Multiscale Electrical Contact Resistance Between Gas Diffusion Layer and Bipolar Plate in Proton Exchange Membrane Fuel Cells

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1 Introduction

The rapid exhaustion of the earth’s natural resources and global warming have led to increased attention being given to alternative energy resources, leading to a focus on highly efficient and eco-friendly fuel cell technology as a promising future means of renewable, efficient, pollution free energy conversion production. A fuel cell is an electrochemical device that converts fuel into electricity. This technology enables high-efficiency electricity generation since it is not constrained by the Carnot cycle, and it contributes less to noise pollution and air pollution such as NOx and SOx than do other electricity-producing methods. Proton exchange membrane fuel cells (PEMFC) operate at low temperatures, produce a lower level of emissions, and are able to be quickly started-up, characteristics which have prompted research to allow the electricity produced via this technique to be used for transportation and stationary and portal devices [1,2].

Performance degradation in PEMFCs stems from the cell stack assembly process, component quality, and contact status between components. During performance degradation, the cell potential decreases from its equilibrium potential due to irreversible losses caused by activation, concentration, and Ohmic resistances [3]. Ohmic resistance consists of contact resistance and the resistance due to the proton flow that passes through the membrane and is dominant during fuel cell operation.

Contact resistance in PEMFC is usually attributable to three sources: the existence of a thin film of poor conductors such as oxides at the interfaces, the constriction resistance associated with the roughness of the contacting surfaces as well as the assembly pressure and the material properties, and the resistance to the electronic flux between gas diffusion layer (GDL) and bipolar plate (BPP). The resistance due to electronic flux could be much lower than the two resistances. The effect of interfacial films can be reduced if a proper contacting material is selected. However, the constriction resistance is inevitable due to the variable microscopic roughness of surfaces. This resistance results in the restriction of contact to a set of distributed, small, discrete actual contact areas. There are two contact surface interfaces in a fuel cell stack: the interface between the bipolar plate (BPP) and the gas diffusion layer (GDL), and the interface between the membrane and the GDL. The contact interface between the membrane and GDL does not contribute to the contact resistance because the membrane is attached to the GDL through hot pressing. The other interface between the GDL and BPP does, however, induce the contact of rough surfaces, which restrict the contact to a set of distributed, small, discrete actual contact areas. Furthermore, since the GDL consists of carbon fiber, the microscopic contact spot distribution is significantly dominant than the case of other rough metal surfaces.

The contact of the rough surface has been mainly investigated in the field of metal-to-metal interfaces. Since the establishment of early models of the contact of rough surfaces introduced by Greenwood and Williamson [4], the concept of distributed asperities or peaks whose contact behaviors mimic that of the real surface has prevailed, the corresponding results have focused on surface roughness as a statistical process, and many subsequent advances have been made using random processes [5–7]. Along with the progress of surface measurement, which reveals surfaces as multiscale processes with no obvious smallest length scales, the fractal contact process allows for the analytical prediction of the contact process as a multiscale process. A series of recent works regarding the fractal contact process [8–11] have elucidated the contact analysis of rough surfaces.

Most of the analyses regarding electrical contact resistance have been performed on the interactions between metals; however, few works have focused on the modeling of contact resistance in fuel cells. Among the research on fuel cells, many works have focused on the experimental approaches [12–14], although there are few analytical models [15–17]. Mishra et al. [15] used a fractal-based model to estimate the contact resistance between the GDL and BPP and compared it with an experimental value. Their results have some limitations in that the contact resistance was calculated using the two-dimensional structure function of the GDL as a key parameter of the fractal model suggested by Majumdar and Bhushan [18]. These authors argued that the fractal properties of the actual contact areas would be similar to those of the set of islands obtained by slicing through the surface at a
constant height, an idea that is appropriate when the resulting microcontacts are in a fully plastic state. Zhou et al. [16] investigated the contact resistance according to the assembly pressure and the rib shape of the BPP, but they did not consider the characteristics of the surface. Zhang et al. [17] established a simple methodology to estimate the contact resistance between the GDL and BPP based on the experimental relationship between assembly pressure and resistance. Their finite element model cannot represent the characteristics of the surface such that the surfaces of the BPP and GDL are smooth and are always in the stick contact state. A microscale numerical model was obtained by Zhou et al. [19], who imposed many constraints on the material surface that may have caused it to behave differently from real surfaces.

