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Article

Experimental Study on Improvement of Performance by Wave Form at Cathode Channels in PEM Fuel Cell

Sun-Joon Byun [1], Zhen Huan Wang[2] Jun Son[2], Young-Chul Kwon [3,*] and Dong-Kurl Kwak [4,*]

[1] SFR NSSSS System Design Division, Korea Atomic Energy Research Institute, 111 Daedeok-daero 989 beon-gil, Yuseong-gu, Daejeon 34057, Republic of Korea; bjky21@korea.ac.kr (S. -J.B)
[2] Graduate student, Department of Mechanical Engineering, Sunmoon University,70 sunmoon-ro 221 beon-gil, Tangjeong-myeon, Asan-si, Chungcheongnam-do 31460, Republic of Korea; hjkang@sunmoon.ac.kr(H.-J.K.), huan_2014@nate.com(Z.-H.W), johnyck0218@gmail.com(J.S)
[3] Department of Mechanical Engineering, Sunmoon University,70 sunmoon-ro 221 beon-gil, Tangjeong-myeon, Asan-si, Chungcheongnam-do 31460, Republic of Korea; yckweon1@sunmoon.ac.kr (Y.-C.K)
[4] Graduate School of Disaster Prevention, Kangwon National University, 346 joongang-ro, samcheck-si, Gangwon-do 25913, Republic of Korea; dkkwank@kangwon.ac.kr (D.-K.K)

* Correspondence: yckweon1@sunmoon.ac.kr (Y. –C. Kwon); Tel.: +82-41-530-2396;
dkkwak@kangwon.ac.kr (D. –K. Kwak); Tel.: +82-33-570-6823.

Abstract: We propose a wave-like design on the surface of cathode channels (wave form cathode channels) to improve oxidant delivery to gas diffusion layers (GDLs) [1-2]. We performed experiments using PEMFCs combined with wave form surface design on cathodes. We varied the factors of the distance between wave-bumps (the Adhesive distance, AD), and the size of the wave-bumps (the Expansion ratio, ER). The ADs are 3, 4, and 5 times the size of the half-circle bump's radius, and the ERs are 1/1.5, 1/2, and 1/3 times the channel's height. We evaluated the performances of the fuel cells, and compared the current-voltage (I-V) relations. For comparison, we prepared PEMFCs with conventional flat-surfaced oxygen channels. Our aim in this work is to identify fuel cell operation by modifying the surface design of channels, and ultimately to find the optimal design of cathode channels that will maximize fuel cell performance.

Keywords: Wave form, PEMFC, Cathode channel, Gas diffusion layer (GDL), Adhesive distance (AD), Expansion ratio (ER)

Nomenclature

F	Force, N
T	Temperature, ℃
RH	Relative Humidity, %
Q	Flow rate, kg/s
T	Time
P	Operating Pressure, kPa
W	Work
u	Velocity component, m/s
R	Radius, m
V	Voltage, V

CD	Current density, A/cm^3
GDL	Gas Diffusion Layer
MEA	Membrane Electrode Assembly

Greek symbols

λ	Stoichiometry
ρ	Density, kg/m^3
σ	Surface tension, N/m

Subscripts

a	Air
g	Gas
act	Activation
sat	Saturated
c	Cell
gen	Generating force
adh	Adhesion
r	Radiation
in	Inlet
out	Outlet
h	Hydrostatic
fore	Force contact angle

1. Introduction

Most of the energy we use is obtained from fossil fuels. However, reserves of fossil fuels will soon reach their limits. Also, the problems of environmental pollution and climate change due to fossil fuel usage have raised the need to develop new energy sources. Thus, study on developing various renewable energy sources is being conducted. The South Korea government is also actively supporting the development of various renewable energy resources. Energy alternatives, including wind energy, solar cells, and fuel cells, are under development. In fuel cell research, researchers are addressing flow field patterns to supply fuel and oxygen more effectively. Since the internal structure in a fuel cell cannot be directly observed, measurement is difficult.

So, research combining computational analysis with experimentation is active. Looking at some of the leading research, Springer *et al*. [3] conducted experiments using Nafion 117 membrane to observe various phenomena, including the electro-osmotic drag phenomenon, and presented parameters of membranes in constant humidity condition, using equations based on the values obtained from their experiments. Natarajan and Nguyen [4] suggested a numerical analysis method of fuel cell flow regarding 2 phase flow, and verified that the fuel cell performance improved in thinner Gas diffusion layer (GDL) and higher porosity. Yoon *et al*. [5] conducted experiments varying the PEMFC Rib thickness and channel form. Variance of fuel cell performance according to rib width was observed, due to its effect on fuel and air diffusion. Fuel cell performance was improved with smaller rib width, because the diffusion of gas to electrode was improved. Kuo *et al*. [6-8] conducted three-dimensional numerical analysis regarding velocity and temperature distribution in the PEMFC channel using wave-like and ladder-like surfaces, thus comparing the current density (CD) with that of the normal surface, to improve performance.

Li and Sabir [9] introduced the separation plate design and latest flow path design made by various research institutions. Also problems were identified, and several suggestions were made regarding the optimization of each channel pattern. Su *et al*. [10] analyzed the fuel cell performance of a straight channel pattern and the S-shaped pattern of a serpentine channel for PEMFC, through three-dimensional computational analysis and experiment. The channel with S-shaped serpentine patterns showed higher mass transfer performance than the channel with straight pattern. Perng and Wu [11] compared fuel cell performance through computational analysis of flow field characteristics in the catalyst layer surface and inside channel, using different forms in the GDL of PEM fuel cells. In addition, they varied the number of forms, to compare the flow characteristics and fuel cell performance [12].

This study suggests design factors of the amplitudes and pitches of waves, to effectively improve the catalysis reaction performance in the catalyst layer, and verifies the effectiveness of this method, by evaluating the performance of the PEM fuel cell. This study provides the design factors and conditions that are necessary for improving the performance of the PEM fuel cell, as information for determining the optimized design of the cathode channel of the PEM fuel cell.

