and $C_{O_2,ref}$ is the reference concentration of oxygen (mol/m³).

2.4 The Compression FEA Model. Porosity is one of the most important parameters that characterize the transport properties of the GDL. During the cell assembly, the GDL section under the shoulder of the bipolar plate is crushed, and the thickness of the GDL decreases accordingly under the effect of the compression, thus causing a decrease in the effective porosity. A finite element analysis (FEA) model was developed to study the compression effect on the effective porosity and permeability of the gas diffusion layer. The shoulder of the bipolar plates is assumed to be rigid and the deformation takes place only within the GDL, mainly under the shoulder, where the compression force is applied. The GDL is modeled as an elastic material. The behaviors of the GDL under compression were found nonlinear in the compressive modulus test [20]. However three linear regions were found for most of the tested GDLs.

In the FEA model, the porosity of the GDL is assumed to vary with the change in the GDL thickness by the following relation [18]

$$\varepsilon = 1 - W_A / (\rho D) \tag{16}$$

where W_A is the area weight of porous materials (kg/m²), ρ is the solid phase density (kg/m²), and *D* is the thickness of the GDL (m). Equation (19) describes the variation in the permeability of the gas diffusion layer due to the change in the porosity [19] with the assumption that the diameter of the pores of the GDL is proportional to the thickness of the GDL

$$K = \frac{K_0}{\varepsilon_0} \left(\frac{d}{d_0}\right)^2 \left(1 - (1 - \varepsilon_0)\frac{d_0}{d}\right) \tag{17}$$

where *d* is the porous media pore diameter (m), ε is the porosity, and the subscript "0" denotes the original value of the parameter before compression.

The deformation of the gas diffusion layer is solved as a plane strain problem. Figure 1 shows the FEA model used to simulate the deformation of the GDL under the effect of a compressive force along the bipolar plate shoulder. Zero displacement was assumed along the catalyst surface and the symmetric sides, whereas zero stress was assumed along the inlet and outlet. The material properties of the GDL are derived from published information for a GDL-10BA [20], using the Poisson's ratio from Ref. [21]. The nominal clamping pressure applied is typically between 0.5 MPa and 3 MPa [20] and is the range of values assumed in this study.

2.5 The Coupling Between the Compression and PEMFC Models. The FEA model simulates the GDL deformation under compression. The boundary of the computational domain changes corresponding to the displacement of the boundary in the com-

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Fig. 2 Polarization curve comparison with the experimental data

pression model. The arbitrary Lagrangian–Eulerian (ALE) module [22] calculates the deformed mesh and assigns the mesh to the PEM fuel cell model. Thus, there is no need to generate a new mesh pattern in the deformed domain, which facilitates the coupling of the mechanical structure and flow interaction simulation. The coupling of these two models enables one to directly study the effects of compression on the fuel cell performance.

3 Results and Discussion

3.1 Model Validation. The aforementioned FEA model and the PEM fuel cell model were implemented into a commercial package, COMSOL MULTIPHYSICS. The COMSOL MULTIPHYSICS is a partial differential equation (PDE) solver based on the finite element method. In this research, the governing equations were discretized by using the finite element method with the second-order Lagrange quadratic elements. A direct solver named PARDISO was selected for this 2D stationary problem. The unstructured triangular mesh was adopted and the total number of mesh elements is 2032. The total number of degrees of freedom solved for is 39,462. The mesh was refined and a grid independent study was performed. The results show a 0.5% difference to conclude that the result is independent of grid size. Because COMSOL MULTIPHYS-ICS does not have a built in module for liquid water saturation, the PDE module was utilized to incorporate this equation. The base case parameters used in both models are listed in Table 1.

To validate the fuel cell model, the numerical simulation results were compared with the experimental data [15] using the same method used by He et al. [15]. The inlet pressure was set to 1.01333 atm to simulate the actual air flow conditions used in the experiment. In order to consider the ohmic loss of the membrane electrode assembly (MEA), the ohmic overpotential term IR de-



Fig. 3 Porosity distribution in the cathode GDL

scribes the linear potential drop, which is predominant in the intermediate current density region. The membrane resistance of a well-hydrated Nafion membrane ranges from 0.19 Ω cm² to 0.09 Ω cm² [15]. However, this value should be higher in a real operation due to the poor hydration of the membrane and the poor contact between the GDL and bipolar plate. In the current model, the ohmic resistance was treated as a tuning parameter when training the model, which is the same as the validation method of He et al. [15]. The cell resistance was found to be 0.24 Ω cm² to fit the experimental data. The anode overpotential is ignored due to a much faster reaction rate on that side compared with the one on the cathode side. Therefore the actual cell potential is calculated as

$$V_{\text{cell}} = V_{\text{oc}} - \eta_c - IR_{\text{cell}} \tag{18}$$

where V_{cell} is the fuel cell operating voltage (V), *I* is the fuel cell operating current density (A/cm²), and R_{cell} is the ohmic resistance of the fuel cell (Ω cm²).

