Water control by employing microgrooves inside gas channel for performance improvement in polymer electrolyte fuel cells

Ryo KORESAWA^a and Yoshio UTAKA^b

^aGraduate School of Engineering, Yokohama National University
79-5 Tokiwadai, Hodogaya, Yokohama 240-8501, Japan

^bFaculty of Engineering, Yokohama National University
79-5 Tokiwadai, Hodogaya, Yokohama 240-8501, Japan

* Corresponding author: Yoshio UTAKA

Tel. / fax: +81 45 339 3909

E-mail address: utaka@ynu.ac.jp

Postal address: Faculty of Engineering, Yokohama National University, 79-5 Tokiwadai, Hodogaya, Yokohama 240-8501, Japan

ABSTRACT

Further performance improvement in polymer electrolyte fuel cell (PEFC) and their popularization face several problems even though they have been commercialized. The water behavior in PEFCs is closely related to cell performance. To enhance the cell performance, it is necessary to effectively remove the generated water. In this study, to improve the water control in gas channels, a novel gas channel with microgrooves, which are fabricated inside the channel walls, is applied. The generated water is removed through the microgrooves to facing side of the gas channel by capillary and shear forces from air flow. The performance of the PEFC with and without microgrooves was examined in various experimental conditions: cell temperature, relative humidity of gas, and air velocity. It was shown that the PEFC with microgrooves showed better performance than conventional PEFC without microgrooves. In particular, value of current density increased by approximately 16% when the air velocity was 8.0 m/s.

Keywords

Polymer electrolyte fuel cell, Microgrooves, Water management, Flooding, Gas channel

1. Introduction

Moisture management is very important for improving the performance of polymer electrolyte fuel cells (PEFCs). In particular, at a high current density, the generated water increases and accumulates in the gas diffusion layer (GDL) and gas channel at the cathode side. The cell performance decreases significantly because of the generated water, which blocks the oxygen transport. To improve the cell performance, it is necessary to efficiently remove the generated water.

Many attempts have been made to improve the moisture control and removal performance of water at the cathode side; that is, the application of a surface treatment or finish in the GDL or on the inner surface of the gas channel wall has been tested for water management in PEFCs. For example, in studies concerning GDL, hydrophobic material, such as polytetrafluoroethylene (PTFE) and fluorinated ethylene propylene (FEP), have been used to investigate the hydrophobic treatment of GDL [1-4]. Furthermore, the effects of PEFCs with and without a micro-porous layer (MPL), change in the PTFE content [5-7], and the component fraction of hydrophobic and hydrophilic materials [8-10] were also examined. In addition to the hydrophobic treatment of the GDL and coating on the MPL, moisture control using the GDL perforated with laser-cut holes [11, 12] and the multi-layer of hydrophobic and hydrophilic MPLs [13, 14] have been examined. Moreover, to enhance oxygen gas diffusion, the control of water movement using the GDL with planar-distributed wettability has been proposed and examined [15, 16]. Furthermore, the effects of the gas channel and various flow channels - such as parallel, serpentine, interdigitated, and hybrid - have been investigated [17-26]. Considering the special configuration of the flow channel, passive water removal by capillary droplet actuation [27] and the effect of channel wall wettability [28] have also been investigated.

Nomenclature

d	Width of gas channel or microgroove	mm	θ	Crossing angle between microgroove and gas flow
h	Depth of microgroove	mm	V	Cell voltage
P	Pitch of microgroove	mm	Q	Water supply

Subscripts

g	Gas channel	ave	Average
1	Side wall of gas channel	min	Minimum
2	Upper wall of gas channel	max	Maximum
$I = 2.0$	Current density of 2.0 A/cm ²	$I = 4.0$	Current density of 4.0 A/cm ²