The purpose of this study is to suggest contemporary alternatives to reduce the concentration loss. For this reason, we examined the performance according to variations of the heights and distances of the wave form, and the changes of variations induced by the suppression of concentration loss. We fabricated the optimized channel, which was verified by experiment, as a unit cell of the PEM fuel cell, to compare the performance of the optimized channel with those of other channels.

2. Theoretical Background

2.1. Polarization curve

Equation (1) demonstrates three voltage losses. First, activation loss depends on the activation levels of the electrochemical reactions. Ohmic loss is the resistance loss induced by the unique resistances of the components of the fuel cell. Concentration loss occurs when the reaction rates of hydrogen and oxygen are faster than their supply rates.

$$V = E_{thermo} - \eta_{act} - \eta_{ohmic} - \eta_{conc} \quad (1)$$

Among these, mass transfers of hydrogen and oxygen occur during concentration loss through the GDLs in the channels. The GDLs have low permeability, and minimal convection effects [13].

In Figure 1, c_R^* and c_P^* represent the catalyst layer reactant and product concentrations, respectively, and c_R^0 and c_P^0 represent the bulk reactant and product concentration, respectively. δ represents the thickness of the GDLs. The fuel cell begins producing current at time $t = 0$. Starting from constant initial values (c_R^0 and c_P^0), the reactant and product concentration profiles evolve with increasing time, as shown for $t_1 < t_2 < t_3$. Eventually, the profiles approach a steady-state balance, where concentration varies linearly with distance across the diffusion layer. The diffusion flux created according to this linear concentration gradient in the steady-state accurately balances in the catalyst layer. Eq. (2) defines this balance.

$$j = nFJ_{diff} \quad (2)$$

Here, j is the CD in the fuel cell, and J_{diff} is the diffusion flux of a reactant transferred to the catalyst layer. J_{diff} is defined as in Equation (3).

$$J_{diff} = -D\frac{dc}{dx} \quad (3)$$

The steady-state of this equation is defined as Equation (4).

$$J_{diff} = -D^{eff}\frac{c_R^* - c_R^0}{\delta} \quad (4)$$

The diffusion flux of a reactant according to CD in the steady-state can be calculated by substituting Equation (4) into Equation (2).

$$j = -nFD^{eff}\frac{c_R^* - c_R^0}{\delta} \quad (5)$$

$$c_R^* = c_R^0 - \frac{j\delta}{nFD^{eff}} \quad (6)$$

Here, c_R^0 is always less than c_R^*, and the consumption rate of a reactant increases as j increases, leading to a concentration loss in the area of high-CD. The j value becomes greatest when $c_R^* - c_R^0$ is zero, which is called the limiting CD [14].

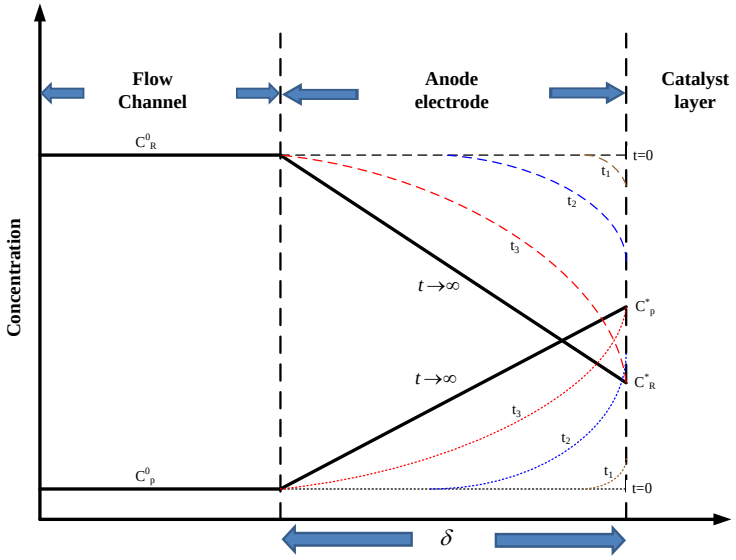

Figure 1. Schematic variation of a fuel cell reactant and product concentration according to time [14].

2.2. *Factors for displacement in the wave form channels*

In order to reduce concentration loss in the area of high CD, alternatives to improve mass transfers are suggested in this study. The bottoms of the channels were fabricated to have a wave shape, to create a greater flow velocity gradient in the GDLs, and to suppress the concentration loss induced by unstable mass transfers, in order to improve the performance of the fuel cell.

The amplitudes and pitches of the waves determine the pattern of wave channels [15], as shown in Figure 2. The ER is defined as the ratio of the channel height to the channel amplitude, and the AD is defined as the ratio of the pitch (the distance between one crest and the following crest) to the amplitude.

$$ER = H / h \quad (7)$$

$$AD = L / h \quad (8)$$

In order to verify the effect of the ER and AD, the effect of the variance of AD is considered.

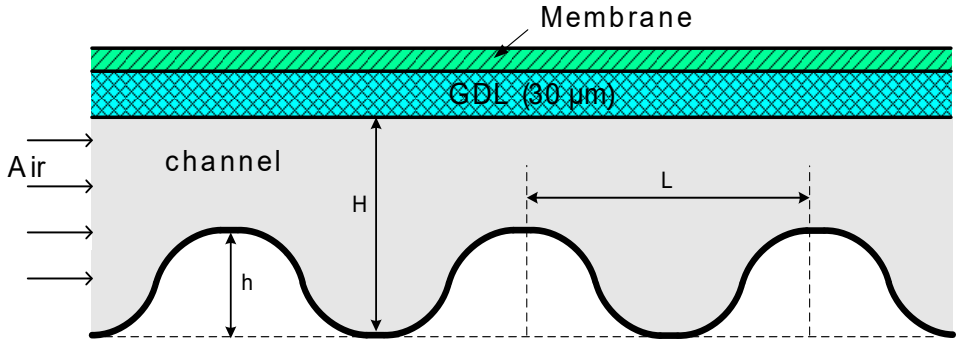

Figure 2. The parameters of a wave form channel.

