The effects of channel depth on the performance of miniature proton exchange membrane fuel cells with serpentine-type flow fields

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Abstract

Flow channels are one of the key components of a fuel cell, because they perform various essential functions that enable the system to operate correctly. In this study, three-path serpentine and parallel-serpentine flow fields with various depths were analyzed experimentally. Die-sinking microelectrical discharge machining was applied to fabricate miniature SUS316L bipolar plates, of which both the rib and channel widths were 500 μm and the channel depths varied among 200, 300, 400, and 600 μm in an active area of 20 mm × 20 mm. The clamping test was performed to examine the magnitude of membrane electrode assembly deformation and the contact resistance. The pressure drops for each cell were analyzed to determine the effects of channel depth. The results revealed that a deep channel is required to leave sufficient space for reactant transportation and water removal; however, too low flow velocity reduces the convective mass transport and cell performance when the channel is too deep.

Introduction

Fuel cells are a promising power technology because of their compactness, silent operation, and high power density, and because they emit nearly no pollution. Among various types of fuel cells, proton exchange membrane fuel cells (PEMFCs) are the leading technology for portable electronic devices and light-duty vehicles, because they operate at relatively low temperatures (normally below 100 °C) and produce electrical output to meet dynamic power requirements. A substantial knowledge base that focuses on the development of high-efficiency PEMFCs exists [1–13]. It is generally agreed that the geometric parameters and flow patterns of flow channels strongly influence the performance of PEMFCs.

Bipolar plates with various flow fields can be fabricated using various methods, namely machining, etching, and embossing. For economic reasons, embossing is the preferred process for mass production. However, embossing exhibits limitations in forming channels with high depth-to-width ratios, especially for narrow channels. In addition, plate
fractures or variances in channel dimensions might occur. Research has been conducted on enhancing the embossing process to form deeper narrow channels [14–16]. Therefore, investigating the impact of channel depth on the performance of miniature PEMFCs is worthwhile.

Various simulations have been performed to explore this topic based on computational fluid dynamics. The results of simulating a 200-cm² cell indicated that that fabricating a channel that is too deep tends to reduce the local gas pressure, leading to variances in fuel distribution [10,17]. Modeling a 130-cm² cell indicated that the optimal channel-to-rib width ratio is approximately one, and a channel that is too deep provides redundant fuel [18]. Simulating a 24.6-cm² cell revealed that the performance of a PEMFC with a serpentine flow channel is insensitive to channel depth in certain operation conditions [3]. In the simulation of a 2.56-cm² miniature cell, the results indicated that cells with a high aspect ratio yield higher current densities [19].

These simulation results reveal a trend that deeper channels are favored for miniature cells, whereas shallower channels are preferred for larger cells. Several studies have experimentally examined the impacts of channel dimension on PEMFCs of various sizes [20–32]. Few of these studies have focused on the impacts of channel depth on miniature PEMFCs. A miniature PEMFC normally has narrow channel and rib widths to provide sufficient channel length in a small active area. Fabricating a PEMFC with fine, deep channels that produces an efficient power density is challenging. For a PEMFC with low power densities, the impact of channel dimensions might be less substantial because efficiency in mass transportation is lower. This study examined the effects of channel depth on the performance of highly efficient miniature PEMFCs. Die-sinking microelectrical discharge machining (micro-EDM) was applied to prepare micro flow channels in metallic bipolar plates. Two serpentine-type flow fields were processed on an area basis where electricity was discharged in a single direction.

The representation of (a) SFF and (b) PSFF and the finished unipolar plate for (c) SFF and (d) PSFF.

Experimental and procedures

Fabricating the bipolar plates

In this study, SUS316L stainless steel was used as the plate material because it features excellent heat and corrosion resistance. Micro-EDM is applied to fabricate unipolar plates. Micro-EDM can be classified into various categories based on the tool electrodes. The process applied in this study involves using cubic electrodes and is called the die-sinking micro-EDM. During the process, copper tool electrodes were manufactured using micro-high-speed milling. A 1-mm-thick SUS316L plate was cut into a 50 mm × 50 mm area by using a wire machine and then served as the workpiece electrode. All channels were processed on an area basis where electricity was discharged in a single direction.