The objective of contact resistance analysis in fuel cells is to precisely predict the resistance value. To achieve this objective, it is necessary to consider the current research trend for the analysis of contact between rough surfaces and to identify the differences between the contact of disparate materials such as metal or carbon fiber. For the analysis of contact with rough surfaces, it is believed that multiscale contact analysis [9,20,21] can predict the contact morphology explicitly, particularly considering that the refined surface mesh resolves into clusters of smaller contact area, the number of contact spots increases, and the actual contact area progressively decreases. Thus, the contact resistance is subject to the contact process, requiring the contact analysis to be performed relative to the proper scale. One limitation of multiscale contact analysis is that it requires considerable CPU time. A methodology that avoids this limitation should be devised.

In this paper, we investigate a numerical approach to calculate the contact resistance by considering the rough surfaces of the GDL, measured using a confocal scanning laser microscope at several different scales. Through the finite element models using ABAQUS, the contact area is obtained via static mechanical analysis, and the corresponding contact resistance is estimated using electrical analysis. Multiscale contact resistance is analyzed, and a limiting value is predicted through error analysis.

2 Multiscale Contact Model

2.1 GDL Surface Measurement. The surface morphology of the GDL is obtained using a Carl-Zeiss laser confocal microscope LSM 5 PASCAL (CSLM) at different scales to produce a finite element model for the surface of the GDL, as shown in Fig. 1. The total size of the surface ($L_x \times L_y$) is 460 × 460 μm$^2$. The total surface is discretized into $2^x \times 2^y$, ($x = 4 \sim 7$). Thus, several different surface models can be achieved according to the resolution of $L/2^x$, ($x = 4 \sim 7$). As the scale is reduced, the surface becomes significantly more apparent. The surface parameters such as skewness, kurtosis, and rms slope for the GDL at different scales are shown in Fig. 2.

Skewness is a measure of the average of the first derivative of the surface contour. A positive skewness defines a predominance of peaks. Kurtosis measures whether the data is sharp or flat relative to a normal distribution. A kurtosis coefficient of three indicates a normal distribution. Kurtosis greater than three indicates a sharp/hight peak with a thin midrange and fat tails. RMS slope means the average slope of surface. It is noted from Fig. 2 that the skewness is approximately 1.54 and kurtosis approaches around 7. However, the RMS slope diverges with scale variability, showing that the surface changes with slope. Since some contact analysis determining the contact resistance is affected by the slope of surface [4], this dependence of surface parameters on the resolution of the roughness measuring devices is critically limited to the contact analyses, which may produce widely different values of contact resistance for the same contact surface because a proper scale cannot be determined. Furthermore, the contact analyses for a rough surface using direct numerical simulations in a fixed scale usually have difficulty covering the whole spectrum of asperities because asperity sizes range over many different length scales and are much smaller than the component size. The calculation is usually limited by the cutoff size of the mesh and by the asperity measurement resolution. Thus, in order to accurately estimate the contact resistance dependent on the scale of surface roughness, a multiscale contact analysis is proposed to consider a contact process to determine the contact area and the corresponding contact resistance that are expected to converge in several consecutive scales.

2.2 FEM Model. Four separated FEM models are developed using the ABAQUS package [22] incorporating length scales. From the imported surface data, the mesh grid of the contact interface is established with a resolution from $L/2^4$ to $L/2^7$, resulting in a strong mesh gradation in the vicinity of the contact interface and meshes that become gradually coarser as the distance from the contact interface increases. The mesh is discretized with tetrahedral elements.

