Using Orthorhombic Lattice Boltzmann Model to Research the Liquid Transport in Gas Diffusion Layer with Different Micro Porous Layer Coated

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Abstract. Water management in gas diffusion layer (GDL) and micro porous layer (MPL) poses a great impact on performance of proton exchange membrane fuel cells (PEMFCs). And enhancement of the performance of fuel cells requires an appropriate water balance between the conservation of membrane humidity and the discharge of excess water produced in the cell. The Lattice Boltzmann method (LBM) can enable more straight simulation of fluid flow with complex solid structures, compared with conventional computational fluid dynamics (CFD) method based on Navier-Stokes equations. In this study, the orthorhombic pseudo-potential multiphase lattice Boltzmann method (LBM) is used to investigate liquid water transport in the MPL and GDL of polymer electrolyte membrane fuel cells (PEMFC). And the GDL and MPL structure image are all acquired by the stochastic generation method. We compared the GDL coated by the MPL with different thickness and different porosity. Numerical results confirm that influence of porosity is much greater than the thickness, which can help to improve the GDL and MPL design.

AMS subject classifications: (or PACS) To be provided by authors

Key words: Proton exchange membrane fuel cell, lattice Boltzmann method, stochastic generation method, water management, gas diffusion layer, micro porous layer.

1 Introduction

Proton exchange membrane fuel cell (PEMFC) has been considered as one of the most promising power sources for practical applications such as automotive and backup power station due to its zero emission, low operating temperature, high efficiency, high power density. One of the key technologies in PEMFC is the water management. Enhancement

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of the performance of fuel cells requires an appropriate water balance between the conservation of membrane humidity and the discharge of excess water produced in the cell. Excessive amount of water floods porous media in high current or low temperature situations, thus blocking the reactant gas channel from flow field to catalyst layer (CL); Loss of water leads to dehydration of membrane and poses a threat to performance and durability of cell. Therefore, the optimization of water management is of vital importance to improve fuel cell performance.

There is much potential for material design to optimize fuel cell performance such as hydrophilic and hydrophobic treatment of porous media, refinement of carbon substrate, application of novel flow filed. In the typical MEA design, an MPL between CL and MPL is basically made from a mixture of carbon black power and hydrophobic agent. The hydrophobic agent is usually composed of polytetrafluoroethylene (PTFE), yielding a finer pore geometry and highly hydrophobic characteristic than GDLs [1]. The design parameters for the gas diffusion layer (GDL) in the PEMFC are pore size, thickness, hydrophobic/hydrophilic properties, porosity, which impact the water management characteristics during PEMFC operation [2]. One of the beneficial effects of an MPL is the achievement of better water management because it results in a more favorable water profile in cell [3]. Several investigations have been demonstrated that MPL coated on the GDL substrate can effectively improve the water management characteristic and then enhances the performance. T. Kitahara et al. [2] clarified that optimized MPL design parameters depend on humidification of supplied gas significantly and GDL coated by MPL not only prevent the deterioration of MEA in low humidity condition but also reduce the flooding phenomenon under high humidity condition. Decreasing the MPL pore diameter and PTFE content is effective in preventing the dry of MEA in low humidity condition, whereas downsizing the MPL mean flow pore diameter to $3\mu m$ leads to flooding. The authors also developed a novel triple MPL coated GDL, in which a hydrophilic layer was coated on a hydrophobic double MPL with a gradient of hydrophobicity inside [4]. And the results showed that the thin hydrophilic layer in the triple MPL is good to maintain the hydration of MEA in low humidity while the hydrophobic double MPL prevents the removal of water from hydrophilic layer. T. Kitahara then developed a new hydrophilic and hydrophobic double MPL coated GDL to enhance PEMFC performance under no-humidification condition at the cathode and the influences of the pore diameter, thickness, and hydrophilic and hydrophobic properties for the double MPL on PEMFC are investigated [5]. An MPL is not only effective for water management in normal temperature but also in subfreezing temperature. Extending ice storage of electrode into MPL region is useful for fuel cell to start in cold environment. J. Ko [6] carried out three-dimensional simulations with and without the dual-functional MPL for a numerical comparison and found that the dual-functional MPL kept cell operational, even after CL was completely filled with ice, extending the cold start time before failure. To summarize, there is a great potential to optimize the water management thus improving the cell performance when focusing on optimizing the design parameters of the porous media.