2. Results of previous report and objective of this study

To reduce the accumulation of water on the GDL surface, Okabe and Utaka [29] proposed a method in which thin microgrooves, with an axis tilted at an angle with respect to the air flow, are arranged at both side walls and at the upper wall inside the gas channel composed of the GDL surface and separator walls, and excluded its effect. Figure 1 shows the schematic view of water distribution in the case of the proposed method. As shown in Fig. 1(a), in the case of a normal separator, a liquid–gas two-phase flow is formed. Water tends to accumulate on the GDL surface with a large amount of water generation. To reduce the accumulation of water on the GDL surface, the water on the GDL surface and from upstream of the gas channel moves through the opposing surface of the microgrooves to the GDL owing to the capillary and shear forces of the air flow; that is, as shown in Fig. 1(b), microgrooves with an axis tilted at an angle toward the gas flow direction were arranged inside the walls and the upper wall of the gas channel, which is composed of separator inner walls and the GDL surface. The experimental apparatus, which simulates water production by chemical reaction, is shown in Fig. 2. In this apparatus, microgrooves, with a tilted axis, were arranged toward the gas flow direction on the side walls and the upper wall of the gas channel. Two gas channels with a rectangular cross section of $d_g = h_g = 1.0$ and 2.0 mm were prepared. The microgrooves at both side and upper walls were used with a rectangular cross section with a width and depth of $d_1 = 0.2$ mm, $h_1 = 0.2$ mm and $d_2 = 0.3$ mm, $h_2 = 0.2$ mm for two gas channels with cross sections of 1.0 and 2.0 mm, respectively. The crossing angle between the microgrooves and the gas flow direction and pitch of microgrooves are expressed as θ and P , respectively. Experiments were performed under inclination angles of 20, 30, and 45°. The surface velocity of water flow in the microgrooves was measured to clarify the water behavior in microgrooves using the laser-induced fluorescence method (LIF). Figure 3 shows the surface velocity of the water in the mid-height of microgrooves at the side wall. The positive velocity indicates that the water was removed

from the GDL surface. The surface velocity of the water was measured at total length of 200 mm at tilt angle $\theta = 20^\circ$ in the case of water supply rate $Q_I = 2.0$, which denotes that I is 2.0 A/cm^2 in PEFC power generation. Therefore, the arrangement of the microgrooves was confirmed to be effective throughout the gas channel at a total length of 200 mm, which shows that it is possible for microgrooves to be used for actual stack dimensions of PEFCs.

However, because these investigations were focused on the effect of water movement, it is necessary to confirm the effectiveness of microgrooves on the performance of an actual PEFC, in which various phenomena such as generation of water by an electrochemical reaction around the catalyst layer, water evaporation in air at the gas channel, and anode side reaction occur. Therefore, the objective of this study is to confirm the effectiveness of the microgroove arrangement on the enhancement of the power generation of an actual PEFC.

3. Experimental apparatus and method

3.1 Schematic of experimental system

Figure 4 shows a schematic of the experimental system. Pure hydrogen gas and air (approximately 79% nitrogen, approximately 21% oxygen, and approximately 1% argon) were supplied from each gas cylinder to the anode and cathode, respectively. The flow rates of hydrogen and air were controlled by a mass flow controller. Subsequently, they were humidified in a moisture chamber and flowed to the PEFC. To avoid condensation in the pipe between the moisture chamber and PEFC due to cooling, the pipe was heated and covered by an insulator. The temperatures of the separators at the anode and cathode were controlled by water circulated from a constant-temperature bath. For data acquisition of the PEFC performance, the cell voltage and cell resistance were measured by a data logger and an LCR meter, respectively, while the current loaded on the PEFC was kept constant and changed step by step using the electrical load. Finally, the current voltage characteristic and the cell resistance via the current density were obtained.

Figure 5 shows the components of the PEFC. In this study, to investigate the difference between PEFC performances with or without microgrooves, separators with relatively long gas channels were manufactured, considering the application to an actual PEFC. The gas channel of gold plated brass, whose contact angle of water is around 45° , has a rectangular cross section with a width and height of $d_g = h_g = 1.0 \text{ mm}$ and a length of 200 mm. Eleven gas channels were arranged parallel to the reaction area of 42 cm^2 ($21 \text{ mm} \times 200 \text{ mm}$) in membrane electrode assembly (MEA). The carbon paper GDL (Toray Industries, Inc. TGP-H-060) with hydrophobic treatment and MPL application was used. The porosity and thickness of GDL are 78% and 190 μm , respectively. The MPL is made of carbon (2.0 mg/cm^2) and PTFE (2.0 mg/cm^2). The silicone rubber sheet was used at the anode side and the silicone sponge sheet was used at the cathode side as the gaskets.