A typical finite element mesh is shown in Fig. 3, which illustrates the FEM model for a surface grid of $L/2^7$. The upper and lower parts of Fig. 3(b) are the BPP and GDL, respectively, and the total numbers of nodes and elements are 89,528 and 421,429, respectively. The material properties of the BPP and GDL are shown in Table 1 and were selected from FU 4369 and TGP-H-060, respectively [23,24]. As stated in the previous work [24], the material property of the GDL was properly found in the continuum scale and confirmed by a FEM model. The thickness of GDL is 200 μm. Since the elastic modulus of the GDL is nonlinear, it is fitted to the Ogden order of 3 [25] by evaluating the stress and strain data. Periodic boundary conditions are imposed at the contact surfaces in order to eliminate the boundary effects.

2.3 Material Property of the GDL Contact Surface. The structure of GDL is comprised of random carbon graphite fibers. To appropriately describe the mechanical behavior of this complex GDL structure, a detailed numerical model should be achieved to investigate the fiber assembly. However, the...
3 Analysis of Contact Resistance

3.1 Static Analysis. Static analysis is performed to investigate the deformation of the contact surface between the BPP and GDL when a constant assembly pressure of 6 MPa is applied on the top of the BPP. Previous works [17,19] regarding the clamping pressure have reported the range of the pressure up to 3 MPa with the area of the location where the clamping force is applied. What we found that the apparent contact area between BPP and GDL in our model is reduced to half the area. Because the same force should be applied in the BPP, the clamping pressure should be twice. The variation in contact area is analyzed on different scales. Figure 4 shows the distribution of contact pressure on the GDL surface. The contact pressure ranges from 0 to 4.68 GPa. As shown in Fig. 4, a few separated actual contact areas for a coarse mesh were identified at a given total normal load, but as the mesh was refined, these were resolved into clusters of smaller areas. The total area of actual contact was reduced by each progressive refinement and the results approximately followed an inverse power law. Thus, for a given total normal load and the reduction of the total actual contact area, the contact pressure in each smaller contact areas (spots) should be increased. Since the ultimate strength of carbon graphite fiber is generally greater than 5.7 GPa, the results confirm that the analysis of the hyperelastic GDL is valid. For the contact boundary condition, it is clear that the contact pressure distribution above zero is identical to the contact area distribution. Figure 5 shows the variation in total contact area according to the scale, in which it is evident that the contact area is reduced as the scale decreases.

3.2 Electrical Analysis. The deformed model obtained in the previous step is utilized to calculate the contact resistance through electrical conduction analysis. Unlike the mechanical contact analysis, the material property of the porous GDL must be speculated. Since the GDL is a porous structure consisting of carbon graphite fibers, the porosity of the GDL is reduced, affecting the bulk resistance of the GDL when the assembly pressure is applied.

The change in the GDL bulk resistance according to the deformation is calculated using [18]

$$R_D = \frac{\rho_f h^2}{h_0(1 - \phi_0)}$$  (1)

where $R_D$, $\rho_f$, $h$, $h_0$, and $\phi_0$ are bulk resistance, resistivity, thickness after deformation, initial thickness, and initial porosity of the GDL, respectively.

The top surface of the BPP and the bottom of the GDL are prescribed to possess potentials of 0 V and 1 V, respectively. The current passages in the contact interface can be readily obtained. Figure 6 shows the current density distribution according to scale, illustrating that the current density is shown at the region of contact. As the scale is reduced, the current density increases and is not fixed to a specific location.