3. Experimental Method

3.1. *Experimental apparatus*

The efficiency of the PEMFC is affected by the stoichiometry at the cathode, temperature of the cell outlet, pressure difference between the inlet and outlet of the cell, and channel depth [16]. To block the drying effect caused by high-temperature air, the PEMFC humidifies all of the air and hydrogen, before they are supplied to the unit cell. This type of water produced by the electro-chemical reaction induces channel flooding. To determine the effects of stoichiometry, temperature of the cell outlet, and differential pressure on flooding, an experimental apparatus was set up, as shown in Figure 3. A mass flow controller (MFC) adjusted the flow rates of air and hydrogen, and passed the adjusted flow rate of air and hydrogen through each humidifier, to maintain the appropriate humidity. By controlling the humidifier temperature, the relative humidity at the inlet was maintained at an appropriate level.

Figure 4 shows a schematic of the fuel cell experimental apparatus. The flow rate and relative humidity of reactant gases controlled by the MFC and the humidifier must maintain appropriate temperatures before they enter the unit cell. To maintain the fixed temperature of the humidified air and hydrogen, a line heater was placed at the entrance of the cell. The fixed temperature of reactant gases controlled by the line heater can vary from heat transfer within the unit cell. To prevent such changes, a heater was inserted into the unit-cell endplate, and a thermocouple was placed in the bipolar plate, to maintain the bipolar temperature of the unit cell. To measure the inlet temperature and outlet temperature of the cell, T-type thermocouples were inserted at the inlet and outlet of the cell. The inlet pressure and the outlet pressure were measured by a pressure transducer installed at the inlet, and a differential pressure transducer installed at the outlet of the cell, respectively. Data received from the pressure transducer, differential pressure transducer, and thermocouple were recorded by a channel recorder (fluke), and transmitted to the computer by the network connection process.

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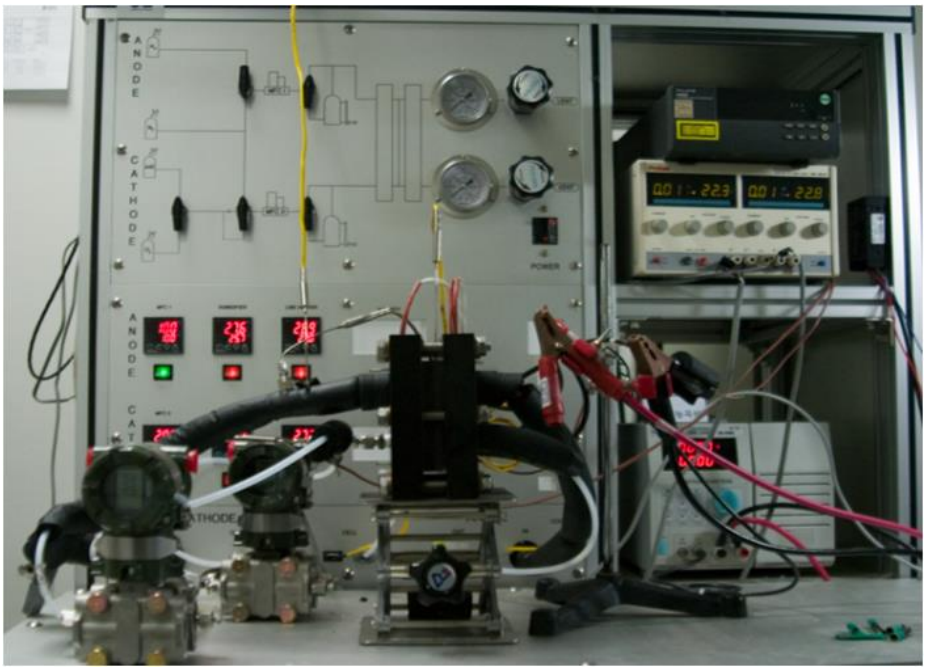


Figure 3. Experimental apparatus of the fuel cell system.

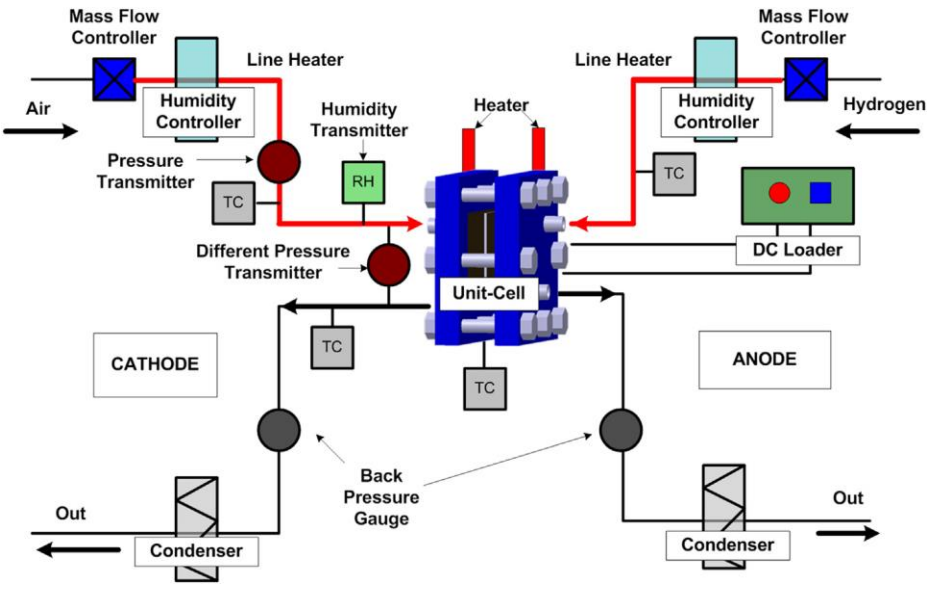


Figure 4. Parameters of a wave form channel.