3.2 Selection of gasket

It is necessary for cell sealing to clamp the MEA at an appropriate pressure between the separators. In addition, precise evaluation of the cell's clamping pressure is essential to secure the measurement reproducibility of the PEFC performance because the clamping pressure is determined by the difference between the load on the gasket and the total load. If the gasket is stiff like typical silicone rubber, the pressure for sealing tends to be larger on the

gasket than on the MEA. Therefore, it will be difficult to determine the precise clamping pressure, and the measurement results will be scattered. Figure 6 shows examples of pressure distribution using pressure measurement film, which was inserted between the separator and the GDL. Figures 6(a) and (b) show the pressure distribution using a silicone rubber sheet of 0.2 mm in thickness and a silicone sponge sheet as the gasket of 1.0 mm in thickness, respectively. The red portion denotes the higher pressure. Figures 6(a) and (b) show the cases of a 22.1 kN load and 1.0 MPa of average clamping pressure, and a 20.9 N load and 1.0 MPa of average clamping pressure on the MEA and gasket, respectively. As Fig. 6(a) shows, because the clamping load is heterogeneously dispersed on the GDL and gasket, it is difficult to precisely determine the clamping pressure on the MEA. Therefore, in this study, to accurately determine the clamping pressure, a gasket material is chosen such that the pressure on the MEA is increased and the clamping pressure on the gasket is relatively decreased. To satisfy such a requirement, the silicone sponge, which is relatively soft and squishy, was selected for the gasket. Figure 6(b) shows that the load is added mainly on the MEA in the case of the silicone sponge. The load on the MEA is determined from the difference between the two loads when the silicone sponge is pressed to the same thickness as the GDL, with MPL using the calibrated relation between the load and the thickness variation of the silicone sponge. As a result, the load fractions on the gasket and MEA were approximately 8% and 92%, respectively, when the clamping pressure was 1.23 MPa. To determine the clamping pressure of the PEFC, the springs were arranged concentrically to every 18 clamping bolts for measuring the axial forces of the bolts by using a spring constant and spring displacement.

3.3 Configuration of gas channel with microgrooves

Figure 7 shows a schematic of the gas channel with microgrooves. Microgrooves, with a 20° axis of tilt angle to the air flow, were arranged on both side walls and the upper wall at 0.4 mm intervals perpendicular to the groove axis. Additionally, these microgrooves were connected to the single groove axially arranged at the center of the upper wall. The width and depth of microgrooves are the same: 0.2 mm. Considering that the water generated accumulates less upstream of the gas channel, the microgrooves were arranged from 50 mm downstream of the gas channel. In addition, the gas channel with microgrooves was applied only to the cathode separator, and the gas channel without microgrooves was used at the anode side. The separator is made from gold-plated brass with a hydrophilic surface.

3.4 Experimental conditions

Table 1 lists the experimental conditions. To evaluate the performance of PEFCs with microgrooves, experiments were performed by changing the cell temperature, relative humidity of the supply gas (both the same for the anode and cathode), and air flow velocity of the supply gas (air). The standard conditions, as shown in boldface text in Table 1, are the cell temperature of 70°C, relative humidity of 70%, and air flow velocity of 6.0 m/s. The standard conditions were kept except for a varied parameter. Air velocity was calculated using the air flow rate before humidification. Furthermore, the rates of utilization and stoichiometry were calculated based on the flow rate of the supply gas at a current density of 2.0 A/cm².