The serpentine-type flow field was applied as the flow design. Previous studies [1,33] have reported that single-pass serpentine flow fields tend to cause polarization problems attributable to excessive channel length, and executing too many passes tends to produce an uneven fuel distribution. Therefore, the three-pass design was adopted. Fig. 1 shows two types of commonly used serpentine flow field; Fig. 1(a) illustrates the three-path serpentine flow field (SFF), and Fig. 1(b) illustrates the three-path parallel-serpentine flow field (PSFF). Fig. 1(c) and (d) show the finished unipolar plates for SFF and PSFF, respectively. The plates were finished using 5 A of peak discharging current at a material removal rate of 7 mm³ min⁻¹. The most obvious difference between SFF and PSFF is that for PSFF there are single paths collecting and distributing both gas and water. The PSFF has been considered a serpentine-type flow field in various studies [9,34]. For the test samples, the channel and rib width are constant as 500 μm in a reaction area of 4 cm². The rib-to-channel width ratio was set as 100% because a previous study [18] has reported that such a ratio enables high power densities to be achieved. Channel depths are varied as 200, 300, 400 and 600 μm to test their impacts.

The clamping test

When assembling PEMFCs, a strong clamping force is usually required to prevent the leakage of reactants and to reduce the contact resistance. However, the clamping force causes the membrane electrode assembly (MEA) to protrude into channels, leaving insufficient space for reactant flow and water removal. This study explored the deformation of the MEA by using the MEA compression test. During the test, unipolar plates with parallel channels 200 μm in depth were cut in half by using a wire machine and assembled to become a “half-cell,” as shown in Fig. 2. The channel and rib widths are 500 μm, consistent to the bipolar plates in Fig. 1. Clamping
Torques ranging from 10 to 25 kgf cm were applied to examine the magnitude of MEA deformation. The length of the MEA protruding into channels (l_p) is approximated as follows:

\[ l_p = \frac{l_{ch} - l_{rib}}{2} \]  

where \( l_{ch} \) and \( l_{rib} \) are the thicknesses of the MEA in the channels and ribs, respectively.

In addition, to determine the optimal clamping force, the contact resistances (\( r_c \)) between unipolar plates and gas diffusion layers (GDLs) are calculated as follows:

\[ r_c = \frac{V}{J} \]  

where \( J \) is the applied current density and \( V \) is the measured electric potential in the test.

The single-cell test

In this study, the cell performance of metallic bipolar plates with various channel depths was tested using the TEI-P300-1AB2CS surveying instrument. In addition, the pressure drops for the testing cells were measured to examine the effects of channel depth. The pressure drop is defined as the difference between input and output gas pressure and was obtained using a data acquisition (DAQ) system. During the tests, a single cell 50 × 50 × 23 mm in dimensions was assembled. The cell was fabricated with end plates, gaskets, bipolar plates, and an MEA. The MEA comprised a proton exchange membrane and two GDLs with 0.25 mg cm\(^{-2}\) Pt for both the anode and cathode. Pure hydrogen and oxygen were supplied to the anode and cathode electrodes. The anode flow rate was 60 cc min\(^{-1}\), and thermal gas humidification of 30 °C was applied; the cathode flow rate was controlled using stoichiometric numbers of 1.2. The cell was operated under 1 atm of pressure at room temperature.

The mathematical model

In this work, a three-dimensional model for a high temperature PEMFC has been approached and implemented for its solution in COMSOL Multiphysics 4.4. The model is similar to those already existing in scientific literature [9,25], in which it has been applied to study flow channel geometry influence amongst other variables. The values of most simulation parameters are identical to [9]. Specific values consistent with our experiment are listed in Table 1. Fig. 3 illustrates the model geometry for PSFF with the channel depth of 600 μm. Considering the MEA deformation, the channel depth in the geometry is reduced by 40 μm for all simulation cases. Several simplifications assumptions are introduced in this model: (1) all processes are under steady-state conditions; (2) the GDLs, the catalyst layers and the membrane are isotropic and homogeneous porous medium; (3) the gas-phase follows ideal gas law; (4) the flows in the channels and porous layers are assumed to be laminar and incompressible; (5) the transportations of electron and proton are respectively controlled by solid-phase electronic potential and membrane ionic potential.