Figure 2 compares the experimental data and the model results with different correction terms for a carbon paper based GDL. The model is first solved for a uniform distribution of porosity without considering the ohmic losses (IR correction). The model is then corrected by considering the ohmic losses (IR) of cells as shown in Eq. (20). Lastly, the effects of the assembly compression from a shoulder of bipolar plates are added to the model with the IR correction term. The compression pressure is estimated to be 1 MPa. The cathode activation loss is found to be the largest potential drop, followed by the ohmic overpotential. The ohmic overpotential is high particularly in the intermediate to high current density region. The mass concentration overpotential in the high current density region is not obvious due to the fact that the permeability used in this model is relatively high, which results in a



Fig. 4 Velocity distribution of the gas in the cathode GDL in m/s (top: without compression, bottom: with compression, arrow: velocity direction, color: velocity magnitude)

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Fig. 5 Local current density and oxygen concentration along the catalyst layer

high flow rate of reactant gases. This could always provide enough reactant gases even in the high current density region. Overall, the model polarization curve agrees well with the experimental data after considering both the ohmic loss and the compression effect.

3.2 Effective Porosity and Permeability of the GDL. Porosity and permeability are the two key properties of the GDL that influence transport phenomena in the porous GDL material. Figure 3 shows the porosity distribution of the GDL for a compression pressure of 1 MPa on the shoulder with and without liquid water considered. The GDL was initially assumed to have a porosity of 0.4 and a permeability of 1.2×10^{-12} m². The cathode overpotential is at 0.4 V. As can be seen from the figures, porosity decreases due to the compression, especially in the region under the shoulder of bipolar plates. The distribution of permeability shows a similar trend as porosity under the compression. When a two-phase fuel cell model is applied, the water accumulation can be estimated. The outlet region of the cathode gas diffusion layer tends to show a lower porosity and permeability due to the presence of liquid water.

The influence of the compression can be further seen by checking the velocity distribution and reactant gas concentration, and the local current density distribution as shown in Figs. 4 and 5,



Fig. 8 Polarization curves using GDLs with different thicknesses before and after compression (porosity=0.3)

respectively. The magnitude of the gas velocity decreases after considering the compression from the shoulder since the decrease in porosity creates extra friction on the flow. So does the concentration distribution of the reactant gas. A lower oxygen concentration is shown under the shoulder when the cell is under compression compared with that without compression. Accordingly the decrease in oxygen concentration results in a low local current density.

Figure 6 shows the distribution of liquid water in the GDL with and without compression. The saturation level of liquid water increases from the inlet to the outlet as the water is produced along the catalyst layer in liquid form. Because of the compression, the saturation level increased by 7% even though the current density decreased by 25% (with compression: 0.733 A/cm²; without compression: 0.975 A/cm²). Figures 7(*a*) and 7(*b*) compare the liquid water distribution under different current densities when the compression effect was considered. It shows that a higher saturation level is related to the higher current density. Therefore, both the GDL configuration under compression and the fuel cell working conditions influence the water management inside the PEM fuel cell electrode.

3.3 Different Types of GDL. Figure 8 compares the compression effects on the cell performance for GDLs with different



Fig. 6 Saturation distribution in the cathode electrode with and without compression



Fig. 7 Saturation distribution in the cathode electrode at different current densities

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Fig. 9 Saturation distribution using GDLs with different thicknesses (porosity=0.3)



Fig. 10 Polarization curves using GDLs with porosities before and after compression

thicknesses. One is 0.25 mm thick, and the other is 0.3 mm thick. The thickness of the GDL does not appear to influence the fuel cell performance (as measured by the cell polarization curve) when the effect of the compression is not considered. With the compression effect considered, the performance of both cells decreases. The performance of the cell with the thicker GDL (0.3 mm) decreases more rapidly in the high current density region where the mass transportation loss is a major loss. Figure 9 further compares the distribution of the liquid water in terms of the saturation level. For the same cathode electrode overpotential, the 0.25 mm GDL produces higher current density and results in a higher saturation level at the outlet region than the 0.3 mm GDL.

Figures 10 and 11 investigate the effects of compression on the cell performance for the GDL with different porosities. The GDL porosity has no obvious influence on the polarization curve at low current densities. In contrast, at high current densities, this effect becomes more apparent since the concentration loss is the major loss. The effect of the compression is very obvious for the cell with a low porosity GDL. This is because the low porosity GDL has less void space for the reactant gas and product water to pass through, which leads to a higher mass concentration overpotential. However, the compression does not have much influence on the cell with a high porosity GDL since it is always able to provide

enough reactant gases even in the high current density region. As shown in Fig. 11, the liquid water saturation level is much lower for the cell with high current porosity than the one with low porosity.

