공학석사 학위논문

Study on the performance enhancement of polymer electrolyte membrane fuel cell (PEMFC) by modifying bipolar plate

분리판 형상개선을 통한 고분자 전해질막 연료전지의 성능향상에 관한 연구

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유 진 혁

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Abstract

Study on the performance enhancement of polymer electrolyte membrane fuel cell (PEMFC) by modifying bipolar plate

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Researchers have made an effort to increase the performance of polymer electrolyte membrane fuel cell (PEMFC) by using many ways. In order to commercialize fuel cell, it is necessary to make fuel cell small and light. Therefore lots of methods have invented to generate more power per unit active area. Although fuel cell is composed of many parts, especially channel design affects the performance a lot. Well-designed channel structure makes reactant gases diffuse to active area evenly and manages produced water efficiently. So, making optimal channel structure is significant for high current density fuel cell.

In this study, we have focused on cathode channels and suggested novel design. At first, the ribs and channels of cathode bipolar plate were removed and porous media was inserted at the cathode channel region. We chose metal foam as a flow distributor. Several different metal foams were adopted and measured the performance. As a result, fuel cell with metal foam showed better performance entirely and kept high voltage even at the high current density region. Also, steady and dynamic responses were also evaluated to verify that reactant gas can be distributed well inside the channel region. Second, inclined channels were installed at the cathode side instead of using conventional channels. Due to the shallow depth of channels near the outlet, the velocity of reactant gas is increased. The accelerated gas removed water well and, consequently, fuel cell with inclined channel indicated better performance compared to the conventional fuel cell. These results imply that only changing channels appropriately can lead to high performance fuel cell and will motivate many researchers to invent new generation fuel cell.

Keywords: PEM fuel cell (Polymer Electrolyte Membrane fuel cell), Metal foam, Inclined channel, Water management, Gas diffusion, Dynamic response

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Nomenclature

a	Water activity
F	Faraday constant
D	Diffusivity (m^2/s)
EW	Equivalent weight of dry membrane (kg/mol)
I	Current density (A/cm^2)
RH	Relative humidity (%)
SR	Stoichiometry number
T	Temperature (℃)
δ	Thickness (mm)
ρ	Density (kg/m^3)
σ	Proton conductivity (S/cm)
τ	Time constant
λ	Water content

Subscript

a	Anode
c	Cathode
cell	Single fuel cell
g	Gas
m	Membrane

Chapter 1. Introduction

1.1 Background of the Study

As industries develop, the dependence on fossil fuel, represented by coal, natural gas, petroleum etc, has also been increased. However, researchers have predicted that fossil fuels will be depleted in several decades. Especially decreasing the amount of drilling petroleum which is the main power source in almost all industries will bring global chaos. In addition, using huge amount of fossil fuels leads serious environmental pollution such as global warming, damaging environmental ecosystem etc. Because fossil fuels are composed of high rate of carbon, a lot of carbon dioxides, which are one of the major factors for the global warming, are released when combustion happens. Also, nitrogen oxide (NOx), sulfur oxide (SOx) are the typical byproducts arisen during power generation process in fossil fuel using factories and electric power station. These toxic materials cause several health problems, for example respiratory and skin deseases, and air pollution such as smog and acid rain.

To handle these problems, environmentally friendly and renewable power generation methods are taking the center stage in energy research fields. Especially, fuel cell is strongly considered as one of the new power sources, since it has several advantages. Fuel cell generates energy only by using hydrogen and oxygen, in other words, it derives electricity through the simple chemical reaction-hydrogen oxidation and oxygen reduction. As a result of the

chemical reaction in the fuel cell, only water is produced as a byproduct. Moreover polymer electrolyte membrane fuel cell (PEMFC) operates at low temperature - usually the temperature range is 60~80℃ - and doesn't take place vibration or other physical damages because there is no mechanical movements during the operation.

Although fuel cell has lots of advantages, it also has many problems to be solved such as low durability, high production costs, and hydrogen storage problems etc. Among them, relatively low power generation rate, compared to conventional power sources, is a serious problem. In order to commercialize fuel cell, increasing the power generation rate and efficiency is essential. If the power generation rate per unit chemical reaction area is increased, we can downsize a scale and reduce the weight of the fuel cell system. By doing so, we can easily apply fuel cell system to the vehicles or portable devices.

From the early stage, many ways to increase power density have been suggested. Because several factors affect the fuel cell efficiency, a few methods and technologies have been applied. In particular, many fuel cell researchers have attempted to enhance the performance by modifying the structure of the bipolar plate. The bipolar plate plays an important role in the fuel cell. It gives electrons paths to move as well as provides reactant gases to the MEA (membrane electrolyte assembly) properly. Also water removal range and proper heat management depends on the structure of the bipolar plate. Therefore, the bipolar plate is required to have high conductivity, and good heat and mass transfer characteristics. Usually serpentine, parallel, and

interdigitated structures are used in the conventional fuel cell [1], but there is a limit to the amount of increasing the performance that these structure generate in the present.

In this study, novel ways to generate high power density per unit active area were suggested. To achieve a goal, a cathode side bipolar plate was modified. At first, channels in the bipolar plate were removed and 3D porous structures were inserted. 3D porous structures make reactant gases distribute evenly over active area, and remove liquid water well compared to the channel structure, because pressure distribution is much even, and channeless structures give fluids more freedom of stream. Second, we remained serpentine channel structure, but changed channel depth. We made tapered channels by decreasing the depth gradually in gas flow direction. We called this new design of fuel cell as inclined fuel cell. Tapered channels increase the velocity of the gas flow and give momentum toward the MEA. We observed the performance increase when the inclined channels is applied. The experiment results and analysis will be shown in following chapters.

1.2 Literature review

As the polymer electrolyte membrane fuel cell (PEMFC) technology has progressed, and the usages of the PEMFC have been expanded, many researchers have focused on how to increase largely the performance of the PEMFC. Especially researchers have had effort to improve the water removal, reactant gases diffusion and chemical reactions by modifying the structure of the bipolar plate. Tanaka and Shudo [2] researched on the microcoil fuel cell. They removed channel in a cathode bipolar plate, and inserted microcoil. They focused on how to prevent flooding phenomenon and diffuse reactant gas to the MEA directly by using microcoil. According to the experiment results, microcoil fuel cell showed the better performances than the conventional fuel cell. In the low current density region, performance differences were small, but microcoil fuel cell kept its high voltage even in the high current density region. The major disadvantage of it was high ohmic loss due to reduction of the contact area. They expanded their research, and introduced corrugated mesh as new flow field. [3] They also excluded gas diffusion layer (GDL) and made the corrugated mesh contact with micro porous layer (MPL) directly. They were able to observe that the mesh fuel cell had good water drainage characteristics and tended to maintain its high performance at the high current density region. However, corrugated mesh structure also had the high resistance problem due to the small contact region. Tseng *et al*. [4] adopted metal foam as flow distributor in the PEMFC. They used nickel foam and it was coated with PTFE

to reduce electrical resistance and prevent its corrosion. The experiments were divided to 4 cases according to the compression extent. Generally, because the metal foam has high porosity, it allows reactant gases to flow freely in all directions and water droplets can move to outlet easily. Owing to these advantages, they could obtain the results that metal foam used fuel cell generated higher performance than conventional fuel cell. Tsai *et al*. [5] focused on finding optimal flow field design when metal foam is used as flow distributor. They introduced four different flow field designs using metal foam and compared with the traditional serpentine flow field. When flow field was segmented, reactant gases were distributed evenly in all active area, consequently, the performance was highest. Kariya *et al*. [6] studied about the performance difference according to the flow field type with porous media which is consists of Ni-base alloy spherical powders and corrosion-resistant stainless steel powders. They made partitions, grooves, and fine space networks on the flow field and measured the performance. Karthikeyan *et al*. [7] investigated on porous inserts applied flow field. Basically they used pintype flow field and assembled porous inserts which were made by carbon clay. Because porous inserts absorbed produced water from the GDL, and allowed reactant gases to diffuse well, their new design fuel cell generated higher power output. Usually, produced water gathers on the ribs and it is hard to push away. Porous inserts in this paper play a role as ribs and water absorbers. Koresawa and Utaka [8] tried to control produced water by applying microgrooves inside gas channels. Water was removed through the microgrooves due to the high

capillary forces. Because of the improvement of a water management, the maximum current density and power density was increased. In addition to that, voltage fluctuation was reduced drastically since the water was removed quickly. Han *et al*. [9] applied a concus-fin condition to channels to prevent flooding phenomenon at a cathode side. As a result of the experiment, water droplets moved upper narrow part of the concus finn channel, so water droplets didn't block wider part of the channels. Consequently, water flooding phenomenon tended not to occur, the efficiency of the fuel cell enhanced about 5%. Bunmark *et al*. [10] applied up and down slanted channels to the flow field. Because slanted channels increased water back diffusion, the membrane was hydrated much easily compared to the normal cell and the conductivity was also improved.

Meanwhile, unlike the papers above, many studies were conducted by using CFD codes. CFD codes help researchers who are interested in bipolar plate to try a variety of shapes when they design flow fields. Tiss *et al*. [11] carried out the numerical analysis about partially blocked gas channels. Several obstacles which are getting higher along the channel were installed, and reactants gas flew through these obstacles. They predicted that the higher obstacles are, the better the performance shows, by using CFD modeling. Perng and Wu [12] conducted simulation research on a trapezoid baffles inserted fuel cell. Because trapezoid baffles blocked a reactant gas flow, hydrogen and air were forced to flow to the GDL and MEA. This phenomenon led better reactant gas transport. Ghanbarian and Kermani [13] performed simulations to consider the effect of

obstacles in the middle of the channel. They examined three different cases, and located different shape dent in the channel at each cases. In this study, they observed that high oxygen concentration is shown and high local current density exerted above the dent, because the new geometry helped reactant gas to move toward the GDL and catalyst layer. Kuo and Chen [14] conducted numerical simulations to assess the heat transfer and flow characteristics of a new wave like form gas flow channel in the PEMFC. Their simulations showed that wave-like form gas channel increased the mean Nusselt number and gas flow velocity. Consequently, they concluded that these properties will enhance the chemical reaction rates and improve the performance of the PEMFC.

A few researchers got ideas from nature, and s biomimetic channel structures. Roshandel *et al*. [15] designed a bipolar plate inspired from a leaf. They imitated the veins on the leaf to induce uniform velocity distribution and even species spreading. They verified that the leaf-imitated design provided adequate velocity, pressure and species distribution. Similarly, Kloess *et al*. [16] considered leaf vein and lung structure to improve the performance. They measured and compared flow diffusion characteristics, pressure drop ranges and velocity distribution etc on a different temperature, relative humidity (RH), and back pressure.

As mentioned above, a lot of studies have suggested a variety of bipolar plate designs. Because the performance of the PEMFC largely depends on flow control, much more researches will be conducted continuously.

1.3 Objectives and scope of the study

The objective of this study is designing novel fuel cell which generates much electricity from same active area by modifying cathode channel structure. The study is categorized two parts largely. At first part, porous media is considered as a flow distributor. Metal foam was used as a porous media which improves the gas flow pattern and water management characteristics. Second part, normal serpentine channel structure was modified. Serpentine channel design was kept but the channel depth was changed along the flow path. After the installation of the new cathode channel structure, performances were measured and compared with the normal, conventional fuel cell.

In chapter two, experimental setup is shown. Because we have focused on the cathode bipolar plate and channel structure, BOP (Balance Of Plant) was not changed or other devices were not added a lot. And Single fuel cell which was used for all cases, is introduced. Lastly, the specification of Membrane Electrolyte Assembly (MEA), Gas Diffusion Layer (GDL) and bipolar plate etc is mentioned.

In chapter three, porous media applied fuel cell study is presented. Various metal foams which have different pore size were used and installed inside the cathode channel region, and the performance was measured. By using porous media, we showed that even gas distribution can be achieved, and water management characteristics are able to be improved.

In chapter four, steady and dynamic responses of porous media applied fuel

cell is presented. Fuel cell has applied many areas such as plant, automobile. Especially, in case of automobile application, the transient response is one of the important factors, because the operation conditions, such as temperature, stoichiometry number, relative humidity, are fluctuated according to the drive conditions. So, in chapter four, how the metal foam applied fuel cell shows better transient performance in various environment will be explained.

In chapter five, inclined channel applied fuel cell study is presented. Different from the conventional fuel cell, its depth of channel is gradually changed. The velocity of gas flow is accelerated, as a result, liquid water is removed much easily. In this chapter, it is shown that how much the performance is increased.

In chapter six, experiment results and analysis are summarized. And, the vision of the high current density fuel cell research is shown.

Chapter 2. Experimental setup

2.1 Introduction

The experimental setup is shown in Fig. 2.1. It consists of a single fuel cell and auxiliary parts. The auxiliary parts, called BOP (Balance of Plant), are composed of air supply system, hydrogen supply system, humidifying system (bubbler, humidifier), pressure difference gauge (differential pressure transmitter), measuring instruments (electronic loader (Fig. 2.2), impedance meter (Fig. 2.3)). In this paper, since the modified cathode bipolar plate is the primary issue, the only part which is changed is cathode bipolar plate. The experimental setup is maintained for every experiment cases. 99.999% hydrogen was used for the anode side, and air was fed for the cathode side. Hydrogen and air were humidified up to 100% through the humidifiers. The differential pressure transmitter was installed between cathode inlet and outlet in order to measure the pressure differences depending on modified cathode bipolar plates. By using electronic loader, current and voltage values were evaluated, and EIS (electrochemical impedance spectroscopy) was measured under different conditions.