4 Experimental results and discussion

4.1 Effect of clamping pressure on cell performance

Because the power generation of PEFCs depends remarkably on the clamping pressure [30–32], determination of the appropriate clamping pressure is essential for the purpose of this study. To investigate the effect of the clamping pressure on the characteristics of power generation, experiments were conducted by changing the clamping pressure under the standard conditions of the cell temperature of 70°C, relative humidity of 70%, and air flow velocity of 6.0 m/s for comparison. The effect of the clamping pressure on cell performance is shown in Figs. 8 and 9. Figures 8(a) and (b) show the relations between the current density and cell voltage and the power density curve. Figure 9 shows the relation between the current density and cell resistance. Figure 8 shows that the upper limit of the current density and maximum power density increases with increasing clamping pressure up to approximately 1.23 MPa and then decreases. In addition, it was found that the cell resistance decreased with increasing clamping pressure up to 1.23 MPa and became constant or reduced slightly at above 1.23 MPa; this is because the contact resistance of the MEA reduces by clamping the PEFC. However, the concentration overvoltage is increased because the effective porosity is reduced by larger clamping pressure with getting crashed. Therefore, the clamping pressure of 1.23 MPa, at which maximum current density is obtained, was set as the standard condition to examine the effects of cell temperature, relative humidity, and air flow velocity.

4.2 Confirmation of reproducibility

The reproducibility of the PEFC performance was examined using a normal separator without microgrooves under the standard conditions. Figure 10 shows the performance characteristics for two kinds of reproducibility experiments. The first case was performed using different MEAs under the same conditions. In the second case, the same MEA was used and reassembled four times after each performance experiment. The maximum power densities were within 556–588 mW/cm², and the average was 572 mW/cm². Subsequently, the maximum power density was distributed at 2.9% ± 2.7% from the average value. In the range of higher power density, the power densities were easily affected by a concentrated overvoltage and, in general, tended to scatter. However, such a tendency did not occur, and favorable reproducibility was shown—that is, at approximately 1400 mA/cm², the current densities stuck together for both same MEA and different MEA. The current densities were distributed within −2.8% ± 3.2% from the average value at a cell voltage of 0.2 V.

4.3 Effect of cell temperature on cell performance

Experiments were performed after changing the cell temperature from 50 to 90°C. For comparison, two kinds of cathode-side separators, with and without microgrooves, were used. Figures 11(a) and (b) show the variation of the current density against the cell voltage and the power density curve, respectively.

Figure 11 shows that the qualitative tendency was similar with or without microgrooves, and the power density reached maximum at a cell temperature of 70°C. In addition, it was found that the limit of the current density increased and the effect of the concentrated overvoltage could be reduced by the addition of microgrooves. As shown in Fig. 11(a), at a cell temperature of 70°C, the addition of microgrooves can enhance the current

density from 1450 to 1650 mA/cm² when the cell voltage drops sharply to 0.1 V from the concentrated overvoltage. Furthermore, Fig. 11(b) shows that the addition of microgrooves causes the current densities at maximum power densities to increase and be moved to the region of larger current density. The maximum power density increased to 591 mW/cm² after the addition of microgrooves from 585 mW/cm² without microgrooves; an improvement by approximately 3.3%. It was confirmed that the addition of microgrooves inside the gas channel enhanced the removal performance of the water accumulated on the GDL surface, as shown in [Utaka et al. \[29\]](#).

4.4 Effect of relative humidity of supply gas on cell performance

The effect of the relative humidity of the supply gases was investigated, as shown in Fig. 12. Two kinds of cathode-side separators with and without microgrooves were used. Figures 12(a) and (b) show the relations between the current density and cell voltage and between the power density and current density, respectively. The qualitative tendencies were similar despite the arrangement of the microgrooves, and there were appropriate conditions of relative humidity on the power density and current density. The power density increased with increasing relative humidity, and the maximum was reached at 70%; then, this decreased at 100% relative humidity because it was easily influenced by the concentrated overvoltage owing to lack of room for vaporization in the supplied saturated air.