Much attention has been paid to the investigation of fluid flow in porous media by
many researchers using experiments. Recently, more advanced radiography techniques, i.e., X-ray [7–11], neutron radiography [12–14], nuclear magnetic resonance (NMR) [15, 16] have been employed to explore water transport in PEMFCs. By using X-ray method, Sinha et al. [7] investigated liquid water saturation distribution in the GDL during gas purge and obtained that water distribution in the GDL was in form of irregular clusters from three-dimensional map of liquid water saturation image. Lee et al. [8] utilized synchrotron X-ray radiography to visualize the liquid water distribution in a fuel cell and investigated influence of MPL thickness on water content distribution. It was observed that MPL coated GDL can significantly reduce the water content at the interfacial area between CL and GDL and increasing the thickness of MPL resulted in a reduction of liquid water accumulation at the interface between the substrate and MPL. By using neutron imaging method, Pekula et al. [12] studied water transport phenomenon in the GDL and gas channel within an operating PEMFC. They found that liquid water was accumulated at specific locations of GDL under channel walls. These experiments were lack of micro-scale understanding of fluid flow in porous media even though visualization studies successfully observed water distribution in PEMFCs. Qualitative results for in-plane water distribution inside MEAs, GDLs, Catalyst layer (CLs) are mainly obtained in these studies and most of them could not measure through-plane water distribution because of small dimensions of MEA. Moreover, low spatial resolution of neutrons imaging and less water sensitivity of X-ray limit their use to study water transport in GDL.

Lots of numerical simulations made for multiphase transport model of fuel cell in numerous literatures are conducted by applying commercial CFD software, such as Comsol, Fluent, Star-CD. There are two major methods based on the continuum approaches for modeling two-phase flow in porous media, i.e., multiphase mixture model and [17–24] and two-fluid model [25–36]. The multiphase mixture model was mainly attributed to the work of Wang and co-workers [17–24]; and the two-fluid model is mainly developed by Nguyen and co-workers [25–29], Djilali and co-workers [30–32], and Li and co-workers [33–36]. In conventional CFD method, mass, Navier-Stokes and energy equations in the form of partial difference equations are numerically solved using the finite element, finite difference, or finite volume discretization methods. Commercial CFD packages are always a black-box structure and no core code is displayed to the user except input, output, and some user modifiable functions. It is even difficult to adjust for the precomposed PDE model and numerical method when built-in model algorithms and program present any numerical divergence and instability [37]. On the other hand, continuum models based on partial difference equations have several limitations when considering microscale liquid transport phenomena in hydrophobic porous media, because they are on a basis of macroscale properties, such as the relations between water saturation and capillary pressure, relative phase permeabilities and phase change rate [38].

The lattice Boltzmann method (LBM) is a numerical method developed in the past two decades which can enable more straightforward simulation of fluid flow with complex solid structures, compared with conventional computer fluid dynamics (CFD) based on Navier-Stokes equations. However, the fluid is described using distribution functions
that represent the probability of finding a fluid particle in the LBM method. Distribution functions are given for different directions in each node in the fluid domain and each probability distribution function moves to the neighboring node of its own direction. Accordingly, the lattice Boltzmann method is one of the appropriate methods for microscale simulations. Several LBM models have been developed since the 1980s with each having pros and cons, including the earliest lattice-type two-phase model proposed by Rothman and Keller [39] based on the lattice gas algorithm, model proposed by Shan and Chen [40, 41] and relevant modified versions [42, 43], free-energy approach developed by Swift et al. [44, 45] and Multi-block lattice Boltzmann method is proposed by H. Liu et al. [46, 47]. The lattice Boltzmann method has been nowadays widely used for various simulations related with PEMFCs. Y. Gao [48] used LBM to research the influence of nano-pores on the ability of CL to conduct gases when gas flow is driven by pressure gradient, where the dragging force of solid wall to the gas flow varies with the Knudsen and proposed a new simplified catalyst structure, in which the permeability calculation of catalyst is closely linked with the pore. We also used a combination of the LBM and imaging technology to investigate gas flow in a carbon paper and estimated permeability of GDL in good agreement with experimental measurements. K. N. Kim [38] studied liquid transport in multilayer hydrophobic PTLs (GDL and MPL) in PEMFCs by two-dimensional pseudo-potential LBM method. The results found that liquid water in the PTLs is mainly governed by capillary effects and a thicker MPL thickness reduced the time required to approach to a steady-state water distribution indicating faster removal of liquid water from MEA to the gas channel.