Because our purpose of experiments is to observe performance changes according to various cathode bipolar plate designs, single fuel cell was used and modified cathode bipolar plate.

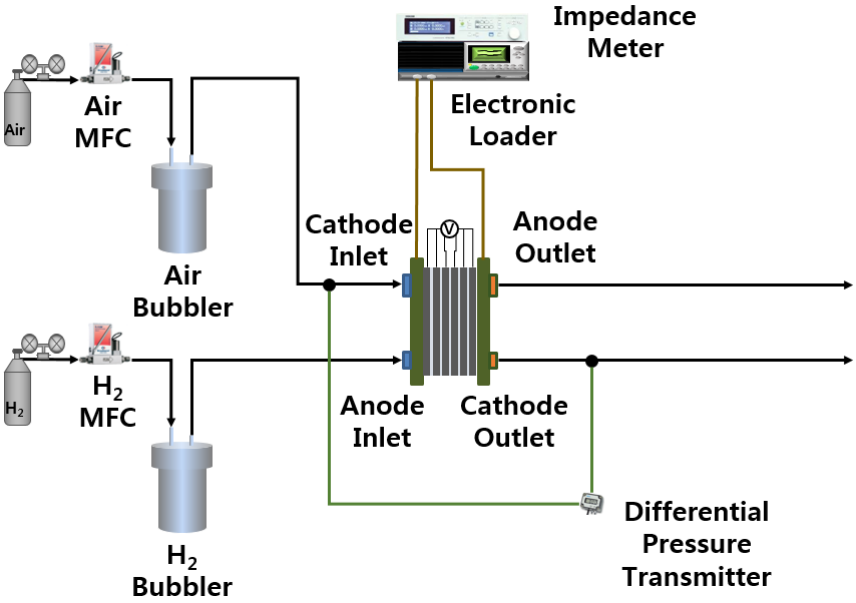


Fig. 2.1 Experimental setup

Fig. 2.2 Electronic loader

Fig. 2.3 Impedance meter

2.2 Single fuel cell specification

As mentioned previous section, single fuel cell was used in this study. Fig. 2.4 shows the single fuel cell which was used in experiments. The active area of the fuel cell was 25 cm^2. The bipolar plate of the fuel cell was made of graphite. In this paper, because the only cathode bipolar plate and channel structure were changed, the bipolar plate and channel structure of the anode side were same as the conventional one. Anode side had five channels and channel width and depth were 1 mm and 0.6 mm respectively.

2.3 Fuel cell assembly

The single fuel cell consists of several parts. Table 2.1 summarizes the specification of the components in the fuel cell. Membrane Electrolyte Assembly (MEA) was made of Nafion® 211 membrane, catalyst layer, and micro porous layer. MEA is coated by different quantity of catalyst depending on the electrodes - 0.45 $mgPt/cm^2$ for cathode side and 0.3$mgPt/cm^2$ for anode side. We used Sigracet® 39BC Gas Diffusion Layer (GDL). The thickness of the GDL is 325μm, PTFE load of backing is 5±1%, and PTFE content of micro porous layer (MPL) is 23%. The porosity is 50~52%.

Fig. 2.4 Single fuel cell

Table 2.1 Fuel cell components

Components	**Specification**
MEA (Membrane Electrolyte Assembly)	Nafion® 211 Membrane
CL (Catalyst Layer)	0.45mgPt/cm^2 for Cathode
	0.3mgPt/cm^2 for Anode
GDL (Gas Diffusion Layer)	Sigracet® 39BC
Bipolar plate	Graphite material
	5 × 5 cm^2 Active area

Chapter 3. Fuel cell with porous media

3.1 Introduction

In this chapter, fuel cell with porous media is introduced. In order to improve gas diffusion and water management, porous media is installed as a flow distributor instead of using conventional serpentine channel structure. Among various porous media, metal foam is one of the promising materials because metal foam has high porosity, and conductivity. Therefore metal foam has used as filter, gas diffusion media, and electrode materials and so on. Metal foam is made by using various metals, such as stainless-steel, copper, nickel, titanium, silver etc, and can be made several different shape and thickness.

Many fuel cell researchers have focused on this characteristics of metal foam and tried to use it as a gas diffusion media to substitute the conventional channel structure. Tseng *et al*. [4] inserted metal foam in the cathode flow field region and compare the performance. They used nickel metal foams and changed the compression rate. Also, performances were measured depending on the different cathode humidification temperature. Tsai *et al*. [5] also applied metal foam, but they prepared five different flow field designs and inserted metal foam inside these various flow field. By using the parallel and metal foam installed flow field, much performance enhancement was achieved. This design showed the importance of reactant gas separation from the inlet region. Ting *et*

al. [17] showed the effect of operational parameters on the PEMFC with metal foam. They conducted experiments under different operating temperatures, humidification temperatures, and cathode stoichiometry numbers, and evaluated the performance. Kumar and Reddy [18] adopted metal foam to the fuel cell and measured the performance under different temperatures and pressures. As mentioned above, metal foam has been considered as a flow distributor importantly.

In this chapter, we applied metal foam as a porous media to the fuel cell. Cathode channel structures were removed and various metal foams were inserted. Basic performances were measured and compared with the conventional fuel cell. In addition, the analysis were followed.

3.2 Experimental conditions

In this chapter, various metal foams which have different specifications were adopted and used for experiments. Table 3.1 presents the experimental conditions. Experiments were conducted at 40℃ and 60℃ and the stoichiometry number was 1.5 for anode and 2 for cathode side. At 40℃, due to the low temperature, vapor water is easily condensed. So, liquid water is produced a lot and flooding phenomenon is observed at low temperature. By measuring the performance at this unfavorable environment, we tried to elucidate the advantages of the metal foam. The relative humidity was 100% for anode and cathode both sides.

Table 3.1 Experimental conditions

Parameter	**Value**
T_{cell} (℃)	40, 60
SR_a	1.5
SR_c	2
RH_a (%)	100
RH_c (%)	100

3.2.1 Metal foam specifications

Fig. 3.1 shows various metal foams. Metal foams that were used in this experiment have different pore sizes – 450, 580, 800, 1200, 3000 μm. Metal foams were made of Nickel and the surface was coated by gold, in order to increase the electric conductivity. Also, they have anti-corrosion characteristic owing to the gold coating. Table 3.2 indicates the detail specifications of the metal foams. The pictures under the metal foam photos in Fig. 3.1 are the structure of each metal foam photographed by digital microscope. As can be seen the structure photos, the hole sizes are becoming larger as the pore sizes are increasing. Especially, the pore sizes of 1200 and 3000 μm are too big to capture the unit cell. The metal foams had different thickness originally, due to the different pore sizes, however they were compressed and coincided as 1mm thickness. Talking of the porosity, they have more than at least 90% high porosities.

The metal foams were cut into 5 cm×5 cm square shape, and inserted in the cathode flow field.

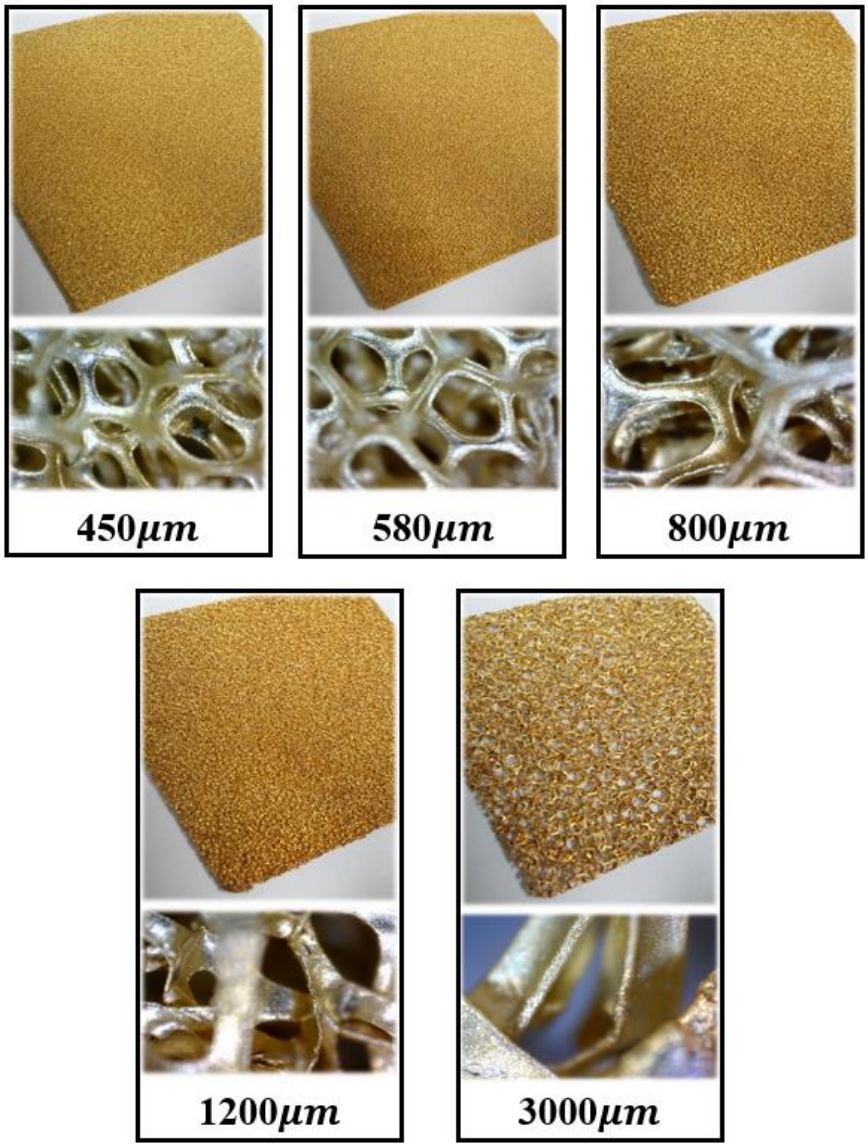


Fig. 3.1 Various metal foams having different pore sizes

Table 3.2 Metal foam specification

Metal foam pore size (μm)	**Original thickness (mm)**	**Thickness after compression (mm)**	**Porosity (%)**
450	1.5	1	95
580	1.7	1	95.3
800	2.4	1	94.8
1200	2.9	1	94.4
3000	4.5	1	90.7

3.2.2 Fuel cell with metal foam assembly

Fig. 3.2 indicates the anode and cathode bipolar plate. The active area is 5 cm×5 cm (25 cm^2). In case of anode bipolar plate, it has serpentine structure and five channels. The depth of the channels is 0.6 mm. However, the cathode channels were all removed, hollow space exists. In this region, the metal foam was put.

Fig. 3.3 shows the fuel cell with metal foam assembly. Metal foam was inserted at the flow field and then, the gas diffusion layer was put on it. Because the metal foams were compressed as 1mm thickness, one metal foam is necessary to fill out the flow field.

3.3 Experiment results

In this section, the experiment results are reported. I-V polarization curve and power density curve were deducted. In addition to that, EIS (electrochemical impedance spectroscopy) data had gotten from impedance meter and the graph of EIS was drawn. Lastly, we chose two metal foams which showed good performance at low current density region and high current density region and combined them. The experiment results of this combined metal foam applied fuel cell also presented.

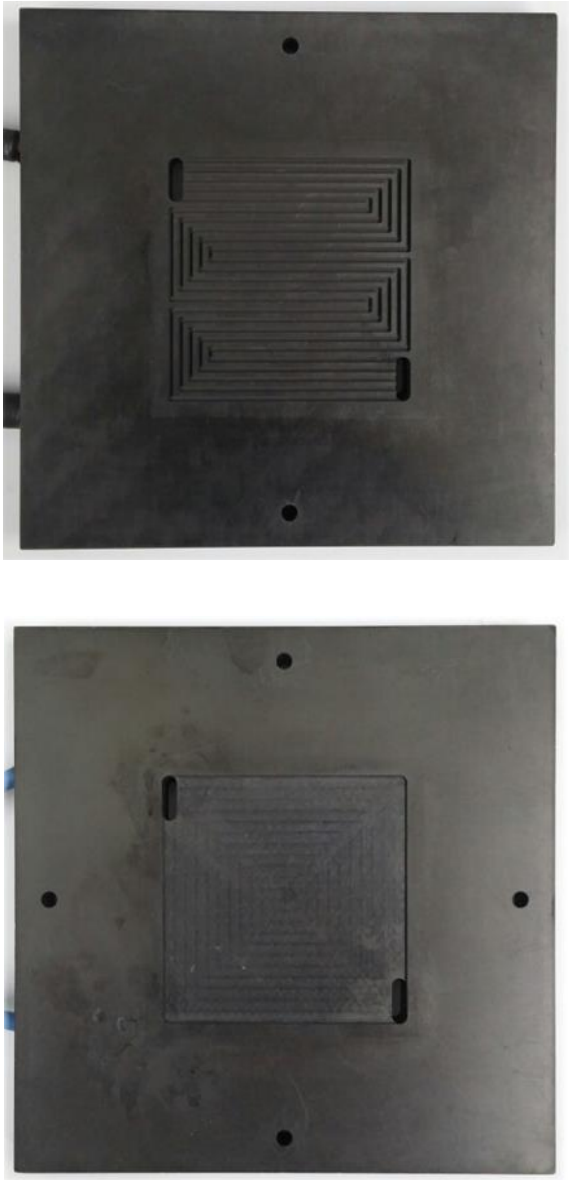


Fig. 3.2 Anode (up) and cathode (down) bipolar plate

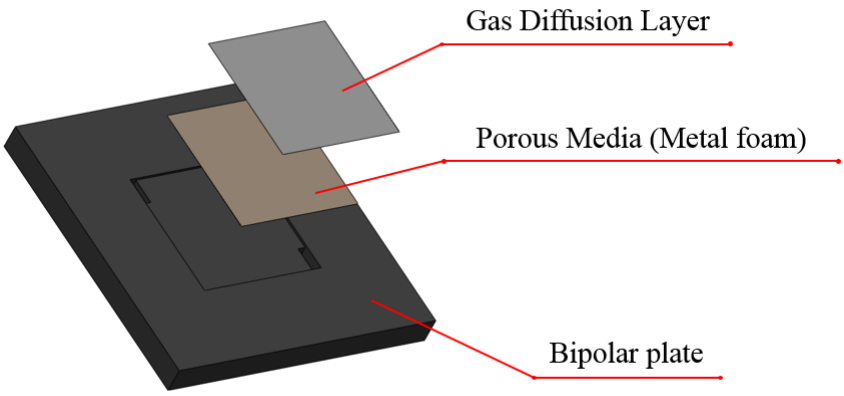


Fig. 3.3 Fuel cell with metal foam assembly

3.3.1 Performance comparison of conventional fuel cell and fuel cell with metal foam

I-V performance and power density were measured at 40 and 60℃. 40℃ cases were done in order to observe the results when the fuel cell with metal foam was operated under flooding phenomenon. At this temperature, the vapor water is easily condensed and liquid water is produced a lot due to the low temperature. So, the flooding phenomenon occurs frequently. Under this phenomenon, if the fuel cell doesn't drain liquid water appropriately, the performance will be deteriorated. On this point, the water management and gas diffusion characteristics of the fuel cell with metal foam can be evaluated.