4 Results and Discussion

4.1 Contact Resistance. The contact resistance is calculated through the analysis for electrical conduction. The electrical contact resistance is defined as $R = \Delta V/I$, where $I, \Delta V$ are the total current and the voltage difference at the interface, respectively. It is generally difficult to directly measure the current and voltage at the interface. Thus, we devise a way of first calculating the total resistance and then the bulk resistances of the GDL and BPP, $R_{\text{GDL}}$ and $R_{\text{BPP}}$, respectively, and then subtracting the two bulk resistances from the total resistance. It is noted that $R = R_{\text{total}} - R_{\text{GDL}} - R_{\text{BPP}}$, where $1/R_{\text{GDL}} = \sum_{i=1}^{n} I_i/\Delta V_i$ and $1/R_{\text{BPP}} = \sum_{i=1}^{m} I_i/\Delta V_j$, and $n$ and $m$ are the number of nodes at the interfaces of the GDL and BPP, respectively. The FEM models at each length scale give the contact spot distribution and the corresponding electrical current density distribution, resulting in electrical contact resistance. We can gather the contact resistances through the same analysis procedure. Figure 7 shows the contact resistances according to the different scale of $L/2^x$. It is evident that the contact resistance increases as the scale decreases. If we proceed continuously with the analysis, the contact resistance may approach a certain value. However, the contact analysis for the next small scale is difficult to perform because of the memory and CPU time limitations of the computer. Since it is believed that the general tendency of contact resistance according to scale variation shows that the contact resistance approaches a certain

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic modulus (MPa)</th>
<th>Porosity (%)</th>
<th>Poisson’s ratio</th>
<th>Density (g/cm³)</th>
<th>Electrical resistivity ($\mu \Omega \cdot m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPP</td>
<td>10</td>
<td>—</td>
<td>0.25</td>
<td>1.9</td>
<td>190</td>
</tr>
<tr>
<td>GDL</td>
<td>Nonlinear</td>
<td>78</td>
<td>0.25</td>
<td>0.44</td>
<td>800</td>
</tr>
</tbody>
</table>
Fig. 4 Contact pressure distribution on the GDL according to different scales of $L/2^\alpha$

Fig. 5 Variation in total contact area according to different scales of $L/2^\alpha$
value [21], the contact analysis must be analyzed to overcome this current drawback.

4.2 Error Analysis for Estimating the Asymptote in a Multiscale Contact Process. The contact resistance calculation is accompanied by scale-dependent transport, so the calculation needs to be investigated in the multiscale process. The valuable outcome of this analysis is that there is a converged contact resistance. However, when the contact analysis for the next smaller scales is performed, the number of meshes and the degree of freedom of the FEM models increases exponentially, requiring a large computer memory and longer CPU time. Thus, it would be practically beneficial to identify the contact resistance curve with respect to scale. The explicit form of contact resistance can simplify the calculation. To identify the contact resistance curve with an asymptotic behavior according to scale, we utilize the error between the contact resistance and an asymptote at a certain scale.

\[
\text{Error} = \text{Asymptote} - R(z) = e^{C_1} z^{-C_2}
\]  

(2)

As shown in Fig. 8, the errors with different asymptotes are plotted to identify a proper asymptote. If the asymptote is appropriate and the scale \( z \) becomes larger, the error approaches zero and the power law equation also gives a limit of zero. If the contact resistance is not converged and is above the converged value, the positive error increases as the length scales increases, where the positive direction means the upward direction with respect to the line. If the contact resistance is not converged and is less than the converged value, the negative error increases as the length scales decreases. Thus, for the error after the scale of 5, a straight line denotes the result of an appropriate asymptote, while the other curved lines represent the deviation from the appropriate asymptote. Then, we curve fit the straight line for the errors and invert the error to the contact resistance with respect to scale, which is obtained as

\[
R(z) = 2.1 - e^{5.982} z^{-3.323} \text{ (m}\Omega \cdot \text{cm}^2)
\]  

(3)

We emphasize that Eq. (2) is obtained under the conditions that the contact resistance is converged in the multiscale process, and electrical resistivity is dependent on the sizes of the contact areas during scale variation.