According to collision operator, LBM can be classified into two aspects: multi-relaxation time (MRT) collision operator and single-relaxation time (SRT) collision operator. It is believed that single-relaxation time schemes are frequently utilized because of lower computational cost and simplicity even though multi-relaxation schemes show a higher accuracy and stability especially when the flow is diffusion dominated [49]. Therefore, single-relaxation time LBM is adopted in this paper.

LBM has been used for simulating the fluid transport in the GDLs, whereas few studies have investigated the impact of GDL coated by the MPL on the water management using LBM. Although K. N. Kim did similar works related with MPL coated with GDL, impact of thickness and porosity of MPL is not studied. The purpose of this study is to improve our understanding of fluid flow in the MPL coated GDL. Three dimension 19 velocities LBM is used to modeling the fluid transport in the gas diffusion layer with different thickness and porosity of MPL in this research.

2 Methodologies

2.1 Material preparation

There are two types of reconstruction methods of the porous media, i.e., virtual stochastic generation method and 3D imaging combination method. In this paper, Virtual stochastic
A generation method is utilized to generate GDL and MPL structure due to its low cost and easy implementation of geometry generation, which consists of three stages to get a virtual stochastic image. The first is to distribute the center of the representative elements at each scale stochastically; then the specific tridimensional geometry will be generated around each center; finally, a random manner surrounding is filled until the required volume fraction is fulfilled. Fig. 1 shows the microstructures of four reconstructed MPL coated GDL with thickness of MPL 11\(\mu\)m, 16\(\mu\)m, 26\(\mu\)m, 51\(\mu\)m respectively, and Fig. 2 shows the microstructures of four reconstructed MPL coated GDL with porosity of MPL 35\%, 40\%, 55\%, 80\% respectively. Specific details of reconstructed MPL coated GDL are given in Table 1 and Table 2. It is noted that MPL porosity 45\% and 50\% are added to form a wide range of MPL porosity and expected to obtain overall impact of MPL porosity on the fluid flow, thinking of not taking much computational cost as well as. It is assumed that the porosity of GDL is 76\%. 

Figure 1: 3D geometry of the reconstructed carbon paper GDL with MPL with different thickness: (a) 11\(\mu\)m; (b) 16\(\mu\)m; (c) 26\(\mu\)m; (d) 51\(\mu\)m.

Figure 2: 3D geometry of the reconstructed carbon paper GDL with MPL with different porosity: (a) 35\%; (b) 40\%; (c) 55\%; (d) 80\%. 

Table 1: Specific parameters for reconstructed carbon paper GDL with MPL of different porosity.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Images size in voxel (µm)</th>
<th>Image size (µm)</th>
<th>Pixel size: 1.2µm</th>
<th>MPL porosity</th>
<th>MPL thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51×51×(51+11)</td>
<td>61.2×61.2×(61.2+7.2)</td>
<td>35%</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>51×51×(51+11)</td>
<td>61.2×61.2×(61.2+7.2)</td>
<td>40%</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>51×51×(51+11)</td>
<td>61.2×61.2×(61.2+7.2)</td>
<td>45%</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>51×51×(51+11)</td>
<td>61.2×61.2×(61.2+7.2)</td>
<td>55%</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>51×51×(51+11)</td>
<td>61.2×61.2×(61.2+7.2)</td>
<td>80%</td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Specific parameters for reconstructed carbon paper GDL with MPL of different thickness.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Images size in voxel (µm)</th>
<th>Image size (µm)</th>
<th>Pixel size: 1.2µm</th>
<th>MPL porosity</th>
<th>MPL thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51×51×(51+6)</td>
<td>61.2×61.2×(61.2+7.2)</td>
<td>50%</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>51×51×(51+11)</td>
<td>61.2×61.2×(61.2+13.4)</td>
<td>50%</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>51×51×(51+16)</td>
<td>61.2×61.2×(61.2+19.2)</td>
<td>50%</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>51×51×(51+26)</td>
<td>61.2×61.2×(61.2+31.2)</td>
<td>50%</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>51×51×(51+51)</td>
<td>61.2×61.2×(61.2+61.2)</td>
<td>50%</td>
<td>51</td>
<td></td>
</tr>
</tbody>
</table>