Figure 13 shows the variation of cell resistance with changes in relative humidity. In the range of lower current density, cell resistance decreases with increasing relative humidity because a small quantity of water was generated and the polymer electrolyte membrane (PEM) tended to be dry. Particularly, in the case of relative humidity of 20%, the proton conductivity significantly decreased, and the cell performance also decreased drastically, as shown in Fig. 12. However, in the case of high relative humidity, the cell performance with microgrooves improved compared with the case without microgrooves, similar to the effect of the cell temperature. In the range of relatively lower humidity from 20 to 50%, the maximum power densities with microgrooves were slightly lower than those without microgrooves because it was likely that the proton conductivity was reduced by the enhancement of the drying PEM.

4.5 Effect of air velocity in cathode-side gas channel on cell performance

Figure 14 shows the effect of air velocity in cathode-side gas channels varying from 5.0 to 8.0 m/s on cell performance for two kinds of cathode separators, with and without microgrooves. Figures 14(a) and (b) show the variations in current density and power density against the cell voltage, respectively. The maximum current density and power density increased with increase in air velocity for both cases. Additionally, it was found that in the case of a normal cell without microgrooves, the variation of power density was relatively small with the variation of air velocity for the case without microgrooves. In contrast, the effect of air velocity was significant, and the increasing rate of power density increased with increasing air velocity for the case with microgrooves. Therefore, the water removal due to the arrangement of the microgrooves was enhanced because increasing the air velocity augmented the movement of water by shearing force due to air flow. The addition of microgrooves for an air velocity of 8.0 m/s improved the current density at cell voltage of 0.2 V by 16.1% from 1490 to 1730 mA/cm² and increased the maximum power density by 3.2% from 598 to 617 mW/cm².

4.6 Effect of microgrooves on fluctuation of cell voltage

Because it is possible for microgrooves to rapidly move water, they can be expected to reduce the fluctuation of power density, which is caused by unstable water behavior on the GDL. Experiments were conducted to validate the effect of microgrooves. Figure 15 shows the variation in cell voltage when the stepwise change in current density was given for the cases with and without microgrooves. Experiments were performed under the conditions of a clamping pressure of 1.23 MPa, a cell temperature of 70°C, relative humidity of 70%, hydrogen velocity of 1.2 m/s, and air flow velocity of 8.0 m/s, at which maximum power density was obtained. Figure 15 shows little difference in the fluctuations between the cell voltages with and without microgrooves. However, the fluctuation of the cell voltage was suppressed drastically because of the addition of microgrooves. Figure 16 shows the ratios of voltage fluctuation to those of the average value for the separators with and without microgrooves shown by the error bars. The voltage fluctuations are defined as $(V_{\min} - V_{\text{ave}})/V_{\text{ave}} \times 100$ (%) and $(V_{\max} - V_{\text{ave}})/V_{\text{ave}} \times 100$ (%), where V_{ave} is the average cell voltage, $V_{\min}$ is the minimum cell voltage, and $V_{\max}$ is the maximum cell voltage. It was confirmed that the addition of microgrooves improved the reduction of voltage fluctuation and stabilized the output of cell voltage. Therefore, it is possible that the generated water can be rapidly stabilized by the liquid removal of microgrooves from the GDL surface.

5. Conclusions

To improve water management in gas channels, the configuration of a novel gas channel with microgrooves, which are manufactured inside the gas channel walls, was proposed. This structure was applied to the gas channel of an actual PEFC 200 mm in effective length, and improvement of the PEFC performance was examined experimentally. As a result, the following conclusions were obtained:

- [1] The maximum current density and the maximum power density improved because of the reduction in the concentrated overvoltage using the gas channel with microgrooves. In particular, it was found that the increase in the air velocity was more effective for the improvement of water removal by microgrooves. The densities of the maximum current and power increased by approximately 16.1% and 3.2%, respectively, when the air velocity was 8.0 m/s.
- [2] The voltage fluctuations caused by unstable water behaviors in the cell were reduced drastically and the stability of the cell output was improved because it was possible to quickly move water inside the gas channel by the addition of microgrooves.

Acknowledgments

This work was supported in part by a Grant-in-Aid for Scientific Research [23360097] from the Japan Society for the Promotion of Science (JSPS), the Strategic International Collaborative Research Program of the Japan Science and Technology Agency (JST).