Fig. 6 Electrical current density distribution on the GDL contact surface according to different scales of \( L/2^a \)

Fig. 7 Variation in contact resistance according to the scales of \( L/2^a \)
4.3 Comparison of Contact Resistances. The current contact analysis shows that the contact resistance can be varied according to the contact process, which may be affected by rough surfaces. Thus, it is difficult to compare the current contact resistance value with other reported values because the surfaces are not comparable. However, if we assume that the surfaces have similar characteristics, then it is possible to compare the contact resistances and validate the current value. One of the similar results was reported by Zhou et al. [19], who showed experimentally that the contact resistance of the GDL (TGP-H-30) ranged from 0.8 mΩ · cm² to 1.3 mΩ · cm², according to summit density, summit radius, and standard deviation. If we consider the total contact area and the thickness of the specimen, then the current resistance is roughly 1.05 mΩ · cm², within the range of Zhou’s results. Consequently, the current contact resistance is adequately obtained from two comparisons.

4.4 Effect of Applied Pressure. Since the applied pressure can strongly influence the contact resistance, it would be practically beneficial to obtain the contact resistance according to several applied pressures. The contact resistances according to the applied pressure are obtained by the similar analysis explained from the previous subsection. The applied pressures are 4 Ma, 6 MPa, 9 MPa, and 11 MPa. The different pressures are applied to four different FEM models according to the four different length scales. In the course of this analysis, the configuration of the roughness of the GDL surface will be affected. Figure 9 shows the outcome of contact resistance with respect to the applied pressure, showing that the contact resistance decreases as the applied pressure increases, leading to larger total contact area and then smaller contact resistance. To detect the contact resistance in the unknown range of applied pressure, the data of contact resistance is fitted to the inverse power law equation, showing as

\[
R = 11.28p^{-0.8125} - 0.5104 \text{ (mΩ · cm²)}
\]  

where \( p \) is the applied pressure.

All outcome of this analysis are obtained directly from the specific surface data of GDL. If the location of the surface is different, the contact resistance could be different since the contact resistance is affected by the microscopic contact area distribution.
4.5 Comparison of Fractal Contact Resistance. The electrical contact resistance is dependent on the characteristics of surfaces, which roughness varies in the multiscale processes. To overcome this limitation, random surface that had fractal characteristics were investigated especially in the application to fuel cells. A related work was reported by Mishra et al. [15], who calculated the contact resistance of fractal surface which can be expressed as

\[
R = A_a \Gamma(m)G^{D−1} \left( \frac{D}{(2−D)P} \right)^{D/2}
\]

where \( G, D \) are a scaling constant and the self-similar fractal dimension, respectively, \( \Gamma(m) \) is a constant whose expression may be found in Majumdar and Tien [26], \( A_a \) is the apparent contact area of the contact interface and \( \lambda \) is the effective electrical conductivity of the two surfaces in contact. The reported fractal dimension of GDL ranges between 1.52 and 1.72. However, we find that the fractal dimension of the surface of our GDL is 2 by using the box counting method [27], even under the compaction pressure. From Eq. (5), when the fractal dimension is 2, the contact resistance cannot be defined. If the surface has the fractal dimension of 2, it means that it has very high roughness. Thus, the previous work [26] is not suitable to estimate the contact resistance of the contact surface that has high surface roughness. Our methodology can predict the exact contact resistance regardless of the high fractal dimension.

5 Conclusions

We have presented a numerical multiscale contact resistance between the GDL and BPP of a fuel cell system with a rough GDL surface in which the surface morphology changes with scale. The contact interface in the numerical model is modeled as a layer of carbon graphite fiber. It is demonstrated that as the scale decreases, the total contact area decreases and the corresponding contact resistance increases; the contact resistance was obtained as a function of scale, a process which can provide an exact value in the multiscale process. Using the above technique, the contact resistances according to the applied pressure are then sought. We validated the computed contact resistance via comparison with previously reported values.

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Greek Symbols

- \( \alpha \) = index of resolution of \( L/2^{\alpha} \)
- \( \Gamma \) = constant in Eq. (5)
- \( \phi \) = GDL porosity
- \( \lambda \) = effective electrical conductivity \((\Omega^{-1} \text{m}^{-1})\)
- \( \rho_f \) = resistivity of fiber \((\Omega \cdot \text{m})\)

References