Governing equations of the model are derived as follows (Table 2 for nomenclature):

(1) The convection and diffusion for the gaseous species (in channels, GDLs, catalyst layers):

\[ \nabla \cdot (-D \nabla C_i + u_i C_i) = S_i \]  

(1.1)

The diffusion coefficient of gaseous species in the diffusion layer can be expressed as:

\[ D = D_{eff} \cdot \varepsilon^{1.5} \]  

(1.2)

Table 1 – General values used during simulations.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active area</td>
<td>400</td>
<td>mm(^2)</td>
</tr>
<tr>
<td>Membrane thickness</td>
<td>0.1</td>
<td>mm</td>
</tr>
<tr>
<td>GDL thickness</td>
<td>0.4</td>
<td>mm</td>
</tr>
<tr>
<td>Catalyst layer thickness</td>
<td>0.01</td>
<td>mm</td>
</tr>
<tr>
<td>Cell temperature</td>
<td>333</td>
<td>K</td>
</tr>
<tr>
<td>Inlet flow rate</td>
<td>60</td>
<td>cm(^3)/min</td>
</tr>
<tr>
<td>Active specific area</td>
<td>16000</td>
<td>1/m</td>
</tr>
</tbody>
</table>

![Fig. 2](image-url) – (a) The half bipolar plates, (b) half gasket, (c) testing MEA, and (d) the clamping test.

![Fig. 3](image-url) – The model geometry for PSFF with the depth of 600 μm with the cut plane for further observation.
(2) Momentum equation for the gaseous species (in channels, GDLs, catalyst layers):

$$
(u_j \cdot \nabla) u_j = F - \frac{1}{\rho_j} \nabla p_j + \frac{\mu_j}{\rho_j} \nabla^2 u_j
$$

(2.1)

$$
\nabla \cdot u = 0
$$

(2.2)

The average velocity of phase $j$ is calculated by continuous function based on Darcy’s law:

$$
\nabla \cdot \left( \rho_j \left( \frac{K_{eq}}{\mu_j} \nabla p_j \right) \right) = H_j
$$

(2.3)

$$
u_j = -\frac{K}{\eta} \nabla p_j
$$

(2.4)

(3) The transportations of electron (in bipolar plates, GDLs, catalyst layers) and proton (in PEM):

The source term of electronic current is set to be zero because of no electrochemical reaction in GDLs.

$$
- \nabla (-\sigma_t \nabla \phi_t) = 0
$$

(3.1)

Similarly, the source term for the ionic current in PEM is zero.

$$
- \nabla (-\sigma_s \nabla \phi_s) = 0
$$

(3.2)

The catalyst layer is the region where reaction happens and the ionic balance and electron balance are described as follows:

$$
- \nabla (-\sigma_{s,eff} \nabla \phi_s) = -S \cdot i_{loc}
$$

(3.3)

$$
- \nabla (-\sigma_{t,eff} \nabla \phi_t) = S \cdot i_{loc}
$$

(3.4)

The local current density ($i_{loc}$) generated by the porous electrode reaction in the catalyst layer can be described by Bulter-Volmer equation:

$$
i_{loc} = i_o \left( \exp \left( \frac{\alpha F \eta}{RT} \right) - \exp \left( -\frac{\alpha F \eta}{RT} \right) \right)
$$

(3.5)

$$
i_{loc} = i_o \left( \exp \left( \alpha F \eta \frac{RT}{H} \right) - \exp \left( -\alpha F \eta \frac{RT}{H} \right) \right)
$$

(3.6)

$$
\eta = \phi_s - \phi_l - E_{cell}
$$

(3.7)

Results and discussion

The clamping test

Fig. 4 shows the deformation of the MEA at various clamping forces. The values of $l_p$ and contact resistances are listed in Table 3. The clamping force of 20 kgf-cm was adopted in the single-cell test because the contact resistance was low. The contact resistance did not decrease substantially when further clamping force was applied. However, when a clamping force of 20 kgf-cm was applied, approximately 92 $\mu$m of the MEA protruded into the channel. Obviously, a considerable portion of channel space is required for shallow channels.