A differential pressure transducer (Model-EJA110A, Yokogaya Co.) and pressure transducer (Model-EJA530A, Yokogaya Co.) were used for measurement. The accuracy of the devices was ±0.075 per cent. A 1 l/5 l mass flow meter was used to control the flow rate of the anode and cathode. An electronic load (model ESL-300Z, E.L.P. Tek Co.) was used to power the experiment on the fuel cell system: the maximum power was 300W, and maximum electric current was 60A. Experiments could be carried out at a fixed electric current, fixed voltage, and fixed reaction, with an accuracy of ±0.1%. Using an exterior signal, we could simulate the unit-cell response feature and output feature. The specifications of the experimental device are similar to those shown in Table 1.

Table 1. Specifications of the measurement devices

	Location	Manufacturer	Model No.	Accuracy
Pressure transducer	Cathode inlet	YOKOGAWA	EJA530A	±0.075%
Differential pressure transducer	Cathode	YOKOGAWA	EJA110A	±0.075%
Electronic load		E.L.P. Tek	ESL-300Z	±0.1%
Mass flow controller	Anode and cathode	Bronkhorst High-Tech	EL-flow F-201C	0.5%
Thermocouple	Test section	Omega Engineering Inc.	T-type	0.5°C or 0.4%
Humidity	Cathode inlet	VAISALA	HMT 337	±1.5%

3.2. *Experimental conditions*

To measure fuel cell performance, the apparatus was stabilized for 30 minutes in steady state, where humidity, temperature and pressure were maintained constant at the inlet and outlet. The temperature and pressure at the inlet and outlet, relative humidity, unit cell temperature, and open circuit voltage were measured every 1 second. Relative humidity in the unit cell was controlled by controlling the humidifier temperature, and the relative humidity of the humidified air was measured with a hygrometer installed at the cathode inlet.

To operate the unit fuel cell with an operational temperature of 50°C, the unit cell temperature was set to 54°C, so the inlet and outlet temperature were maintained constant for 30 minutes, before the actual measurement. If the calculated humidity and the relative humidity measured by hygrometer differed, the humidifier temperature was adjusted to achieve the desired relative humidity. During the experiment, the relative humidity was maintained at 50%, 75%, and 90%, respectively, and the error range was maintained within ±0.2%.

In this study, pure hydrogen gas and compressed air were used, with stoichiometry of 1.5 pure hydrogen, and 2.0 compressed air, respectively. The variance of fuel cell performance was observed for both cases of fixed pure hydrogen stoichiometry and varied air stoichiometry, and fixed air stoichiometry and varied pure hydrogen stoichiometry. Figure 5 shows a view of the channel shape used in the unit cell performance experiment. The basic channel shape was a serpentine 5 channel, of total area 50 mm × 50 mm, and separation plate area of 80 × 80 mm. To make the diffusion of reaction gases faster, the rib width was 0.5 mm, so it had as small a value as possible, and the channel width was 0.9 mm.

Thus, as shown in Figure 2, this study varied the design parameters ER and AD of the wave form channel, to produce the cathode channel shapes shown in Figure 6 and Figure 7.

4. Results and Discussion

4.1. *Fuel cell performance variation according to the ER variation*

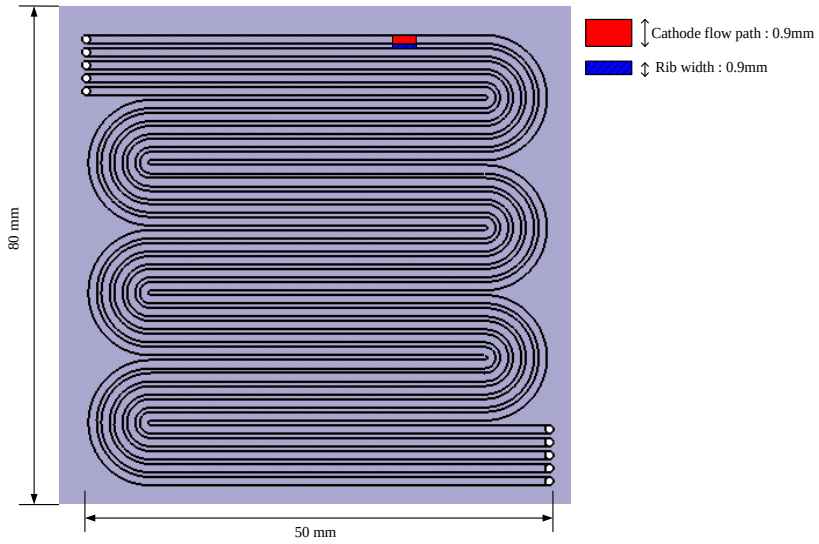
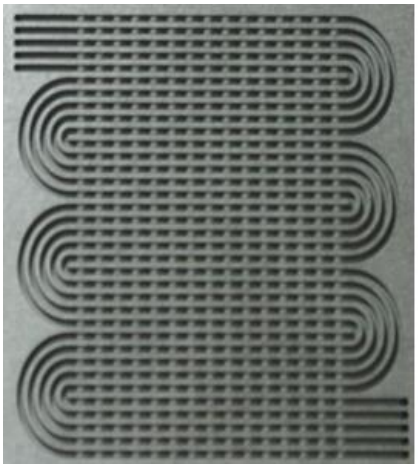


Figure 5. Schematic of the unit-cell channel shape.



(a) ER 1.5

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(b) ER 2.0 (c) ER 3.0

Figure 6. Bipolar plates of the gas flow cathode channels with the three wave form ERs.

(a) AD 4.0

(b) AD 5.0 (c) AD 6.0

Figure 7. Bipolar plates of the gas flow cathode channels with the three wave form ADs.

The fuel cell performance in the normal cathode channel of width and height 0.9 mm × 0.9 mm, with aspect ratio 1, was compared with that of the wave form channel where the ER varied between 1.5, 2.0, and 3.0. The conditions for the fuel cell performance experiment were fuel cell reaction gas temperature of 50°C, relative humidity of 75%, fuel side stoichiometry of 1.5, and cathode side stoichiometry of 2.0.