2.2 Orthorhombic lattice Boltzmann method

The proposed LBM in our work is based on the Bhatnagar-Gross-Krook (LBGK) approach, which uses a single relaxation time parameter to describe the collision between particles [50]. The Orthorhombic single relaxation time lattice Boltzmann model can be presented as follows:

\[
f_i(x + m_i \nabla t, t + \nabla t) = f_i(x, t) + c_i \left[ f_{eq}^i(x, t) - f_i(x, t) \right], \tag{2.1}
\]

where \( \nabla t \) is a time step when the particle moves from one lattice into another; \( x \) is a space vector; \( f_i(x, t) \) is particle distribution function at time \( t \) and location \( x \); \( f_{eq}^i(x, t) \) is the value of particle distribution function at equilibrium state; \( c_i \) is a relaxation parameter that meaning the rate of \( f_i(x, t) \) approaching \( f_{eq}^i(x, t) \). As shown in Fig. 3, the lattice velocity \( m_i \) in the D3Q19 model is presented as follows:

\[
m_i = \begin{cases} 
(0,0,0), & i = 0, \\
(\pm \nabla x / \nabla t, 0,0), & i = 1,2, \\
(0,\pm \nabla y / \nabla t, 0), & i = 3,4, \\
(0,0,\pm \nabla z / \nabla t), & i = 5,6, \\
(\pm \nabla x / \nabla t, \pm \nabla y / \nabla t, 0), & i = 7 - 10, \\
(0,\pm \nabla y / \nabla t, \pm \nabla z / \nabla t), & i = 11 - 14, \\
(\pm \nabla x / \nabla t, 0,\pm \nabla z / \nabla t), & i = 15 - 18.
\end{cases} \tag{2.2}
\]
The equilibrium distribution function for D3Q19 model is given by:

\[
f_i^{eq} = \begin{cases} 
  \frac{\delta y \delta z}{\delta x \Delta} \rho + \left( \frac{a_x u_x + \frac{u_x^2}{2m_i}}{6m_i} \right) \rho_0, & i = 1,2, \\
  \frac{\delta x \delta z}{\delta y \Delta} \rho + \left( \frac{a_y u_y + \frac{u_y^2}{2m_i}}{6m_i} \right) \rho_0, & i = 3,4, \\
  \frac{\delta x \delta y}{\delta z \Delta} \rho + \left( \frac{u_z + \frac{u_z^2}{2m_i}}{6m_i} \right) \rho_0, & i = 5,6, \\
  \frac{u_x u_y}{(4m_i m_y)} \rho_0, & i = 7 - 10, \\
  \frac{u_y u_z}{(4m_i m_z)} \rho_0, & i = 11 - 14, \\
  \frac{u_x u_z}{(4m_i m_z)} \rho_0, & i = 15 - 18, \\
  f_0^{eq} = \rho - \sum_{i=1}^{18} f_i^{eq}, 
\end{cases}
\]

where \( \Delta = (\delta x + \delta y + \delta z) / 3 \); \( u \) is the bulk fluid density; \( \rho \) is the fluid density; \( \rho_0 \) is a reference density to ensure that above the LBM model recovers incompressible flow at steady state; \( \kappa \) is a free parameter; \( a_x, b_x, a_y \) and \( b_y \) are the lattice shape parameters. In lattice symmetry, there are

\[
  c_1 = c_2 = c_x, \quad c_3 = c_4 = c_y, \quad c_5 = c_6 = c_z, \\
  c_7 = c_8 = c_9 = c_{xy}, \quad c_{11} = c_{12} = c_{13} = c_{14} = c_{yz}, \quad c_{15} = c_{16} = c_{17} = c_{18} = c_{xz}. 
\]