At first, Fig. 3.6 and Fig. 3.7 show the performance at 60℃. According to the Fig. 3.6, all metal foam cases showed better performances compared to the conventional fuel cell, regardless of the pore sizes. Especially, among them, 800 μm case showed the best performance. Generally, fuel cells with metal foam tend to keep high voltage levels even at the high current density region. According to the power density curve (Fig. 3.7), the peak power density of the fuel cell with 800 μm metal foam was about 51% higher than that of the conventional fuel cell.

Second, Fig. 3.4 and Fig. 3.5 indicate the experiment results at 40℃. As already mentioned above, at this temperature, the flooding phenomenon happens easily. And the chemical reaction rate declines because of the low temperature. Overall, the performances were decreased for all cases, but the

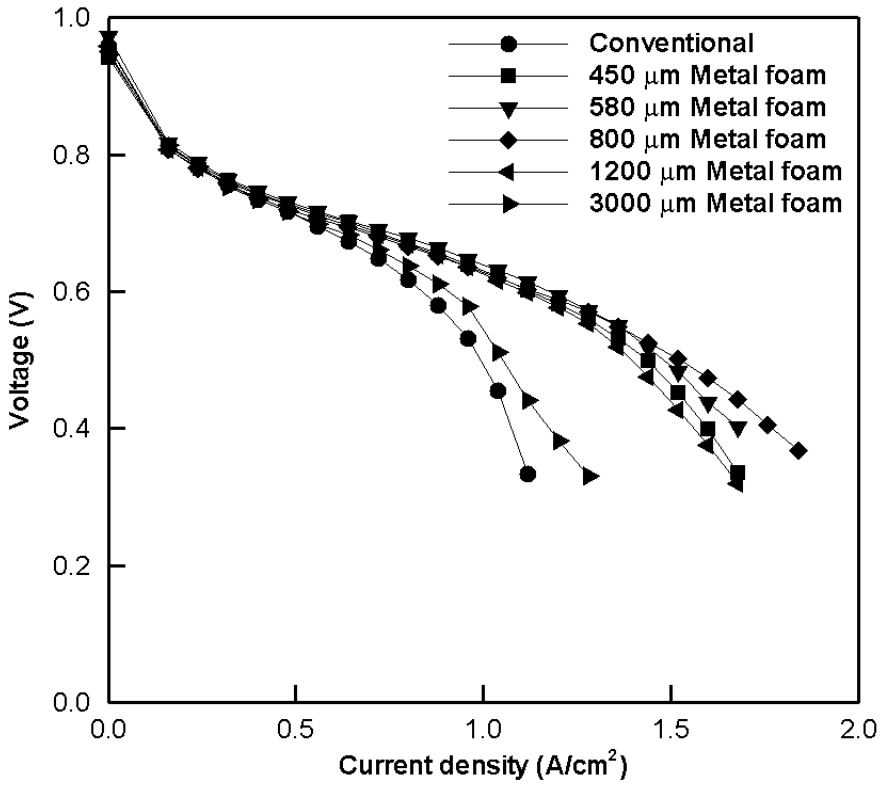


Fig. 3.4 I-V polarization curve of conventional and metal foam applied fuel cell at 40℃

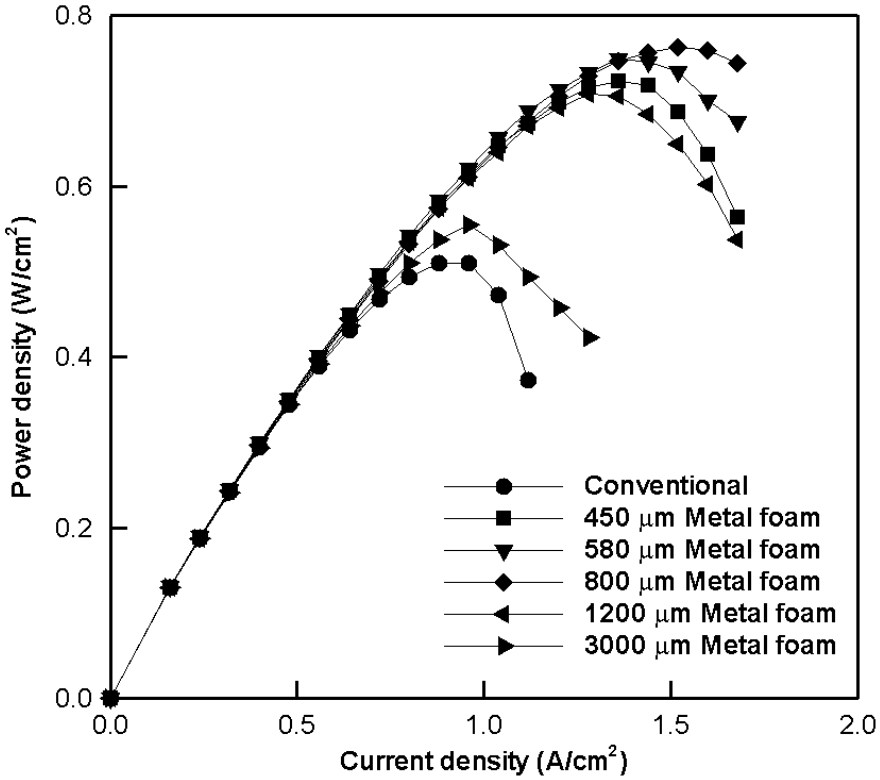


Fig. 3.5 Power density curve of conventional and metal foam applied fuel cell at 40℃

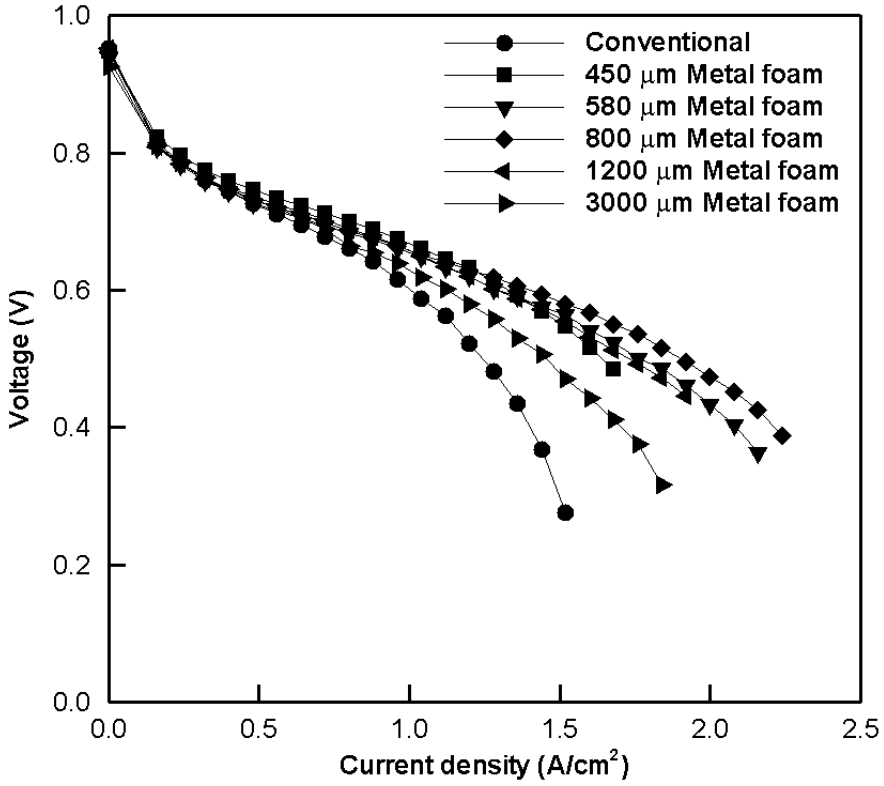


Fig. 3.6 I-V polarization curve of conventional and metal foam applied fuel cell at 60℃

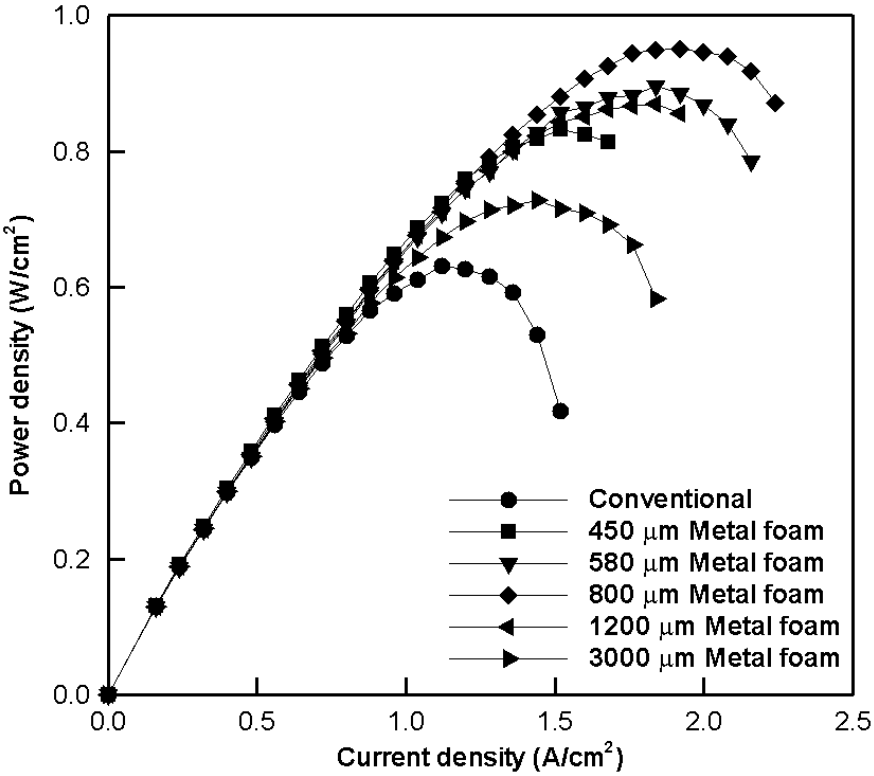


Fig. 3.7 Power density curve of conventional and metal foam applied fuel cell at 60℃

fuel cell with metal foam still presented better performance. The performance of the conventional fuel cell dropped drastically even at the middle current density. Although the 3000 μm metal foam cases showed similar trend with the conventional fuel cell, the other metal foam cases exerted relatively high voltage levels. Among them, the performance of the 800 μm metal foam case was the best. It verified that the metal foam drained liquid water well, so prevented flooding phenomenon efficiently. According to the power density curve (Fig. 3.5), the peak power density value of the fuel cell with 800 μm metal foam was increased about 49.5% compared to the conventional fuel cell.