Figure 8 shows the fuel cell performance according to variation of the Expansion ratio (ER). In the normal channel, the maximum power output was around 11.9W, while the improvements of maximum power output in the wave form channel were around 21% for ER 1.5, 20% for ER 2.0, and 6% for ER 3.0. The cause of this improvement in maximum power output was the high air concentration maintained at the catalyst layer and GDL. In the high CD region between CD 0.8 ~ CD 1.4, the normal channel shows a rapid decrease of power output at CD 1.2, while the wave form

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channel shows a sluggish decrease of power output. This sluggish decrease is caused by reduction of concentration loss.

Figure 9 shows the pressure difference between inlet and outlet in the unit cell. The wave form channel shows a higher pressure difference, compared to that of the normal channel. The fuel cell performance in wave form channels ER 1.5 and ER 2.0 are similar, but rapid pressure increase is observed in ER 1.5. The rapid increase in pressure contributes to overall loss in the system, and demands higher apparatus durability.

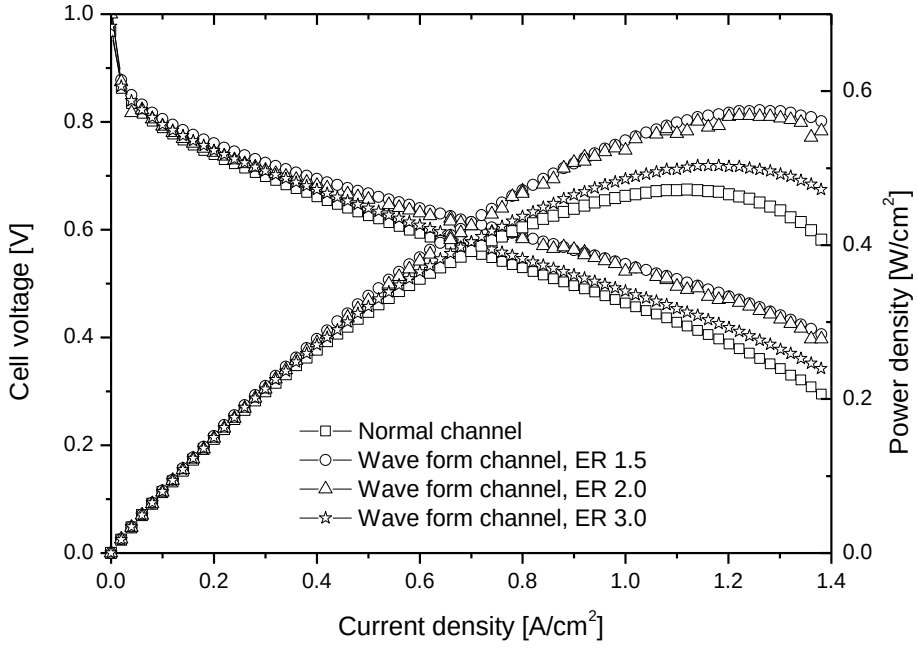


Figure 8. Bipolar plate of gas flow cathode channel with wave form AD.

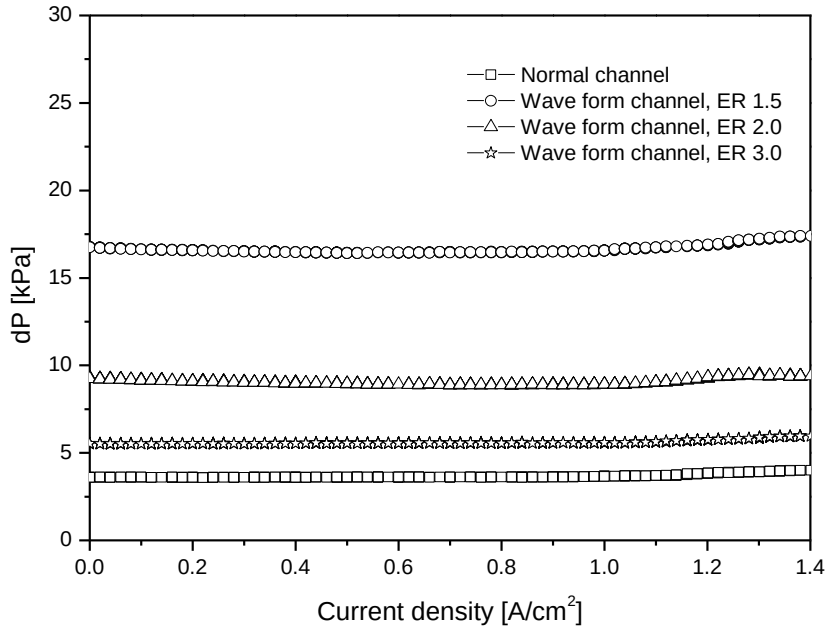
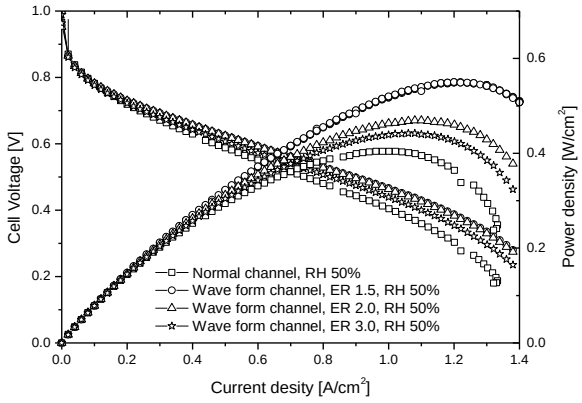


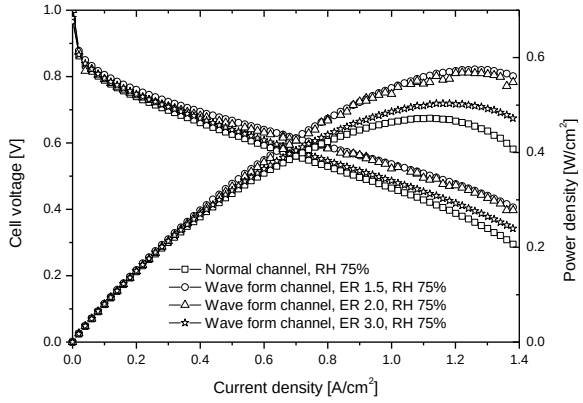
Figure 9. Unit cell difference curve in the normal channel and wave form channel, according to the variation in ER.