Conservation of momentum in the collision needs:

\[
  \sum_{i=0}^{18} c_{ix} m_{ix} \left[ f_i^{eq} - f_i \right] = 0, \quad \sum_{i=0}^{18} c_{iy} m_{iy} \left[ f_i^{eq} - f_i \right] = 0, \quad \sum_{i=0}^{18} c_{iz} m_{iz} \left[ f_i^{eq} - f_i \right] = 0.
\]
Substituting Eqs. (2.3) into (2.5) obtains the following expression for the velocities:

\[ u_x = \frac{3 \sum_{i=1}^{8} c_i m_i f_i}{a_x c_x + b_x (c_{xy} + c_{yz}) \rho_0}, \quad u_y = \frac{3 \sum_{i=1}^{8} c_i m_i f_i}{a_y c_y + b_y (c_{xy} + c_{yz}) \rho_0}, \quad u_z = \frac{3 \sum_{i=1}^{8} c_i m_i f_i}{c_z + (c_{xz} + c_{yz}) \rho_0}, \]  

(2.6)

the Mass conservation requires

\[ \sum_{i=0}^{18} c_i [f_i^q - f_i] = 0. \]  

(2.7)

Substituting Eqs. (2.3) into (2.7) gets equation for fluid density

\[ \rho = \sum_{i=0}^{18} c_i f_i + \rho_0 \nabla^2 \left[ u_x^2 (c_0 - c_x) + u_y^2 (c_0 - c_y) + u_z^2 (c_0 - c_z) / \nabla^2 \right]. \]  

(2.8)

The values of other five relaxation parameters are determined from the following equation to ensure that the viscosity is isotropic:

\[ \omega_{yx} \nabla y^2 = \omega_{xz} \nabla x^2, \quad \omega_{xy} b_y \nabla y^2 = \omega_{xz} \nabla x^2, \]  

(2.9a)

\[ 2 a_x \omega_x + b_x (\omega_{xy} + \omega_{xz}) - 2 b_y \omega_{xy} - 2 \omega_{xz} = \omega_{xz}, \]  

(2.9b)

\[ 2 a_y \omega_y + b_y (\omega_{xy} + \omega_{yz}) - 2 b_x \omega_{xy} - 2 \omega_{yz} \nabla y^2 = \omega_{xz} \nabla x^2, \]  

(2.9c)

\[ 2 \omega_z + (\omega_{xz} + \omega_{yz}) - 2 b_x \omega_{xz} - 2 b_y \omega_{yz} \nabla z^2 = \omega_{xz} \nabla x^2. \]  

(2.9d)

2.3 Boundary

To study flow in the gas diffusion layer that coated by micro porous layer at the pore scale using LB simulations, the bounce back scheme is used at the walls to obtain no-slip velocity conditions. When a particle distribution streams to a wall node, it scatters back to the node it came from. The bounce back scheme is a simple way to fix the unknown distributions on the wall nodes. The fluid flow inside is driven by a pressure drop between the inlet and outlet imposed in the z direction in parallel with axis of the samples. For all the samples, the same pressure drop is applied between the inlet and outlet. The pressure gradient was created by imposing two different pressures on the end side of the sample. More details for the pressure boundary in our previous work [4].

3 Simulation and results analysis

3.1 Impact of MPL thickness

Fig. 4 shows 3D fluid velocity distribution in the porous media obtained from orthorhombic LBM simulations for cases shown in Fig. 1. It can be seen that velocity field in porous
media is complicated because of its heterogeneous characteristics of structure. And larger pores are filled with main fluid flow due to its less resistance. It is observed no clear difference on velocity distribution in terms of MPL with different thickness (constant porosity), indicating that MPL thickness has almost no impact on fluid velocity. The impact of MPL thickness on fluid flow on interface between MPL and GDL is shown in Fig. 5. There is coexistence of carbon power and fiber on interface on the boundary, which lead to larger velocity compared with internal area. This is because overlapping from combination of carbon power and fiber reduce the pore size on the border.