3.3.2 EIS data comparison

In this section, the EIS (electrochemical impedance spectroscopy) measurement results represent. Fig. 3.8 to Fig. 3.13 show the results. The measurements were conducted at 40℃ and 60℃. And, the current values which were loaded were 8 A, 16 A, 24 A for 40℃ case and 8 A, 16 A, 32 A for 60℃ case. These values were selected randomly under low, middle, and high current regions. By doing so, we observed distribution of main losses of the fuel cell and evaluated the performances. The intercept of EIS graph with X-axis is called HFR (high frequency resistance). It means the ohmic loss of the fuel cell. In all cases, the HFR values were similar, and it means that even if the conventional channels were substituted by the metal foam, the electrical resistance was not changed drastically. Also, the contact area with the GDL

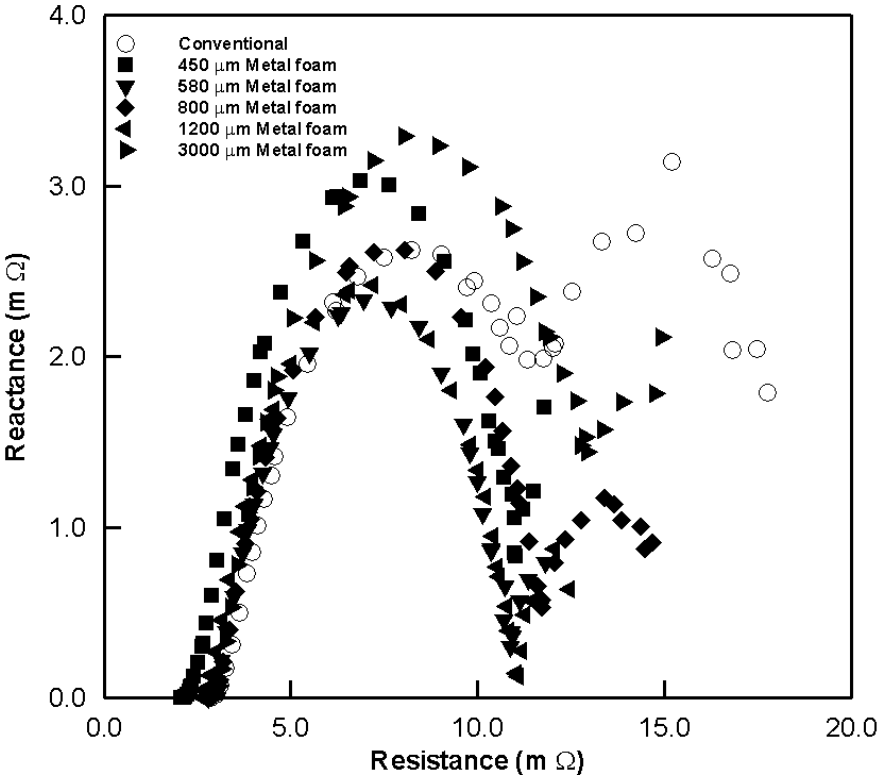


Fig. 3.8 EIS data at 8 A under 40℃

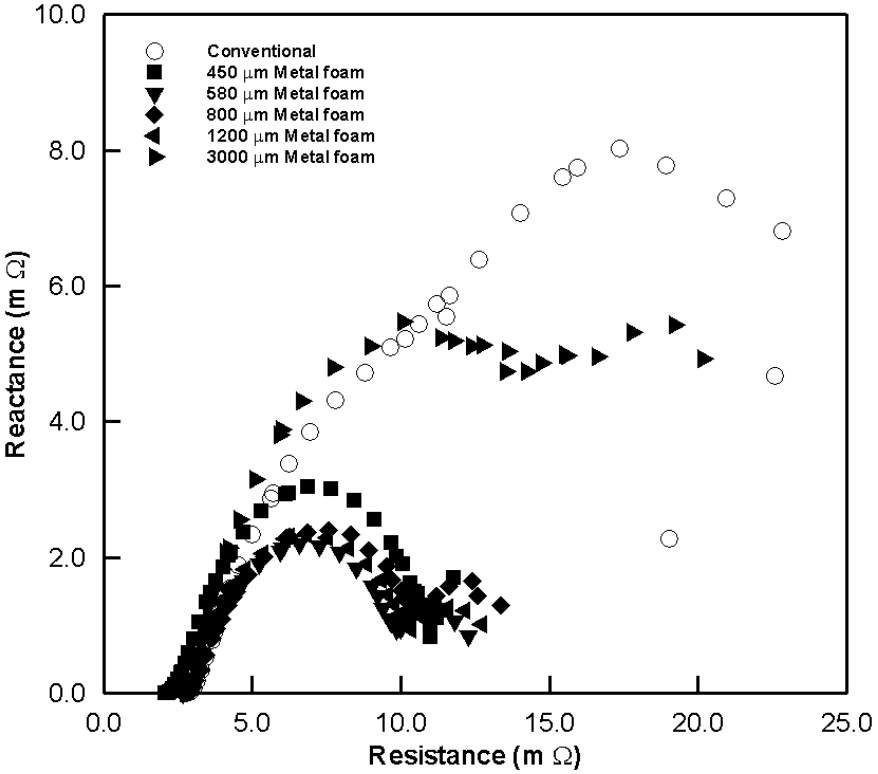


Fig. 3.9 EIS data at 16 A under 40℃

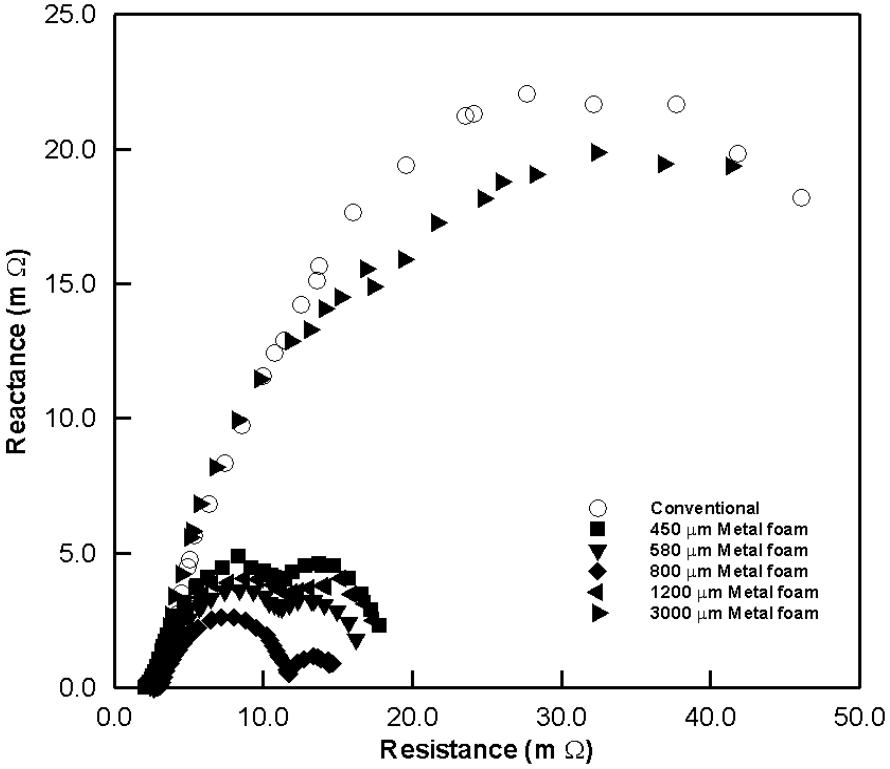


Fig. 3.10 EIS data at 24 A under 40℃

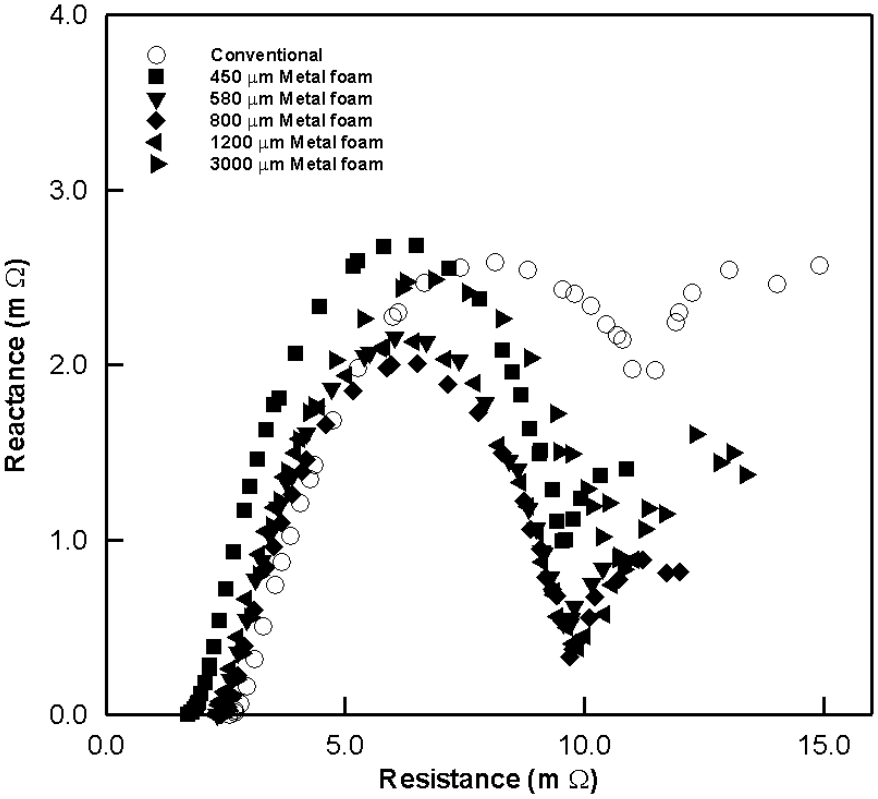


Fig. 3.11 EIS data at 8 A under 60℃

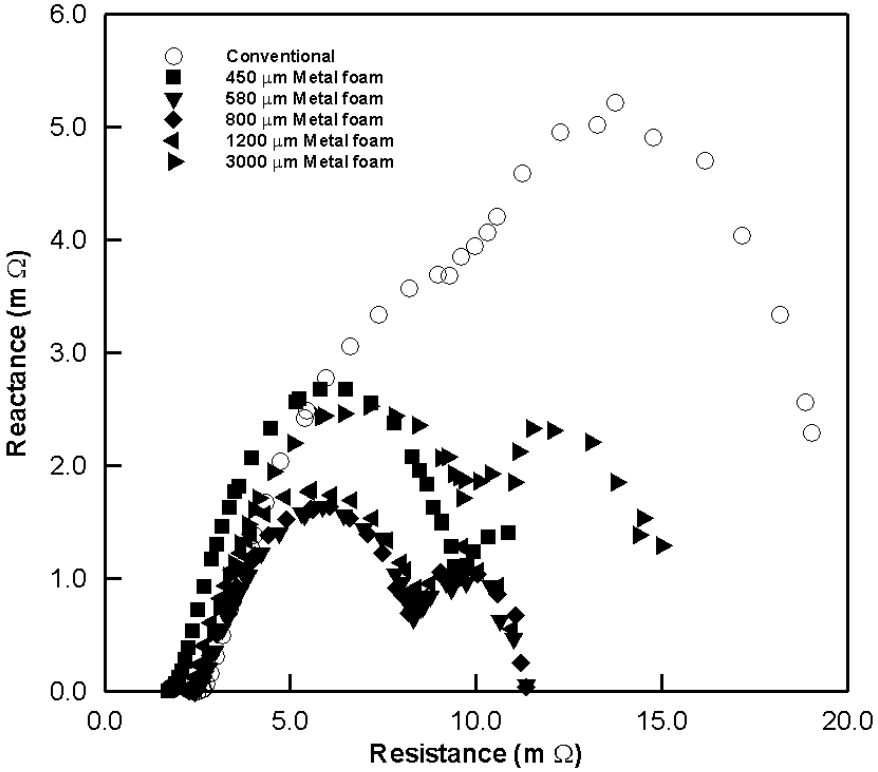


Fig. 3.12 EIS data at 16 A under 60℃

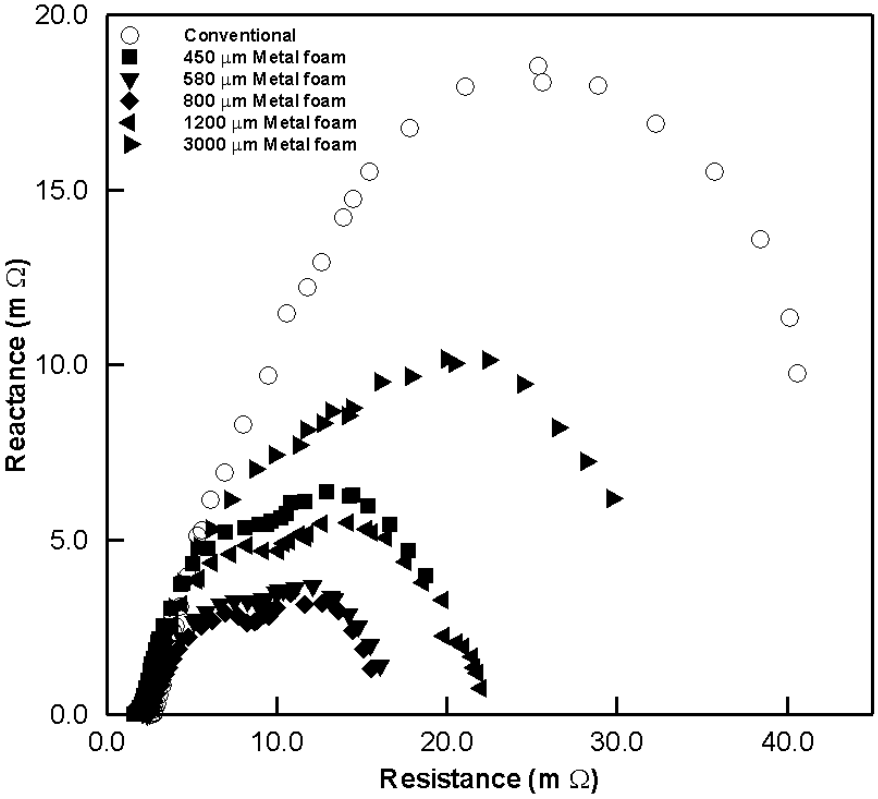


Fig. 3.13 EIS data at 32 A under 60℃

and bipolar plate was almost same if the metal foam was used. It is significant point, because if the flow field is replaced to the metal foam, it is likely that the cross sectional area will be decreased. By measuring and comparing the ohmic losses of all cases, it was verified that the whole contact area was maintained even when metal foam was used.

In case of concentration loss, there were marked differences between the conventional fuel cell and metal foam applied fuel cell. At 40℃ and 60℃ both case, the EIS data at low current region (8 A) were similar for all cases. Meanwhile, as the current values were increasing, the concentration losses were also increasing. Especially, under the middle (16 A) and high (24 A and 32 A) current, the concentration loss of the conventional fuel cell was shown very large. Among the metal foam fuel cells, 3000 μm case showed the largest concentration loss. But, overall, metal foam applied fuel cell had smaller concentration loss compared to the conventional fuel cell.