Figure 10 shows the fuel cell performance curves according to variation in the relative humidity. Figure 10(a) shows the performance curves of the normal channel and wave form channel with various ER, with Relative Humidity (RH) of 50%. As the ER increases, the unit cell performance with respect to maximum power output increases by around 7 ~ 15%. In the high CD region with CD over 1.2, the power density and cell voltage were unstable in the normal channel, but showed a stable trend in the wave form channel. Figure 10(b) shows an insignificant difference in performance between ER 2.0 and ER 1.5 with relative humidity 75%, and the unit cell pressure difference increases greatly, as ER increases. Figure 10(c) shows the fuel cell performance of the wave form channel increases by about 8 ~ 17%, compared to the normal channel, in RH 90, and the performances are similar in ER 2.0 and ER 1.5. Thus, in the wave form channels, the maximum power density and high CD increase, as the relative humidity increases. Low concentration and mass transport of catalyst reactants in high CD are overcome by changing the flow inside the channel, by applying the wave form channel, thus resulting in improvement of fuel cell performance.

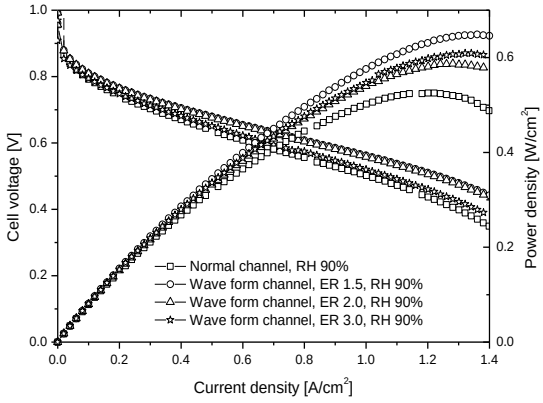
Figure 11 shows the pressure difference inside the normal channel and wave form channel, with varied ER. But after a certain increase of ER, the fuel cell performance is not much influenced, and we predict that increase of the internal pressure might cause system instability.



(a) RH 50%



(b) RH 75%



(c) RH 90%

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298 Figure 10. Performance curve of the normal channel and wave form channel, according to variation
299 in ER at constant relative humidity.

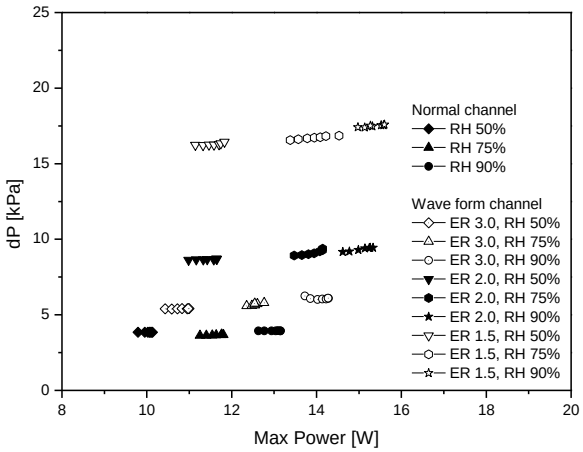
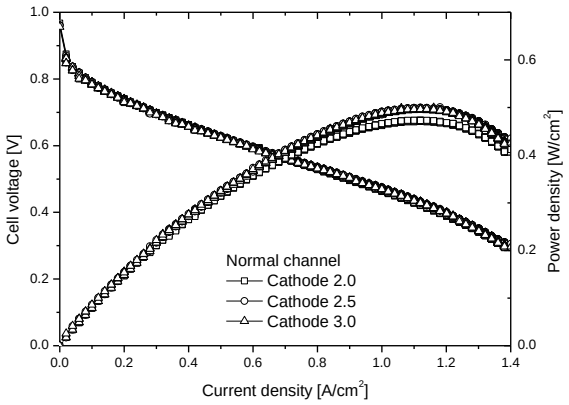
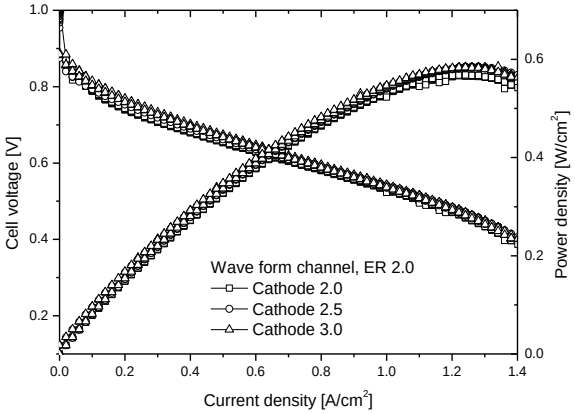


Figure 11. Pressure difference between the normal channel and wave form channel, with varied ER.



300
301 (a) Normal channel



302
303 (b) Waveform channel, ER 2.0

Figure 12. Pressure curve according to variation in stoichiometry at cathode of the normal channel and wave form channel

Figure 12 shows the fuel cell performance according to cathode stoichiometry variation. With stoichiometry of 1.0, the supply of reactant at the outlet is insufficient, due to the reactant gas reaction; thus, the reactant gas must be supplied to the fuel cell at an excessive rate, compared to the exact reacting amount, due to various losses.

This study conducted the fuel cell performance experiment with anode stoichiometry of 1.5, ER 2.0, and fixed RH of 75%. The cathode stoichiometry varied between 2.0, 2.5, and 3.0, in the normal channel and wave form channel.

In Figure 12(a), the performances under CD 0.8 do not vary much, due to increases in the cathode stoichiometry. But in high CD over 1.0, the differences are noticeable. The results suggest cathode stoichiometry of 2.0 is sufficient in the low CD region, while in the high CD region, the reactant supply is not fluent, due to concentration loss, thus yielding no increases in fuel cell performance when the stoichiometry is increased.