### 3.2 Impact of MPL porosity

Figs. 6-7 show the 3D velocity distribution profile and interfacial velocity field respectively for samples with different MPL porosity. It is evident that speed value is higher...
with the increase of MPL porosity, indicating that MPL porosity has a greater impact on fluid flow than MPL thickness. Fluid is prone to flow on the boundary and large pores, which is the same as that in Fig. 5. However, it would make the GDL completely filled up with liquid water if pores and porosity are too large, thus blocking the reactant gas channel. In the future, we will optimize water management by balancing reactant gas diffusion and liquid flow, which is expected by altering hydrophilic and hydrophobic characteristics of GDL or MPL.

### 3.3 Calculation of liquid water saturation

The liquid water saturation of the porous media was defined as the liquid water thickness from contour slices to the porosity profile obtained in the virtual stochastic geometry. In addition, Liquid water saturation level calculated in this study should be considered as average of water saturation distributions in the MPL and GDL respectively even though water saturation gradient is expected to be present along the through-plane and in-plane.
directions. Therefore, the liquid water saturation was calculated from equation:

\[ s = \frac{X}{L_z \varepsilon} \]  \hspace{1cm} (3.1)

where \( L_z \) is the length of the carbon paper in the \( z \)-direction; \( \varepsilon \) is the porosity profile; \( X \) is the liquid water thickness.

Fig. 8 shows influence of MPL thickness on liquid water saturation of MPL coated GDL. There is almost no change of saturation value of GDL and small alteration of saturation level in MPL when MPL thickness range from 6\( \mu \)m to 26\( \mu \)m, indicating MPL thickness has little impact on saturation of GDL and MPL. But, GDL and MPL shared same situation that liquid water saturation value is slightly decreasing with the increase-ment of MPL thickness. It is clear to see from Fig. 8 that increasing MPL thickness has little change in saturation level in both GDL and MPL. These simulation results are consistent with those in K. N. Kim [38], indicating an MPL has little effect on fluid transport when it is insufficiently thick and the reduction of liquid water volume becomes obvious.
when the thickness of the MPL is over 50μm.

Fig. 9 shows the influence of MPL porosity on liquid water saturation of MPL coated GDL. There is an obvious incensement in saturation of MPL and slight incensement in saturation of GDL with improvement of MPL porosity, explaining that MPL porosity has much impact on MPL saturation than GDL saturation, which is same as in Fig. 8. Saturation value is increasing smoothly when MPL porosity is below 45%, whereas a fast and rapid increasing when MPL porosity is above 55%. Therefore, MPL porosity can’t be too large because it would lead to large liquid water saturation value in GDL, blocking the reactant gas channel.

4 Conclusions and future work

A profound understanding of water transport phenomenon in GDL and MPL is needed for improvement of performance in PEMFCs and guideline for design parameters. The Single-time relaxation time Lattice Boltzmann method is used in this paper to investigate liquid water transport in GDL and MPL due to its simplicity and computational cost. By
producing GDL with different porosity and different thickness of MPL using stochastic generation method, we compared their impact on water transport. There is no significant difference of velocity field when different thickness of MPL is applied whereas a large change when different porosity of MPL is used, indicating that impact of porosity is much greater in velocity field than the thickness. In addition, fluid is prone to flow on the boundary and large pores in both two situations due to structural characteristics. Compared with samples of different MPL thickness, a large improvement of saturation value is obtained in samples of different MPL porosity. But too large MPL porosity will lead to high saturation level in GDL, which will lead to blockage of reactant gas channel. Based on existing research, we suggest the thickness of MPL is choosing 11µm and porosity is keep close to 55%. In summary, the influence of porosity has greater impact than the thickness. As for future work, influence of hydrophilic and hydrophobic treatment and different pressure boundaries will be further researched to have a comprehensive understanding of liquid water transport in GDL and MPL.
Acknowledgments

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