Figure 12 presents the polarization curves of the GDLs with different compressive moduli under the same compression pressure (1 MPa). Table 2 shows the compressive modulus assumed for the different cases considered [20]. As can be seen from Fig. 12 and Table 2, the material with the highest compressive modulus, which is B-3/2050, does not deform easily and exhibits better performance under the same compression. The converse is true for the materials with a lower compressive modulus. This explains the importance of carefully selecting the gasket material with a reasonable compressive modulus and thickness to match the properties of the GDL or MEA.

4 Conclusions

The properties of the GDL are affected by many parameters such as the compressive force and the water production at the cathode side. This paper developed a steady-state two-phase fuel cell model coupled with a FEA compression model to investigate this compression effect. The effect of compression on the GDL configuration and parameters (porosity and permeability) has been studied and presented. The influences of the compression on the water management were investigated for GDLs with different thicknesses, porosities, and compressive moduli.

Both the porosity and permeability of the GDL are found to decrease after compression, especially under the shoulder of the bipolar plate. The presence of liquid water also leads to an uneven distribution of the porosity and permeability. These effects severely influence the transport process of the reactant through the porous gas diffusion layer. The oxygen concentration along the cathode catalyst layer was examined and found to decrease after considering the compression and liquid water accumulation effect.

It was determined that the GDL with a high compressive modulus tends to provide better cell performance. The effect of GDL thickness was also investigated, and it was found that assembly compression has less effect on a cell with a thinner GDL than the one with a thicker GDL. The comparison in liquid distribution in terms of the saturation level using GDLs with different porosities



Fig. 11 Saturation distribution using GDLs with different porosities

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Fig. 12 Polarization curves of GDLs with different values of the compression modulus

Table 2 Compressive modulus of the different types of GDLs [20]

| GDL | Pressure range (MPa) | Compressive modulus (MPa) |
|----------|-------------------------|------------------------------|
| GDL-10BA | 0.15-1.12 | 4.59 |
| GDL-10BB | 0.52-3.00 | 8.57 |
| B-3/2050 | 0.57-3.00 | 13.72 |
| B-2/120 | 0.11-1.11 | 6.29 |

showed that the higher porosity GDL provides a higher current density with low saturation at the outlet region of the GDL. The influence of the compression effect is not obvious when the current density is medium (0.6 A/cm^2) or low for either low or high porosity GDLs. However, assembly compression dramatically deteriorates the performance of a fuel cell with a low porosity GDL operating at high current density. Therefore, assembly compression should be a factor to be considered in the fuel cell modeling, and it should be optimized when the interfacial resistance between the gas diffusion layer and bipolar plate is considered.

Nomenclature

- C = molar concentration of gas (mol/m³)
- $D = \text{diffusion coefficient } (\text{m}^2 \text{ s}^{-1})$
- F = Faraday constant (C/mol)
- d = pore diameter (m)
- $I = \text{local current density } (A/m^2)$
- I_0 = exchange current density (A/m²)
- K_0 = gas permeability of electrode (m²)
- $k_c = \text{condensation rate constant (s}^{-1})$
- k_v = vaporization rate constant (Pa⁻¹ s⁻¹)
- M = molar mass (kg/mol)
- p = pressure (Pa)
- q = switch function
- R =universal gas constant (8.314 J/mol⁻¹ K⁻¹)
- R_{cell} = ohmic resistance of the fuel cell (Ω m²)
 - r_w = interfacial mass transfer rate of water between gas and liquid phases $(mol/m^{-3} s^{-1})$
 - s = saturation level of the liquid water
 - T = temperature (K)
 - v = superficial velocity vector (m/s)
- V_{cell} = fuel cell operating voltage (V)
- W_A = area weight of the porous media (kg/m²)
 - y = molar fraction of the species

Greek Letters

- $\varepsilon = GDL$ porosity
- ρ = density (kg/m³)

- θ = contact angle (deg)
- = dynamic viscosity (Pa s) μ
- η = overpotential (V)
- σ = surface tension (N m⁻¹)

Subscripts

- c = capillary/cathode
- oc = open circuit
- $O_2 = oxygen$
- ref = reference condition
- w = water
 - σ = surface tension (N m⁻¹)

Superscripts

- = standard condition 0
 - = effective coefficient е
 - g = gas
- = liquid 1
- sat = saturation