The single-cell test

Fig. 5 shows the curves of electric potential versus power density ($V$–$P$ curves) for both SFF and PSFF. In the following sections, the cell performances are evaluated based on the peak power densities, as shown in Table 4 for various channel depths and flow fields. In general, the peak power densities...
occur around the average potential of 0.4–0.5 V. For lower average potential, the cell performance decreases because of the appearance of large amount of liquid water in the cathode. The cell performance of SFF was generally more favorable than that of PSFF, except when the depth was 200 μm, at which both flow fields exhibited poor performance. However, the difference decreased as the channels deepened, because the single path in PSFF has sufficient space. For both flow fields, the cell performance initially increased as the channel depth increased, and then decreased when the channel was too deep (600 μm). The SFF with a channel depth of 400 μm produced the highest power density of 562 mW cm⁻². Fig. 5(a) and (b) show the pressure drops for the anode and cathode channels, respectively. The pressure drop was higher for the PSFF than for the SFF because of the single paths. Similar to the V–P curves, the difference decreased as the channel depth increased.

Here, the impact of channel depth based on a cross inspection of Fig. 5 and Fig. 6 is discussed. At the channel depth of 200 μm, both SFF and PSFF exhibited poor performance. The pressure drop was high because of MEA deformation. The cathode channel was completely clogged at a current density of approximately 460 mA cm⁻².

At a channel depth of 300 μm, the performance of SFF was much more favorable than that of PSFF. The cathode pressure drop for PSFF was high and increased as the current density increased, revealing that inefficient water removal occurs in the single paths of PSFF flow fields because the channel space is insufficient. It is also shown in Fig. 6 that the pressure drop difference between SFF and PSFF at anode and cathode is highest at 300 μm depth. This is because such depth provides smaller channel cross-sectional area, comparing to deeper channel. The single path in PSFF thus requires larger pressure gradient to receive and distribute fluids. This is evidential for cathode during lower cell potential, where more liquid water is produced.

At a channel depth of 400 μm, both SFF and PSFF produced their highest power densities compared with those at other depths. The peak power density of SFF was the highest of all flow fields; the pressure gradients were approximated to be 0.13 psi mm⁻¹ and 0.83 psi mm⁻¹ for anode and cathode channels, respectively.

At a channel depth of 600 μm, the performance of both SFF and PSFF was similar, indicating that deeper channels provide sufficient space for the single path in PSFF to receive and distribute water in the cathode. The pressure gradient for both

### Table 3 – The length of MEA protruded to channels (l_p) and contact resistance (r_c) in various clamping forces.

<table>
<thead>
<tr>
<th>Clamping forces (kgf cm)</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>l_p (μm)</td>
<td>80</td>
<td>86</td>
<td>92</td>
<td>96</td>
</tr>
<tr>
<td>r_c (mΩ cm²)</td>
<td>72</td>
<td>68</td>
<td>64</td>
<td>63</td>
</tr>
</tbody>
</table>

**Fig. 5** – The V–P curves for the SFF and PSFF.

**Fig. 6** – The pressure drops for (a) anode and (b) cathode channels.
flow fields was approximated to 0.10 psi mm\(^{-1}\). The anode and cathode pressure gradients were nearly identical, indicating that the cathode water flows in the bottom of the channel, leaving free space for gas flow. Two-phase flow considerably complicates oxygen distribution. Therefore, the channel depth cannot be increased excessively to improve the cell performance.

A significant amount of researches have investigated the effects of different channel geometries on cell performance based on experiments or simulations. The results of Scholta et al. [18] suggest that the optimal channel-to-rib width ratio is approximately one, as in Fig. 1. They also show that the relationship between rib width and other channel geometries is less significant. This is because the rib width, although has strong influences on the path length of electron transport, has less or none effects on the gaseous flow. Therefore, the effects of channel depth for various rib widths are theoretically similar to the results described above. On the other hand, Manso et al. [19] numerically investigated the effects channel depth-to-width ratio using ten different channel geometrics. Their results reveal that the cell performance increases for higher channel depth-to-width ratio if the ratio value is less than or close to one. Therefore, for different channel widths, the overall cell performance might change while the effects of channel depth remain the same.