References

- [1] J. Moreira, A. L. Ocampo, P. J. Sebastian, M. A. Smit, M. D. Salazar, P. del Angel, J. A. Montoya, R. Perez and L. Martinez, Influence of the hydrophobic material content in the gas diffusion electrodes on the performance of a PEM fuel cell, *Int. J. Hydrogen Energy*, 28 (2003), pp. 625-627.
- [2] G. G. Park, Y. J. Sohn, T. H. Yang, Y. G. Yoon, W. Y. Lee and C. S. Kim, Effect of PTFE contents in the gas diffusion media on the performance of PEMFC, *J. Power Sources*, 131 (2004), pp. 182-187.
- [3] C. Lim and C. Y. Wang, Effects of hydrophobic polymer content in GDL on power performance of a PEM fuel cell, *Electrochimica Acta*, 49 (2004), pp. 4149-4156.
- [4] K. T. Cho and M. M. Mench, Effect of material properties on evaporative water removal from polymer electrolyte fuel cell diffusion media, *J. Power Sources*, 195 (2010), pp. 6748-6757.
- [5] Z. Qi and A. Kaufman, Improvement of water management by a microporous sublayer for PEM fuel cells, *J. Power Sources*, 109 (2002), pp. 38-46.
- [6] S. Park, J. W. Lee and B. N. Popov, Effect of carbon loading in microporous layer on PEM fuel cell performance, *J. Power Sources*, 163 (2006), pp. 357-363.
- [7] H. K. Atiyeh, K. Karan, B. Peppley, A. Phoenix, E. Halliop and J. Pharoah, *J. Power Sources*, 170 (2007), pp. 111-121.
- [8] S. Park, J. W. Lee and B. N. Popov, Effect of PTFE content in microporous layer on water management in PEM fuel cells, *J. Power Sources*, 177 (2008), pp. 457-463.
- [9] T. Kitahara, T. Konomi and H. Nakajima, Microporous layer coated gas diffusion layers for enhanced performance of polymer electrolyte fuel cells, *J. Power Sources*, 195 (2010), pp. 2202-2211.
- [10] G. Velayutham, Effect of micro-layer PTFE on the performance of PEM fuel cell electrodes, *International J. Hydrogen Energy*, 36 (2011), pp. 14845-14850.
- [11] D. Gerteisen, T. Heilmann and C. Ziegler, Enhancing liquid water transport by laser perforation of a GDL in a PEM fuel cell, *J. Power Sources*, 177 (2008), pp. 348-354.
- [12] M. P. Manahan, M. C. Hatzell, E. C. Kumbur and M. M. Mench, Laser perforated fuel cell diffusion media. Part I: Related changes in performance and water content, *J. Power Sources*, 196 (2011), pp. 5573-5582.
- [13] T. Kitahara, H. Nakajima, M. Inamoto and M. Morishita, Novel hydrophilic and hydrophobic double microporous layer coated gas diffusion layer to enhance performance of polymer electrolyte fuel cells under both low and high humidity, *J. Power Sources*, 234 (2013), pp. 129-138.
- [14] T. Kitahara, H. Nakajima, M. Inamoto and K. Shinto, Triple microporous layer coated gas diffusion layer for performance enhancement of polymer electrolyte fuel cells under both low and high humidity conditions, *J. Power Sources*, 248 (2014), pp. 1256-1263.
- [15] Y. Utaka, I. Hirose and Y. Tasaki, Characteristics of oxygen diffusivity and water distribution by X-ray radiography in microporous media in alternate porous layers of different wettability for moisture control in gas diffusion layer of PEFC, *Int. J. Hydrogen Energy*, 36 (2011), pp. 9128-9138.
- [16] R. Koresawa and Y. Utaka, Improvement of oxygen diffusion characteristic in gas diffusion layer with planar-distributed wettability for polymer electrolyte fuel cell, *J. Power Sources*, 271 (2014), pp. 16-24.
- [17] T. V. Nguyen, A gas distributor design for proton-exchange-membrane fuel cells, *J. Electrochemical Society*, 143 (1996), pp. L103-L105.