Figure 12(b) shows the fuel cell performance of wave form channel ER 2.0, as the cathode stoichiometry varies. Increasing the wave form channel cathode stoichiometry yielded a 2% increase, compared to the maximum power density. The result indicates sufficient reactant supply was achieved in the catalyst layer and GDL of the wave form channel.

Figure 13 shows the pressure difference of the wave form channel and normal channel, according to the change of cathode stoichiometry. The wave form channel shows higher performance compared to the normal channel, and ER 1.5 and ER 2.0 show similar performance, but high pressure difference is observed in the case of ER 1.5. Thus it can be deduced that a fuel cell system stability problem and internal resistance loss can arise, when high pressure difference occurs.

4.2. *AD variation and fuel cell performance*

We varied the wave form channel design parameter AD during the experiment, to select the optimal AD, by comparing the performance with that of the normal channel. ER is fixed during the experiment. The size of ER is related to the increase of reactant internal flow at the catalyst layer and

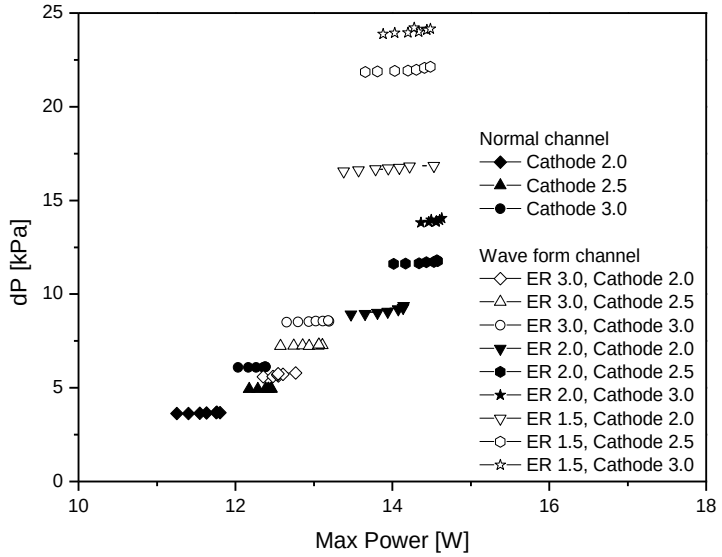
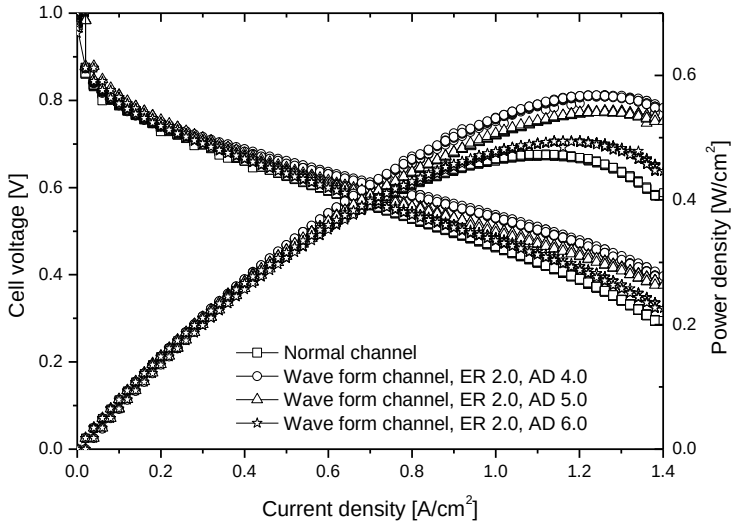
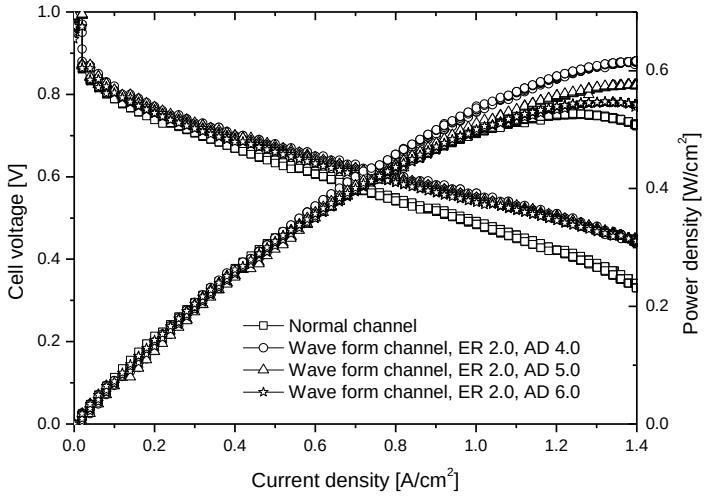


Figure 13. Pressure difference of the normal channel and wave form channel with varied ER, according to variation in the cathode stoichiometry.