As a result of the EIS measurements, metal foam flow distributor reduced concentration loss much, but the ohmic resistance was constant. In conclusion, the metal foam has advantages in the water management and gas diffusion.

3.3.3 Stability comparison

Stable power generation characteristic is also important in fuel cell. if the voltage levels are largely fluctuated when current is generated, it will give bad effect to the durability, stability and safety of the whole fuel cell system. In this

context, the stability of the fuel cell with metal foam was conducted and compared with the conventional fuel cell. Fig. 3.14 to Fig. 3.19 present the results of the stability test. The experiments were conducted for 30 minutes at 60℃, and 36A current was loaded to all fuel cell cases. According to the Fig. 3.14, conventional fuel cell showed unstable voltage levels during 30 minutes. During the first 2 minutes, the decline of voltage level was observed. And then, voltage rose up to peak point and then dropped gradually again. It was difficult to decide the steady state voltage level, due to incessant fluctuation. The deviation from the average voltage level was huge. The standard deviation of the voltage level of the conventional fuel cell was 0.037189. Table 3.3 shows the standard deviation of voltage levels for each case. But, in case of the fuel cell with metal foam, the stability characteristics were improved. In all cases, the deviation range was smaller than that of the conventional fuel cell. However, the 3000 μm case showed sudden overshoot many times. It is because a large amount of reactant gas just move out through outlet without diffusing to the MEA region, due to the too large pore size. So, the chemical reaction rarely occurred and presented unstable voltage levels when the high current was loaded. Among the fuel cells with metal foam, the 800 μm case showed the best stability characteristic. Voltage deviation was 0.003945, this value is a-tenth of the voltage deviation of the conventional fuel cell.

In conclusion, we observed that the fuel cell with metal foam exerted electricity much stably.

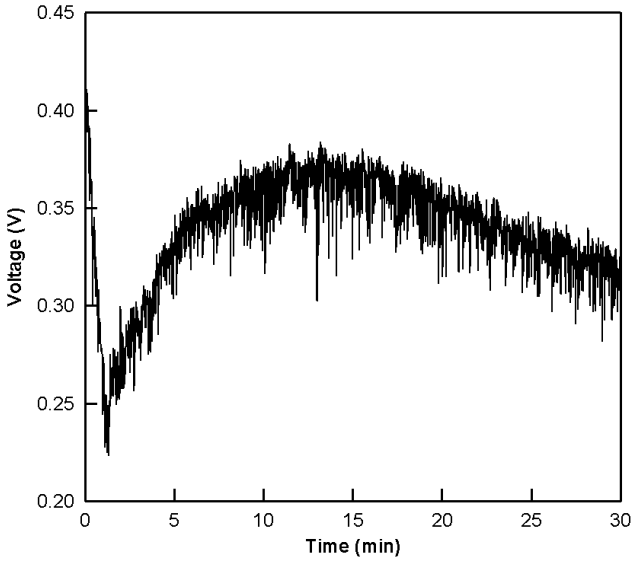


Fig. 3.14 Conventional case voltage measurement during 30 min when 36 A is loaded at 60℃

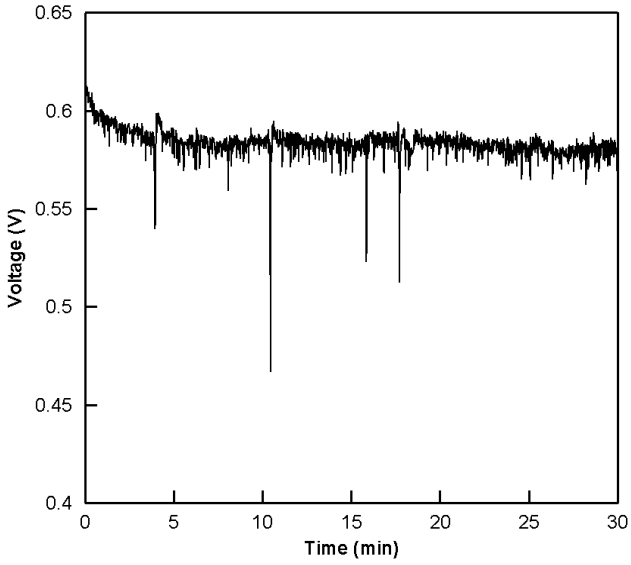


Fig. 3.15 450 μm metal foam case voltage measurement during 30 min when 36 A is loaded at 60℃

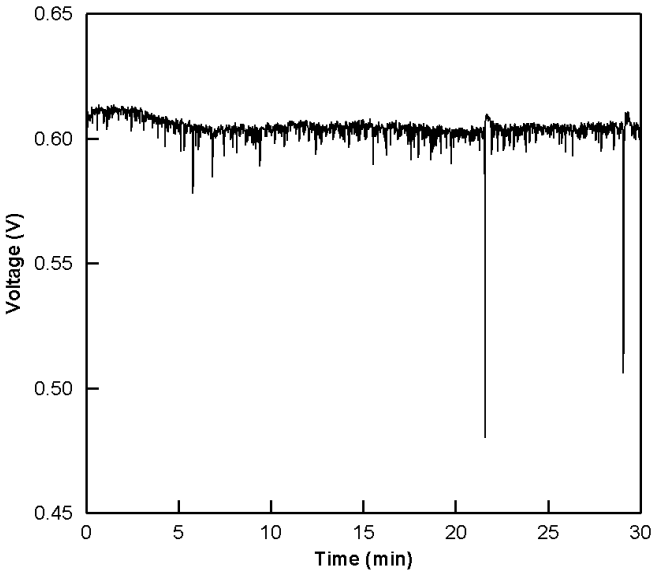


Fig. 3.16 580 μm metal foam case voltage measurement during 30 min when 36 A is loaded at 60℃

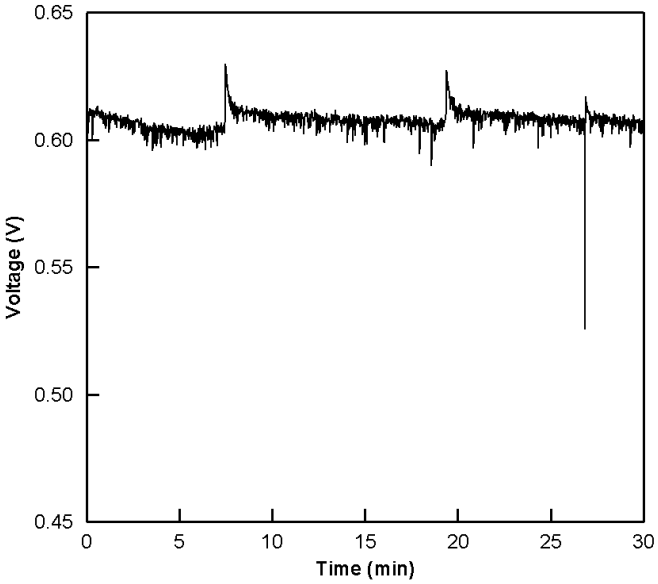


Fig. 3.17 800μm metal foam case voltage measurement during 30 min when 36 A is loaded at 60℃

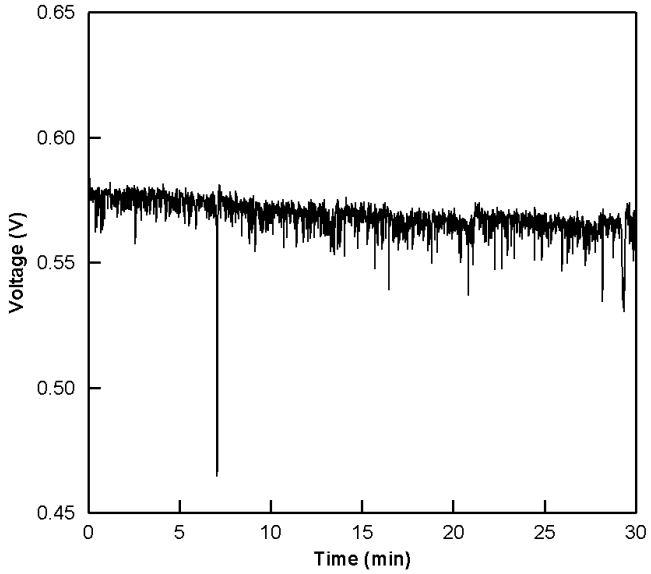


Fig. 3.18 1200 μm metal foam case voltage measurement during 30 min when 36 A is loaded at 60℃

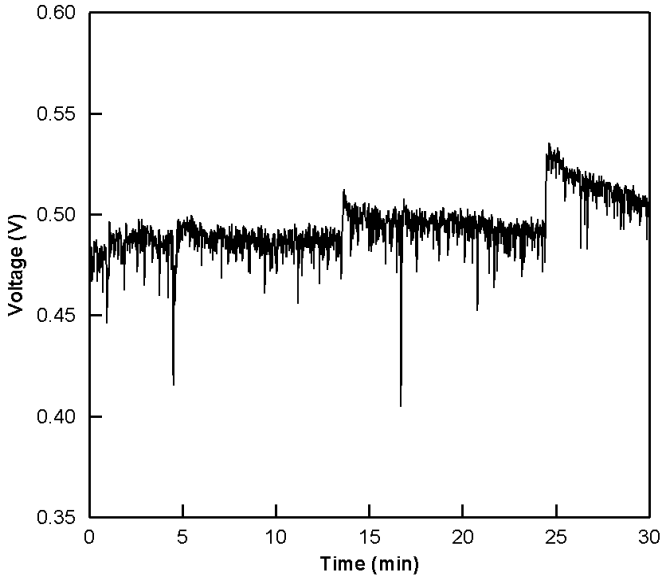


Fig. 3.19 3000 μm metal foam case voltage measurement during 30 min when 36 A is loaded at 60℃

Table 3.3 Standard deviation of voltage level

Fuel cell type	**Standard deviation**
Conventional	0.037189
450μm metal foam	0.00784
580μm metal foam	0.004439
800μm metal foam	0.003945
1200μm metal foam	0.007955
3000μm metal foam	0.019198

3.4 Analysis

Through the experimental results, it was found that metal foam improved water management and gas diffusion characteristics. In this section, we analyzed why the fuel cell with metal foam has better performance, compared to the conventional fuel cell. Fig. 3.20, and Fig. 3.21 are the cross-sectional view of the conventional fuel cell and fuel cell with metal foam assembly.

Conventional fuel cell has many ribs, and the ribs support the gas diffusion layer. These ribs make the channel structure and act as the role of routes for electrons. However, the ribs push the gas diffusion layer when the fuel cell is assembled, consequently, the pore size of gas diffusion layer near the ribs becomes smaller. Liquid water droplets are stuck due to the smaller pores and are hard to be drained well. Reactant gases are also interrupted to flow these regions, as a result, dead zones are made. Serious decrease of active area brings drastic voltage drop and shut down of the fuel cell. It is the main reason of the voltage drop at the high current density region where the flooding phenomenon occurs.

On the other hand, as can be seen in Fig. 3.21, fuel cell with metal foam has no rib structure, but metal foam branches support the gas diffusion layer. So, relatively even pressure distribution is made and partial pressure concentration at specific area doesn’t happen. Therefore, produced water flows much freely and is easy to move out through the outlet. In addition, reactant gas can be diffused evenly over the whole active area because it is not impeded by

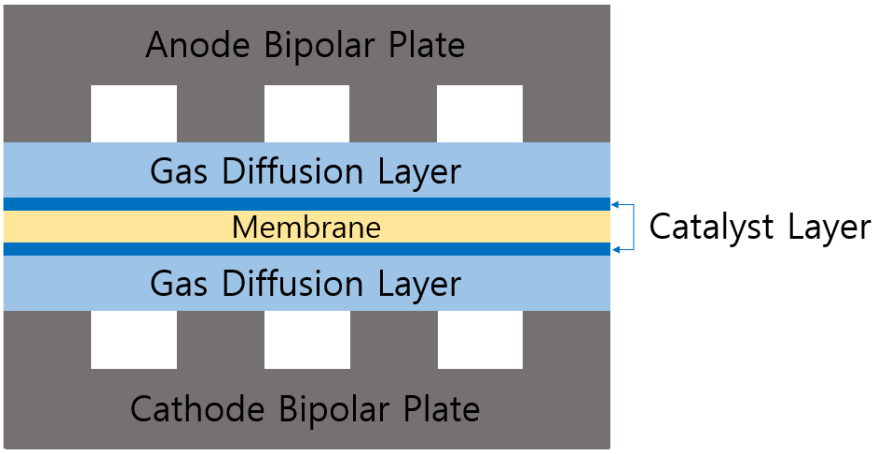


Fig. 3.20 Conventional fuel cell assembly

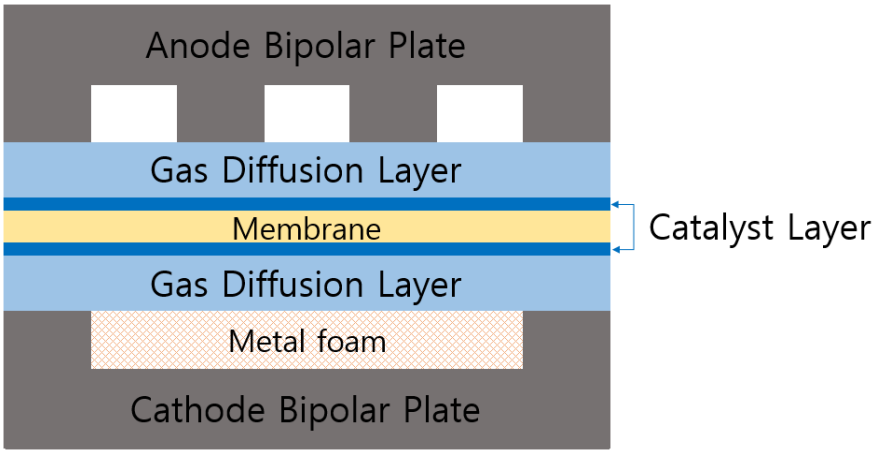


Fig. 3.21 Fuel cell with metal foam assembly

water.