- [18] D. L. Wood III, J. S. Yi and T. V. Nguyen, Effect of direct liquid water injection and interdigitated flow field on the performance of proton exchange membrane fuel cells, *Electrochimica Acta*, 43 (1998), pp. 3795-3809.
- [19] F. B. Weng, A. Su, C. Y. Hsu and C. Y. Lee, Study of water-flooding behaviour in cathode channel of a transparent proton-exchange membrane fuel cell, *J. Power Sources*, 157 (2006), pp. 674-680.
- [20] S. S. Hsieh, S. H. Yang and C. L. Feng, Characterization of the operational parameters of a H₂/air micro PEMFC with different flow fields by impedance spectroscopy, *J. Power Sources*, 162 (2006), pp. 262-270.
- [21] W. M. Yan, C. H. Yang, C. Y. Soong, F. Chen and S. C. Mei, Experimental studies on optimal operating conditions for different flow field designs of PEM fuel cells, *J. Power Sources*, 160 (2006), pp. 284-292.
- [22] S. Shimpalee, S. Greenway and J. W. Van Zee, The impact of channel path length on PEMFC flow-field design, *J. Power Sources*, 160 (2006), pp. 398-406.
- [23] X. Li, I. Sabir and J. Park, A flow channel design procedure for PEM fuel cells with effective water removal, *J. Power Sources*, 163 (2007), pp. 933-942.
- [24] C. Xu and T. S. Zhao, A new flow field design for polymer electrolyte-based fuel cells, *Electrochemistry Communications*, 9 (2007), pp. 497-503.
- [25] W. M. Yan, H. Y. Li, P. C. Chiu and X. D. Wang, Effects of serpentine flow field with outlet channel contraction on cell performance of proton exchange membrane fuel cells, *J. Power Sources*, 178 (2008), pp. 174-180.
- [26] K. S. Choi, H. M. Kim and S. M. Moon, An experimental study on the enhancement of the water balance, electrochemical reaction and power density of the polymer electrolyte fuel cell by under-rib convection, *Electrochemistry Communications*, 13 (2011), pp. 1387-1390.
- [27] T. Metza, N. Paust, C. Muller, R. Zengerle and P. Koltay, Passive water removal in fuel cells by capillary droplet actuation, *Sensors and Actuators A: Physical*, 143 (2008), pp. 49-57.
- [28] A. Turhan, S. Kim, M. Hatzell and M. M. Mench, Impact of channel wall hydrophobicity on through-plane water distribution and flooding behavior in a polymer electrolyte fuel cell, *Electrochimica Acta*, 55 (2010), pp. 2734-2745.
- [29] Y. Utaka, A. Okabe and Y. Omori, Proposal and Examination of Method of Water Removal from Gas Diffusion Layer by Applying Slanted Microgrooves inside Gas Channel in Separator to Improve Polymer Electrolyte Fuel Cell Performance, *Journal of Power Sources*, 279 (2015), pp. 533-539.
- [30] W. K. Lee, C. H. Ho, J. W. Van Zee and M. Murthy, The effects of compression and gas diffusion layers on the performance of a PEM fuel cell, *J. Power Sources*, 84 (1999), pp. 45-51.
- [31] W. R. Chang, J. J. Hwang, F. B. Weng and S. H. Chan, Effect of clamping pressure on the performance of a PEM fuel cell, *J. Power Sources*, 166 (2007), pp. 149-154.
- [32] T. Ous and C. Arcoumanis, Effect of compressive force on the performance of a proton exchange membrane fuel cell, *Proceedings of the Institution of Mech. Eng., Part C: J. Mech. Eng. Science*, 221 (2007), pp. 1067-1074.

Figure Captions

Fig. 1. Schematic of water behavior through microgrooves from GDL.

Fig. 2. Details of microgroove structure.

Fig. 3. Variation of water velocity in microgrooves against distance ($I = 2.0$ and 4.0 A/cm^2).

Fig. 4. Schematic of experimental system.

Fig. 5. Electrolyte fuel cell apparatus.