References

- [1] Nitta, I., Hottinen, T., Himanen, O., and Mikkola, M., 2007, "Inhomogeneous Compression of PEMFC Gas Diffusion Layer, Part I: Experimental," J. Power Sources, 171, pp. 26-36.
- [2] Shi, Z., Wang, X., and Draper, O., 2007, "Effect of Porosity Distribution of Gas Diffusion Layer on Performance of Proton Exchange Membrane Fuel Cells," ECS Trans., 11, pp. 637-647
- [3] Bazylak, A., Sinton, D., Liu, Z., and Djilali, N., 2007, "Effect of Compression on Liquid Water Transport and Microstructure of PEMFC Gas Diffusion Layers," J. Power Sources, 163, pp. 784-792.
- [4] Chang, W., Hwang, J., Weng, F., and Chan, S., 2007, "Effect of Clamping Pressure on the Performance of a PEM Fuel Cell," J. Power Sources, 166, pp. 149-154
- [5] Lee, W., Ho, C. H., Van Zee, J. W., and Murthy, M., 1999, "The Effects of Compression and Gas Diffusion Layers on the Performance of a PEM Fuel Cell," J. Power Sources, 84, pp. 45-51.
- [6] Ge, J., Higier, A., and Liu, H., 2006, "Effect of Gas Diffusion Layer Compression on PEM Fuel Cell Performance," J. Power Sources, 159, pp. 922-927.
- [7] Siegel, N. P., Ellis, M. W., Nelson, D. J., and von Spakovsky, M. R., 2003, "Single Domain PEMFC Model Based on Agglomerate Catalyst Geometry," J. Power Sources, 115, pp. 81-89.
- [8] Um, S., Wang, C. Y., and Chen, K. S., 2000, "Computational Fluid Dynamics Modeling of Proton Exchange Membrane Fuel Cells," J. Electrochem. Soc., 147, pp. 4485-4493.
- [9] Gurau, V., Barbir, F., and Liu, H., 2000, "An Analytical Solution of a Half-Cell Model for PEM Fuel Cells," J. Electrochem. Soc., 147, pp. 2468-2477.
- [10] Chu, H. S., Yeh, C., and Chen, F., 2003, "Effects of Porosity Change of Gas Diffuser on Performance of Proton Exchange Membrane Fuel Cell," J. Power Sources, 123, pp. 1-9.
- [11] Roshandel, R., Farhanieh, B., and Saievar-Iranizad, E., 2005, "The Effects of Porosity Distribution Variation on PEM Fuel Cell Performance," Renewable Energy, 30, pp. 1557-1572.
- [12] Zhou, P., Wu, C., and Ma, G., 2007, "Influence of Clamping Force on the Performance of PEMFCs," J. Power Sources, 163, pp. 874–881.
- [13] Zhou, P., Wu, C., and Ma, G., 2006, "Contact Resistance Prediction and Structure Optimization of Bipolar Plates," J. Power Sources, 159, pp. 1115–1122.
 [14] Zhou, P., and Wu, C., 2007, "Numerical Study on the Compression Effect of Gas Diffusion Layer on PEMFC Performance," J. Power Sources, 170, pp.
- 93 100
- [15] He, W., Yi, J. S., and Nguyen, T. V., 2000, "Two-Phase Flow Model of the Cathode of PEM Fuel Cells Using Interdigitated Flow Fields," AIChE J., 46, pp. 2053-2064.
- [16] Meredith, R., and Tobias, C., 1962, "Conduction in Heterogenous Systems," Adv. Electrochem. Electrochem. Eng., 2, pp. 15-47.
- [17] Meng, H., and Wang, C. Y., 2005, "Model of Two-Phase Flow and Flooding Dynamics in Polymer Electrolyte Fuel Cells," J. Electrochem. Soc., 152, pp. A1733-A1741.
- [18] Barbir, F., 2005, PEM Fuel Cells Theory and Practice, Elsevier Academic Press, Boston.
- [19] Berning, T., 2002, "Three-Dimensional Computational Analysis of Transport Phenomena in a PEM Fuel Cell," Ph.D. dissertation, University of Victoria, Canada.
- [20] Mishra, V., Fang, F., and Pitchumani, R., 2004, "Measurement and Prediction of Electrical Contact Resistance Between Gas Diffusion Layers and Bipolar Plate for Applications to PEM Fuel Cells," J. Fuel Cell Sci. Technol., 1, pp. 2 - 9
- [21] Zhang, L., Liu, Y., Song, H., Wang, S., Zhou, Y., and Hu, S. J., 2006, "Estimation of Contact Resistance in Proton Exchange Membrane Fuel Cells," J. Power Sources, 162, pp. 1165-1171.
- [22] Modeling Guide, COMSOL MULTIPHYSICS Version 3.3.

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