Second, the pore size difference depending on the direction changes the gas flow pattern. Fig. 3.22 presents the pore size of metal foam in in-plane direction and through-plane direction. Since the metal foam is compressed before being inserted in flow field, the pore size in in-plane direction becomes smaller than through-plane direction. So, the metal foam structure impedes the reactant gas flow and gives time to diffuse to MEA region. Also, because pore size in through-plane direction is relatively large, it is easy for reactant gas to flow toward MEA region. In other words, pore size difference intends reactant gas to flow toward MEA and increases the chemical reaction rate.

These two reasons are the main factors explaining why the fuel cell with metal foam has better water management and gas diffusion characteristics.

3.5 Additional experiment: fuel cell with segmented metal foam

In this section, fuel cell with segmented metal foam is introduced. Based on the fuel cell with metal foam experiments, we expanded the studies. According to the performances of five different metal foams, we knew the optimal pore size at different current density regions. According to Fig. 3.6, 450 μm pore size metal foam applied fuel cell showed relatively high voltage level at the low current density region, but, its voltage level dropped drastically at the high current density region. On the other hand, the voltage level of the 800 μm

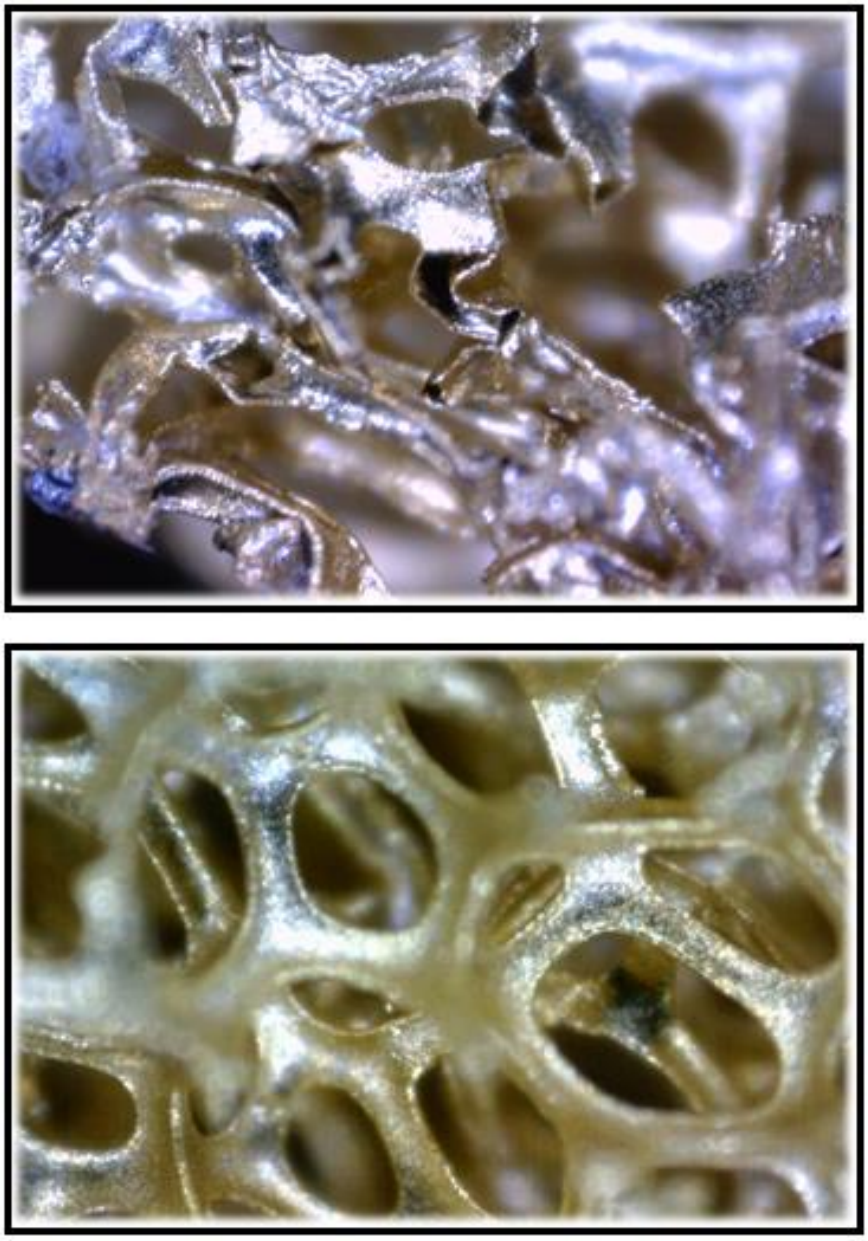


Fig. 3.22 Pore size in in-plane (up) and through-plane (down) direction

pore size metal foam inserted fuel cell was lower than that of 450 μm case at the low current density region, but indicated higher voltage level at the high current density region. These results tell that 450 μm pore size is good for gas diffusion and 800 μm pore size is optimal for managing liquid water. Therefore, we combined these two different pore size metal foams and tried to increase the performance more.

Fig. 3.23 presents the schematic of segmented metal foam flow field. Flow field was divided by diagonal line. 450 μm pore size metal foam was inserted in Ⅰ region, and 800 μm pore size metal foam was applied in Ⅱ region. This metal foam installment was for maximization of gas diffusion and water management. Fig. 3.24 indicates the segmented metal foam flow field.

3.6 Fuel cell with segmented metal foam experiment results

Fig. 3.25 presents the experiment results. Like our assumption, two different metal foams were working complementarily. At the low current density region, the voltage level of the 450 and 800 μm combined metal foam fuel cell increased more than that of 800 μm metal foam fuel cell. Also, at the high current density region, the segmented metal foam applied fuel cell tended to keep higher voltage level than that of 800 μm metal foam fuel cell. It tells that gas diffusion was enhanced at the region where small amount of liquid water was produced, and water management was well done at the region where large amount of liquid water was created.

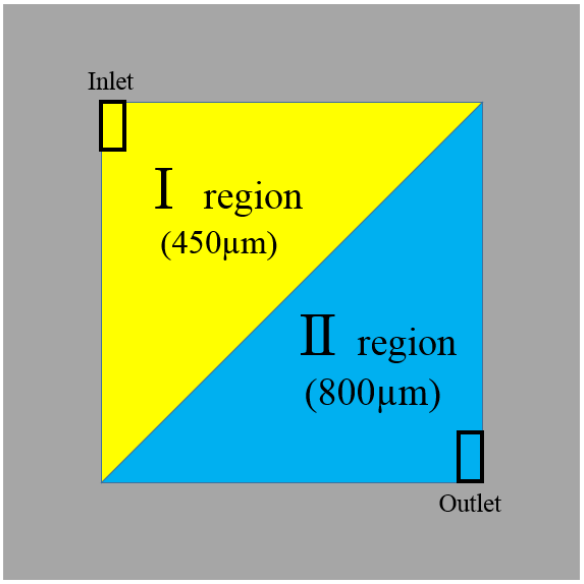


Fig. 3.23 Schematic of segmented metal foam flow field

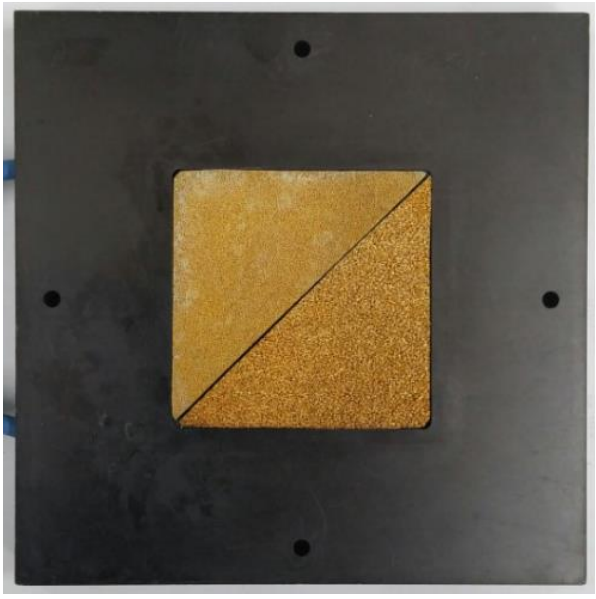


Fig. 3.24 Segmented metal foam flow field

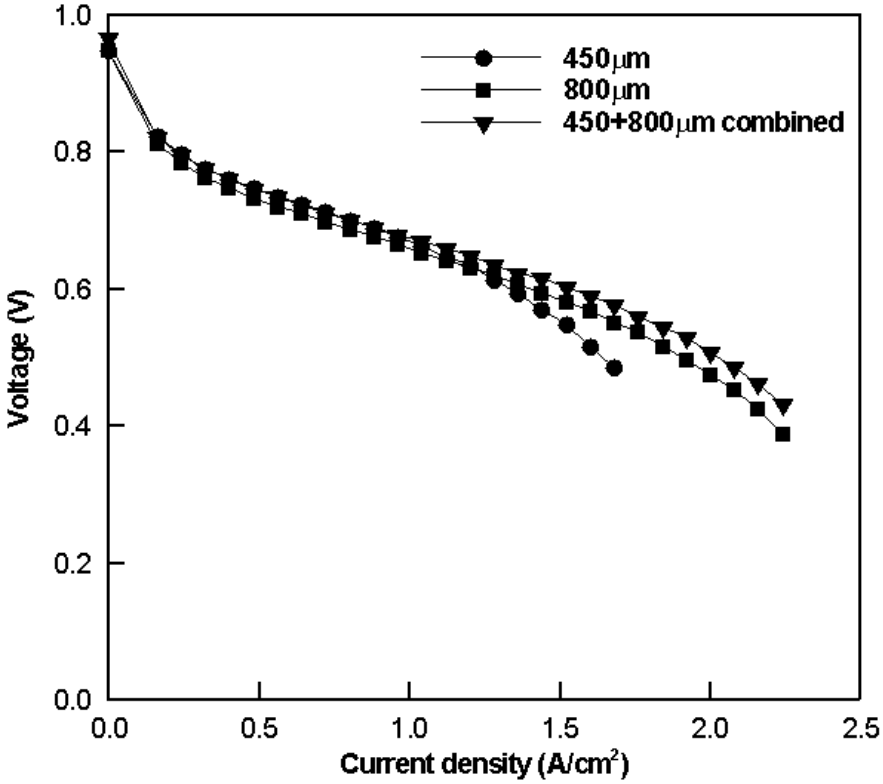


Fig. 3.25 Experiment results of segmented metal foam applied fuel cell

These results indicate that using different porous media which has dissimilar pore sizes or porosities in each area is more effective instead of applying uniform porous media.

3.7 Summary

In this chapter, fuel cell with metal foam was introduced. Five different metal foams which have dissimilar pore sizes were adopted and the performances of them were measured. The experiment results explained that just by substituting the conventional channel structure with metal foam, water management and gas diffusion characteristics were improved. Especially, under low temperature, metal foam prevented flooding phenomenon by draining produced water adequately. Fuel cell with metal foam has no rib structures, so, the partial compression of gas diffusion layer doesn’t happen. Therefore liquid water is not stuck at the specific region, and moves well. Also, reactant gas is able to be diffused evenly over the whole active area because metal foam structure gives freedom of flow. Moreover, we verified that segmented and combined metal foams work complimentarily and this new structure can enhance the performance more.

Chapter 4. Steady and dynamic response of fuel cell with porous media

4.1 Introduction

Unlike laboratory environment, operating conditions of fuel cell are changed and fluctuated in real. Especially understand of transient and dynamic responses is significant for the application of automobile. When the fuel cell system is applied to the transportation, transient characteristics should be considered, because many conditions can be changed suddenly during its operation. For example, when we start up or shut down the fuel cell, it has to be ready to operate or stop the system promptly. Also, when the fuel cell vehicle accelerates or decelerates, the demands of power generation are changed rapidly. Therefore, it is necessary to understand transient responses and study on the dynamic responses is essential for the next generation fuel cell vehicle.

Dynamic response of PEMFC also can be the evidence how it manages liquid water and diffuses reactant gas inside the channels well. The membrane hydration levels are different at each current density because the quantity of the produced water is different. As a result, the membrane resistance also becomes dissimilar. If the water management and gas diffusion occur well, fuel cell have optimal hydration and gas distribution in a short time at each current level.

Consequently, magnitudes of overshoot and undershoot become smaller and time taken to the steady state point reduces. That is why, dynamic response can be the important criteria in an evaluation of fuel cell performance.