Experiments of PSFF with various flow rates are evaluated because the impacts of channel depth are much sensitive in such a flow field. Fig. 7 shows the comparison of cell performances at anode flow rates of 60 and 80 c.c. min\(^{-1}\). The cathode flow rate was controlled using stoichiometric numbers of 1.2. It can be seen at a channel depth of 300 \(\mu\)m that the cell performance improves for higher flow rate. It is because patterns of two-phase flow in the cathode channel are more likely to change from plug flow to more efficient annular flow due to high flow velocity. At a channel depth of 400 \(\mu\)m, the cell performance slightly decreases at higher flow rates. It reveals that the cell performance at the flow rate of 60 c.c. min\(^{-1}\) is at its optimum. Too high flow velocity shortens the gaseous retention time and reduces the cell performance.

At a channel depth of 600 \(\mu\)m, the increase of flow rates improves cell performance a little. In such a flow rate, the \(I-P\) curves is very similar for the cell with the depth of 400 and 600 \(\mu\)m. Deeper channel has larger cross-sectional area, leading to lower flow velocity. It requires larger flow rate to increase flow velocity and convective mass transport. As a result, it is economically inefficient to fabricate bipolar plates with too deep channel and operate at a high flow rate.

**The numerical analysis**

Fig. 8 compares experimental and simulated polarization curves. In general, calculated results agree with experimental data. However, the finite elemental method diverges and fails to find the solution for the average potential smaller than 0.45 V. In addition, simulation results slightly over estimates the current densities for smaller average potential. It appears that the proposed model has limitation in dealing with the complicity of two-phase flow. As described in existent literature [15,16] that the process of random droplet emergence and liquid water clogging is not clearly understood because water clogging is highly localized to certain regions in specific channels. Nevertheless, the observation of individual channel velocity provides some insight about the pattern of two-phase

![Fig. 7](image1.png)  
**Fig. 7** The cell performances of PSFF with different channel depths at anode flow rates of 60 and 80 c.c. min\(^{-1}\).

![Fig. 8](image2.png)  
**Fig. 8** Model validation for (a) SFF and (b) PSFF; Solid line: experiment, Dotted line (Simulation).
flow. Fig. 9 shows the predicted flow velocity distribution at 0.45 V. As mentioned before, the cell with the depth of 600 μm has lower average velocity and thus reduces the convective mass transport and cell performance. However, the cell with shallower depth, although provides higher average flow velocity, shows highly heterogeneous in the distribution of velocity. It can be observed that very low flow velocity exists in most inner channels. In such a case, the plug flow may dominate in the cathode channel and have more chance of water clogging. On the other hand, deeper channel provides sufficient cross-sectional area and may lead to annular flow. Fig. 10 compares the vorticities in the cut plane at the six channels near the cathode output (Fig. 3) for PSFF 300 μm and 600 μm. It can be seen in the channel depth of 300 μm that the vorticities is significant small in the 4th to 6th channels. In contrast, the vorticities is significant and uniform in all channels with the depth of 600 μm. The vortices create centrifugal forces to lead the liquid flow against the channel wall, leaving channel central space for gaseous flow. Such an annular flow removes water more efficiently and yields better cell performance.

**Conclusion**

This study involved applying die-sinking micro-EDM to prepare micro flow channels in metallic bipolar plates. The effects of channel depth were examined by measuring pressure drops, observing MEA deformation, and numerical analysis. The conclusions are listed as follows:

![Fig. 9](image1.png)  
**Fig. 9** – Predicted flow velocity distribution (m/s) at 0.45 V. (a) SFF, (b) PSFF; (1) 300 μm, (2) 400 μm, (3) 600 μm.

![Fig. 10](image2.png)  
**Fig. 10** – The vorticities (1/s) in the cut plane (Fig. 3) for PSFF (a) 300 μm and (b) 600 μm at 0.45 V.
An SFF with a channel depth of 400 μm produced the highest power density of 562 mW cm⁻².

The cell performance of SFF is generally more favorable than that of PSFF. However, the cell performance becomes similar as the channel depth increases, because the single paths in PSFF cathode flow fields have sufficient space to distribute water.

Because MEA deformation occupies portions of channel space, a sufficient channel depth is required to enable reactant transportation and water removal. However, when the channel is too deep, too low flow velocity further reduces the convective mass transport and cell performance. The increment of flow rate slightly improves the cell performance. However, it is economically inefficient to fabricate bipolar plates with too deep channel and operate at high flow rate.

Acknowledgments

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