Fig. 6. Example of pressure distribution using pressure measurement film.

(a) Silicone rubber sheet.

(b) Silicone sponge rubber.

Fig. 7. Schematic of gas channel with microgrooves.

Fig. 8. Effect of clamping pressure on cell performance (relative humidity 70%, cell temperature 70°C)

(a) Current density–versus–cell voltage curve.

(b) Power density curve.

Fig. 9. Variation of cell resistance with variation of clamping pressure (relative humidity 70%, cell temperature 70°C)

Fig. 10. Evaluation of reproducibility (relative humidity 70%, cell temperature 70°C)

(a) Current density–versus–cell voltage curve.

(b) Power density curve.

Fig. 11. Effect of cell temperature on cell performance (relative humidity 70%)

(a) Current density–versus–cell voltage curve.

(b) Power density curve.

Fig. 12. Effect of relative humidity on cell performance (cell temperature 70°C)

(a) Current density–versus–cell voltage curve.

(b) Power density curve.

Fig. 13. Variation of cell resistance with variation of relative humidity (cell temperature 70°C)

Fig. 14. Effect of air velocity on cell performance (relative humidity 70%, cell temperature 70°C)

(a) Current density–versus–cell voltage curve.

(b) Power density curve.

Fig. 15. Time variation of cell voltage with variation of current density in non-steady state (relative humidity 70%, cell temperature 70°C)

Fig. 16. Variation of voltage fluctuation (relative humidity 70%, cell temperature 70°C)

Table Caption

Table 1 Experimental conditions.

Fig. 1. Schematic of water behavior through microgrooves from GDL.

Fig. 2. Details of microgroove structure.

Fig. 3. Variation of water velocity in microgrooves against distance ($I = 2.0$ and 4.0 A/cm^2).

Fig. 4. Schematic of experimental system.

Fig. 5 Polymer electrolyte fuel cell apparatus.

(a) Silicone rubber sheet.

(b) Silicone sponge rubber.

Fig. 6. Example of pressure distribution using pressure measurement film.

Fig. 7. Schematic of gas channel with microgrooves.

Table 1 Experimental conditions

Flow design	Parallel
Gas channel width (mm)	1
Gas channel depth (mm)	1
Rib width (mm)	1
Active electrode area (geometric) (cm ²)	2.1 × 20
Clamping pressure (MPa)	1.23
Cell temperature (°C)	50, 70 , 80, 90
Relative humidity (%)	20, 50, 70 , 100
Gas velocity (flow rate)	
Hydrogen, m/s (mL/min)	1.2 (800)
Hydrogen utilization (stoichiometry)	0.80 (1.25)
Air, m/s (mL/min)	5.0 (3300), 6.0 (3960) , 7.0 (4620), 8.0 (5280)
Air utilization (stoichiometry)	5.0 m/s: 0.46 (2.17), 6.0 m/s: 0.38 (2.60) 7.0 m/s: 0.33 (3.04), 8.0 m/s: 0.29 (3.47)

(a) Current density-versus-cell voltage curve.

(b) Power density curve.

Fig. 8. Effect of clamping pressure on cell performance (relative humidity 70%, cell temperature 70°C)

Fig. 9. Variation of cell resistance with variation of clamping pressure (relative humidity 70%, cell temperature 70°C)

Fig. 10. Evaluation of reproducibility (relative humidity 70%, cell temperature 70°C)

Fig. 11. Effect of cell temperature on cell performance (relative humidity 70%)

Fig. 12. Effect of relative humidity on cell performance (cell temperature 70°C)

Fig. 13. Variation of cell resistance with variation of relative humidity (cell temperature 70°C)

(a) Current density–versus–cell voltage curve.

(b) Power density curve.

Fig. 14. Effect of air velocity on cell performance (relative humidity 70%, cell temperature 70°C)

Fig. 15. Time variation of cell voltage with variation of current density in unsteady state (relative humidity 70%, cell temperature 70°C)

Fig. 16. Variation of voltage fluctuation (relative humidity 70%, cell temperature 70°C)