(a) RH 75%

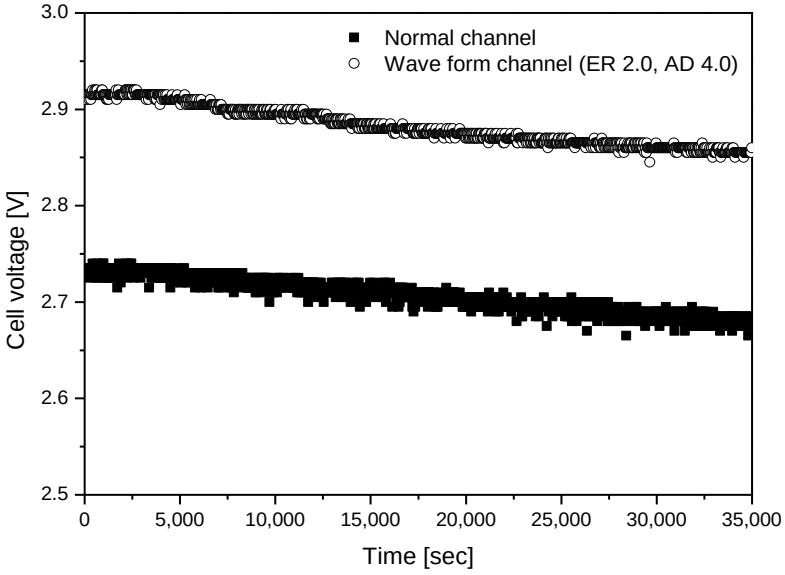


(b) RH 90%

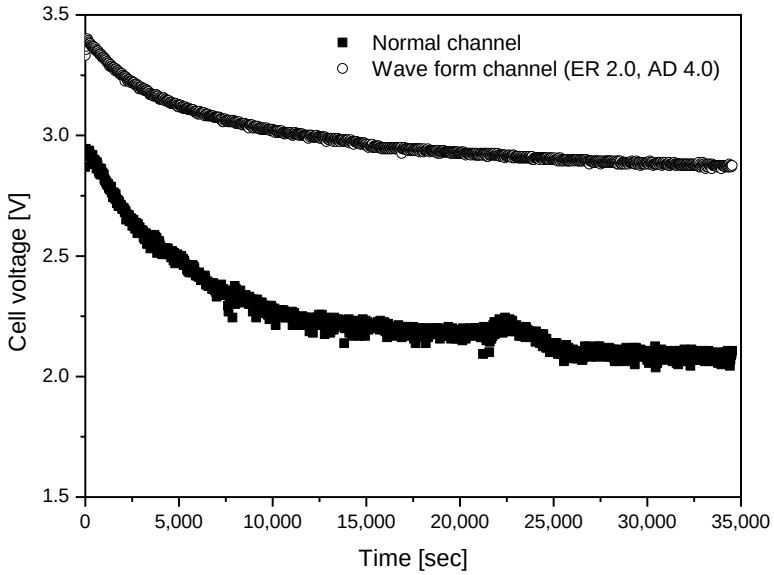
Figure 14. Pressure difference of the normal channel and wave form channel with varied ER, according to variation in the cathode stoichiometry.

GDL inside the channel, while AD reattaches the distance maintained at a certain value, so that the channel internal flow is prevented from steady-state, thus increasing the reactant flow. The experimental conditions in this study were anode stoichiometry of 1.5, cathode stoichiometry of 2.0, operating temperature of 50°C, and ER of 2.0.

Figure 14 shows performance curves of the normal channel and wave form channel with varied AD. As the AD distance increases, the improvement of performance compared to the normal channel decreases. This indicates the mass transport of reactants decreases, as the wave form distance increases. Also, the increase of relative humidity contributes to improvement in the fuel cell performance. We conducted experiments in the wave form channel by varying the ER and AD, to determine the optimal wave form channel shape for ER 2.0 and AD 4.0.



(a) CD 0.8



(b) CD 1.0

Figure 15. Performance curve of the normal channel and wave form channel operated for 10 hours, at CD 0.8 and 1.0.

Figure 15 shows the results of the reliability experiment in high CD. Generally in the high CD region, MEA degradation, Platinum catalyst poisoning, and the flooding phenomenon cause rapid reduction of fuel cell performance.

Figure 15(a) shows the performance of the normal channel and ER 2.0, AD 4.0 wave form channel at CD 0.8, during 10 hour operation. At CD value 0.8, both the normal channel and wave form channel showed around 3% performance decrease, which is insignificant. But in the same CD, the power and

voltage varied more in the wave form channel, than in the normal channel. This indicates the wave form channel is more reliable than the normal channel.

Figure 15(b) shows the time-wise fuel cell performance variation in the normal channel and wave form channel, with CD value 1.0. The performance in all channels is lower than that of CD of value 0.8. Also, the power and voltage variations are greater in the normal form channel, than in the wave form channel at the same CD. But as time passes, the wave form channel shows stable values, while the normal channel shows great decrease after 6 hours. After 10 hours of operation, the voltage in the normal channel reduces by 0.12 V, and the performance reduces by around 28%; while in the wave form, the voltage reduces by 0.7 V, and performance by around 14%. These results suggest that concentration polarization at high CD is minimized in the wave form channel, leading to improvement in the fuel cell performance.

5. Conclusions

This study conducted experiments to improve fuel cell performance, by increasing the mass transport and partial pressure in the fuel cell cathode. We determined the design parameters to yield the optimal wave form shape to be the wave form channel height and wave form shape size ratio, and wave form distance in the cathode channel. The results of the wave form channel fuel cell performance experiments are as follows

(1) We fixed the RH at 75%, with operating temperature of 50°C, anode stoichiometry of 1.5, and cathode stoichiometry of 2.0, while varying the wave form channel parameter ER, in the unit cell performance experiment. Our results show that as the size of the wave form shape increased from ER 1.5 to ER 3.0, the maximum power performance increased by around 6%, 20%, and 21%, respectively, compared to the normal channel.

(2) We varied the reactant RH between 50%, 75%, and 90%, to compare fuel cell performance. As the RH increased, the wave form channel performance showed around 7 ~ 20% increase in fuel cell performance, compared to the normal channel.

(3) We fixed the anode stoichiometry at 1.5, while varying the cathode stoichiometry, to compare the normal channel and wave form channel. In the case of the normal channel, cathode stoichiometry of 2.5 yielded a slight increase in performance in the high CD region with CD over 1.0, but in the wave form channel, increase of the cathode stoichiometry had an insignificant effect on fuel cell performance.

(4) We varied the wave form channel design parameter AD, which yielded 20% fuel cell performance improvement in the ER 2.0, AD 4.0 wave form channel, compared to the normal channel. But the rate of increase of the fuel cell performance improvement decreased as the AD distance increased, due to reduction in reactant mass transport.

(5) In the reliability experiment, the normal channel showed great decrease in fuel cell performance after 6 hours. But, in the case of the wave form channel, the voltage decreased by 0.7V after 10 hours, and the fuel cell performance decreased by around 28%, compared to the beginning of operation. Thus, fuel cell performance is improved by minimizing concentration polarization inside the wave form channel at high CD.

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