Actually, several studies related to the dynamic response have done by many researchers. Loo *et al*. [19] used MATLAB Simulink and conducted numerical study about the dynamic response of PEMFC under various relative humidity and stoichiometry numbers. They also observed the voltage changes depending on the current density magnitude and measured the range of undershoot, overshoot and time delay up to steady state point. Kim *et al*. [20] investigated the effect of stoichiometry on the dynamic response of PEMFC. They kept the flow rates and changed voltage levels, so various stoichiometry conditions were made. Under different stoichiometry, the transient performances were measured. Yan *et al*. [21] changed current density under various operating conditions such as different temperature, pressure, and stoichiometries, and measured voltage changes. Kim *et al*. [22] verified the effect of air stoichiometry and air excess ratio on the transient response of PEMFC. Kumar *et al*. [23] tried to find the relation between the gas flow-field design and transient performance of PEMFC by using simulation program. They made serpentine, parallel, multi parallel, and discontinuous channel structures and checked the voltage level changes according to the sudden current changes. As I mentioned above, many researches related to the dynamic response of PEMFC have done until now, and will continue to carry out.

In this chapter, the study on the dynamic response of fuel cell with metal foam

is presented. In the existing studies, usually the dynamic response of conventional, serpentine fuel cell is assessed. However, we brought fuel cell with metal foam and analyzed its transient characteristics.

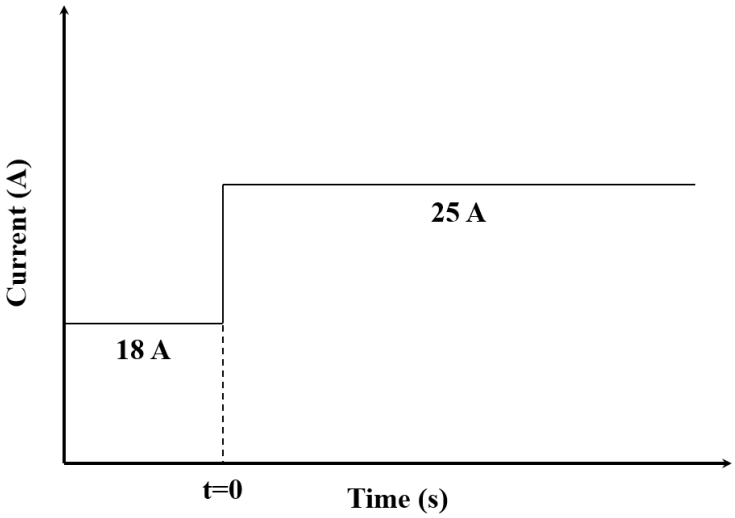
4.2 Experimental conditions

In this study, dynamic response experiments of conventional fuel cell and fuel cell with metal foam were conducted under two different temperatures. Conventional fuel cell has serpentine channel structure, and the channel depth was 0.6 mm for anode side, and 0.9 mm for cathode side. The number of channels was five. Transient performances were measured at 30℃, 60℃. Under these temperature conditions, current values were converted from 18 A to 25 A, and 25 A to 18 A. In case of 30℃ temperature condition, since vapor water is condensed much easily due to the low temperature, we can observe which channel structure manages water well obviously. And by conducting experiment at 60℃ in order to find the response under normal condition. Stoichiometry numbers were kept as 1.5 for anode side and 2 for cathode side.

Talking of the specification of metal foam which was used in this study, the pore size was 450 μm and porosity was 95%. The metal foam was made of nickel and was coated by gold to increase its conductivity. The experimental conditions are summarized in Table 4.1. And Fig. 4.1 presents step current changes.

Table 4.1 Experimental conditions of dynamic response

Parameter	**Value**
T_{cell} (℃)	30, 60
Current change (Low to High)	18A – 25A
Current change (High to Low)	25A – 18A
SR_a	1.5
SR_c	2
RH_a (%)	100
RH_c (%)	100



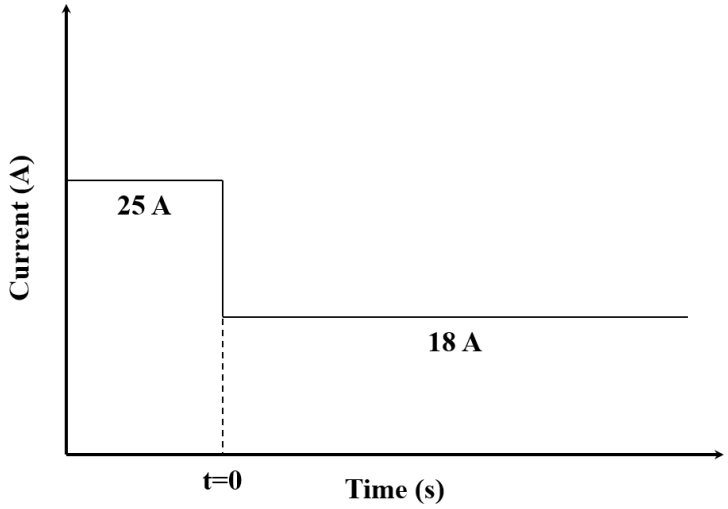


Fig. 4.1 Step current change – low to high (up), high to low (down)

4.3 Results

We measured steady state I-V polarization curve and voltage changes depending on the changes of step current under 30℃ and 60℃ temperature conditions. Especially, by using steady state voltage values, the time taken to the steady state was calculated. Table 4.2 shows the steady state voltage values of conventional fuel cell and fuel cell with metal foam under different temperatures.

4.3.1 Steady state performance of conventional fuel cell and fuel cell with metal foam

Fig. 4.2 indicates the I-V performance of conventional fuel cell and fuel cell with metal foam. Usually, the performance was enhanced with increasing the temperature regardless of fuel cell type. At the same temperatures, fuel cell with metal foam showed better performance compared to the conventional fuel cell. In all cases, the voltage levels were similar each other at low current density region, however, the gap was increasing as the current density was getting larger. The performance enhancement can be explained by the gas diffusivity because the movement of reactant gas molecules is increasing if the temperature is rising. Also high temperature helps to rise chemical reaction rate. It is helpful to hydrate membrane by using adequate quantity of produced water and increase membrane conductivity. But, since the water is easily condensed at low

temperature, water flooding phenomenon happens. Consequently, gas diffusion is interrupted by liquid water, and it deteriorates fuel cell performance.

The effect of water content and temperature is expressed by the followed equation.

$$\sigma(\mathrm{T},\lambda) = \sigma_{303K}(\lambda)\exp[1268\left(\frac{1}{303} - \frac{1}{\mathrm{T}}\right)]$$

$$\sigma_{303K}(\lambda) = 0.005193\lambda - 0.00326$$

In the above equation, σ means the conductivity of membrane(S/cm), λ indicates water content and T is the temperature. So, σ_{303K} means the conductivity of membrane at 303 K. Generally, the conductivity of Nafion membrane increases linearly as the water content increases, and enhances exponentially when the temperature rises. Therefore the results, shown in Fig. 4.2, are fit with this theoretical explanation and reasonable.

Table 4.2 Steady state voltage of conventional fuel cell and fuel cell with metal foam

Type	**Temperature**	**18A**	**25A**
Conventional	30℃	0.68V	0.58V
	60℃	0.71	0.64V
Metal foam	30℃	0.69V	0.63V
	60℃	0.72V	0.67V

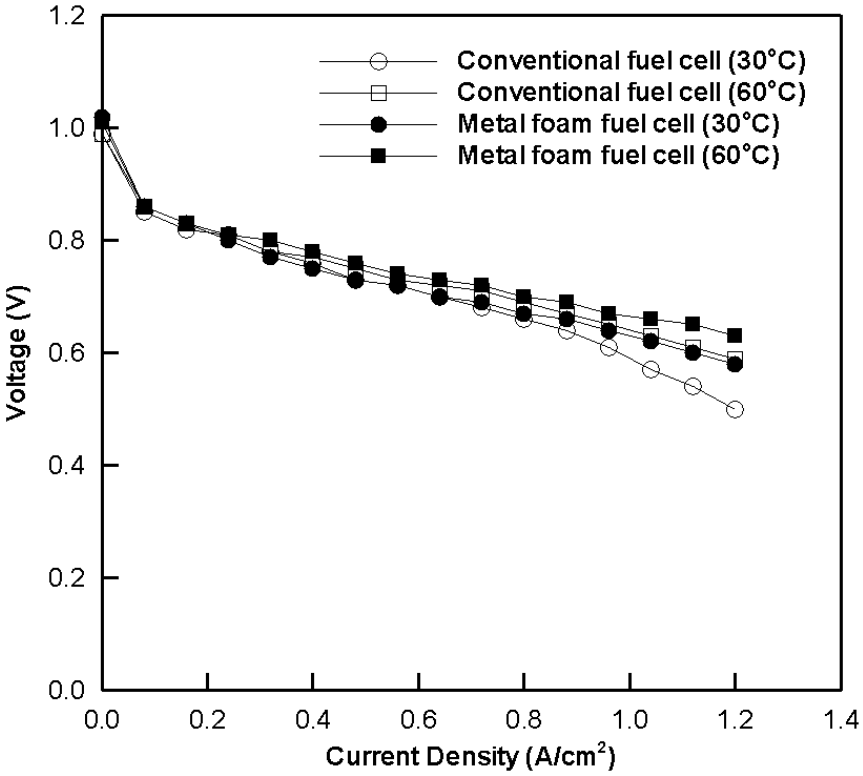


Fig. 4.2 Steady state polarization curve for conventional fuel cell and fuel cell with metal foam at 30℃ and 60℃

4.3.2 Dynamic response of conventional fuel cell and fuel cell with metal foam

Fig. 4.3 to 4.6 presents the experimental results at 30℃. Dynamic response of fuel cell with metal foam and conventional fuel cell was compared. Especially, because water can be condensed much at 30℃ temperature condition, the flooding phenomenon happens easily, if the channel structure is not optimal to drain water.

At first, when the current changes from 18 A to 25 A at 30℃, the voltage level of conventional fuel cell was very fluctuated and unstable. The maximum under shoot of voltage was 0.09 V and it took about 116 seconds to reach the steady state. Unlike this, when fuel cell with metal foam was used (Fig. 4.4), the voltage level was less fluctuated and relatively stable compared to the conventional fuel cell case. The maximum undershoot was 0.07 V and the time taken to the steady state was about 18 seconds.

Second, Fig. 4.5 and Fig 4.6 present the cases of current decrease from 25 A to 18 A. In case of current decrease, the water removal capacity becomes more important, because produced water exists inside the fuel cell a lot during the high load applied, so if the produced water was not removed appropriately, the flooding phenomenon happens, and fuel cell shuts down when the new and low current load is applied. Fig. 4.5 shows the voltage change of conventional fuel cell. The overshoot of voltage was 0.04 V and the time required to the steady state was 79 seconds.

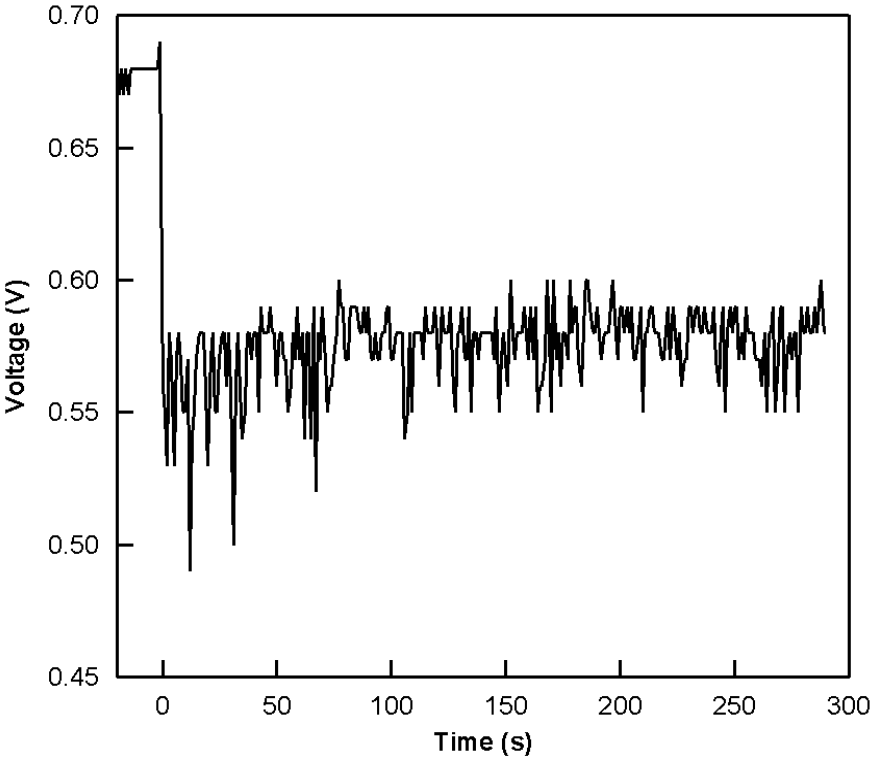


Fig. 4.3 Dynamic response of conventional fuel cell at 30℃, Step current change from 18 A to 25 A

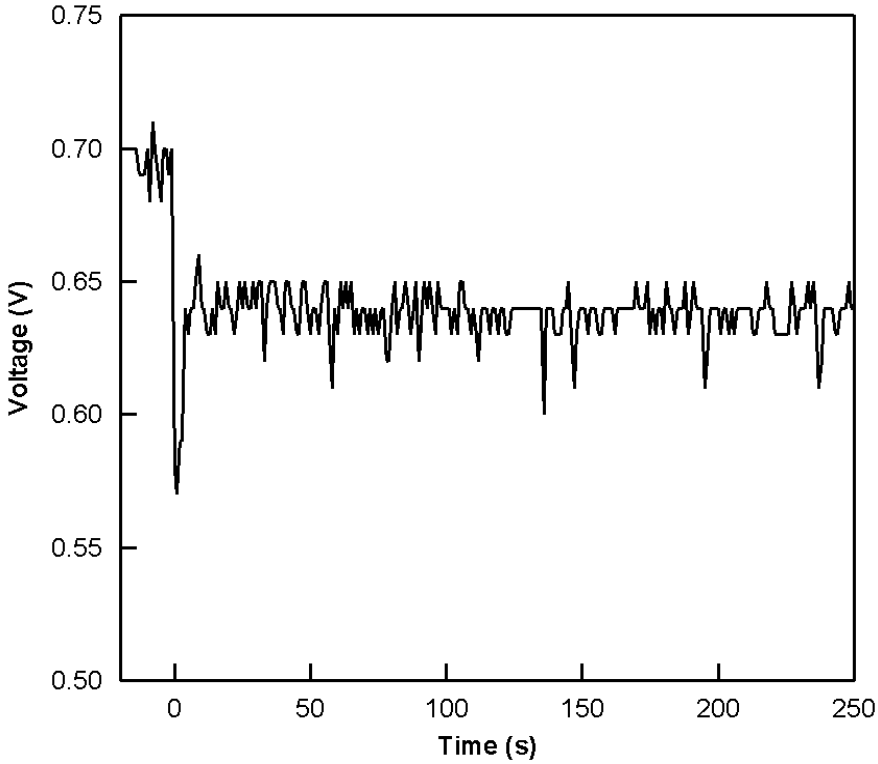


Fig. 4.4 Dynamic response of fuel cell with metal foam at 30℃, Step current change from 18 A to 25 A

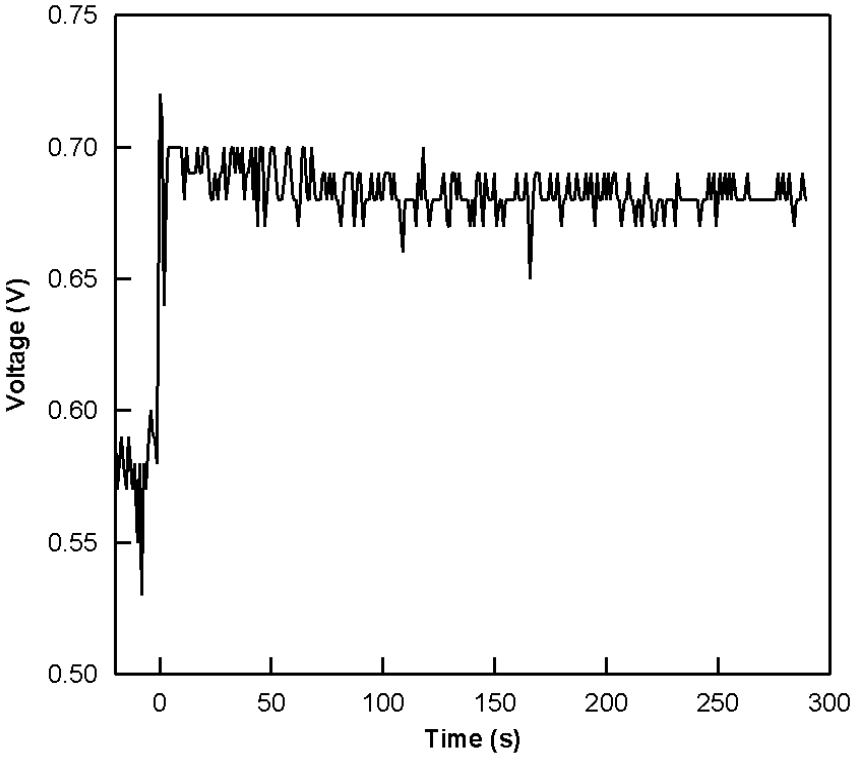


Fig. 4.5 Dynamic response of conventional fuel cell at 30℃, Step current change from 25 A to 18 A

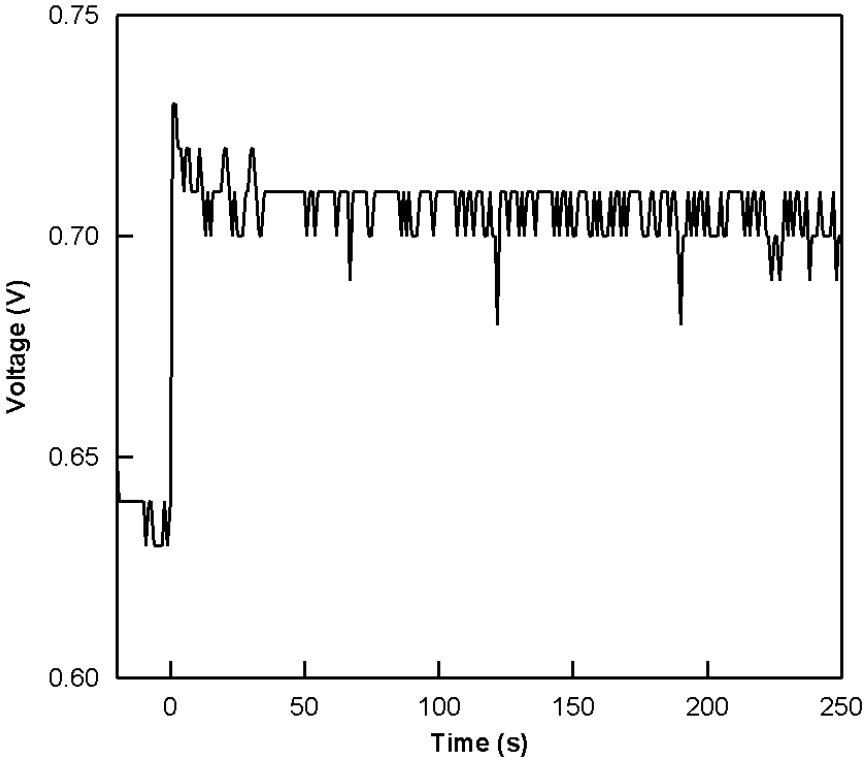


Fig. 4.6 Dynamic response of fuel cell with metal foam at 30℃, Step current change from 25 A to 18 A

However, in Fig. 4.6, the fuel cell with metal foam showed around 0.02 V overshoot, and 36 seconds was taken to reach the steady state voltage level.

Fig. 4.7 to 4.10 indicate the voltage changes according to the current changes at 60℃. Overall, voltage levels were stable and response time was also improved different from 30℃ cases. According to Fig. 4.7 which presents the transient response of conventional fuel cell at 60℃, voltage undershoot was about 0.08 V and the time taken to the steady state was 8 seconds. However, in case of fuel cell with metal foam, the undershoot was 0.04 V and time required to the steady state was about 5 seconds. In addition to that, fuel cell with metal foam shows kept constant voltage, without fluctuation, after the current change.

Fig. 4.9 and Fig. 4.10 present the voltage change when the current shifted from 25 A to 18 A. In case of conventional fuel cell, the voltage overshoot was 0.03 V and reaching time to steady state was 18 seconds. On the other hand, the fuel cell with metal foam showed 0.02 V voltage overshoot and it needed around 16 seconds to enter the steady state.

To summarize, the fuel cell with metal foam shows small voltage undershoot and overshoot and its response time was also instant. Therefore we concluded that dynamic performance can be improved by using porous media.

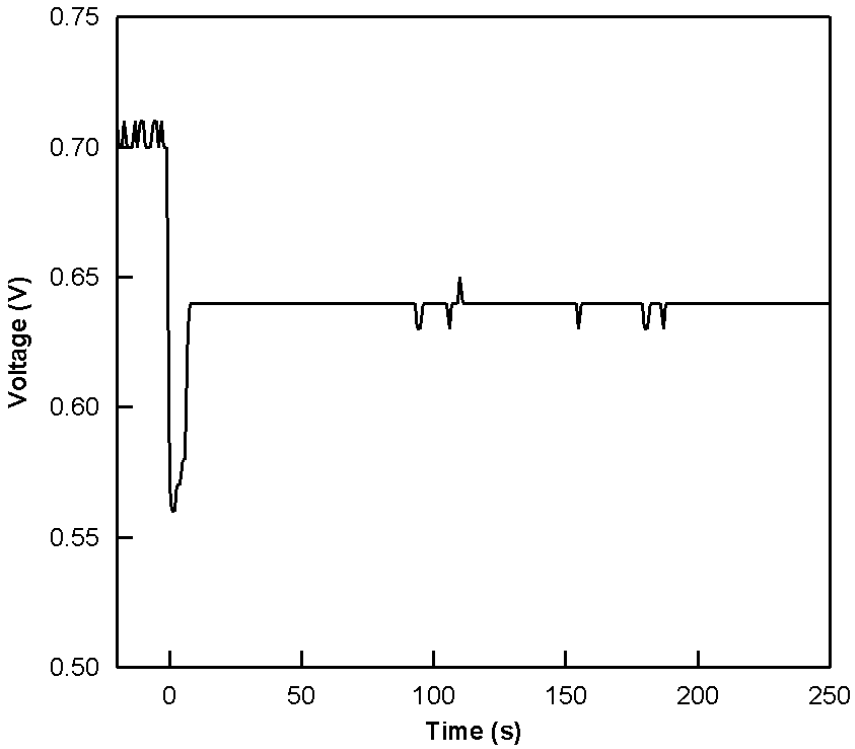


Fig. 4.7 Dynamic response of conventional fuel cell at 60℃, Step current change from 18 A to 25 A

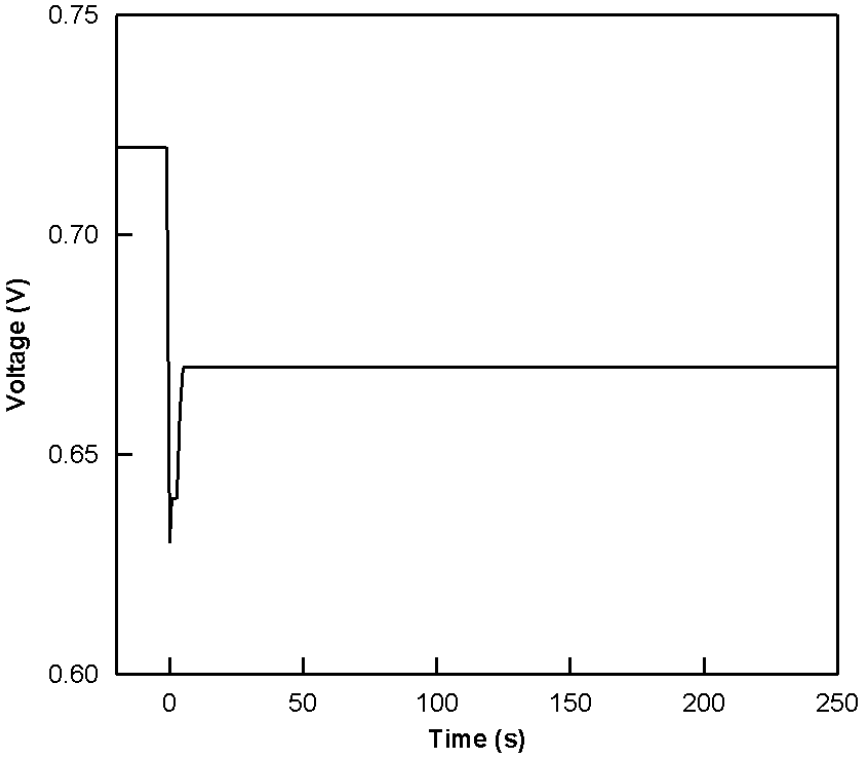


Fig. 4.8 Dynamic response of fuel cell with metal foam at 60℃, Step current change from 18 A to 25 A

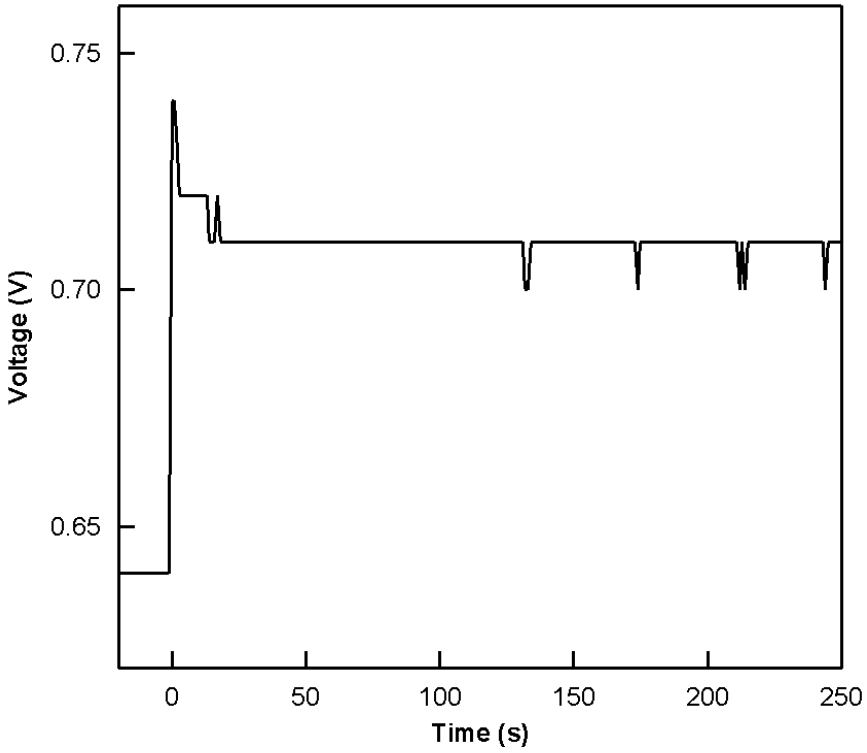


Fig. 4.9 Dynamic response of conventional fuel cell at 60℃, Step current change from 25 A to 18 A

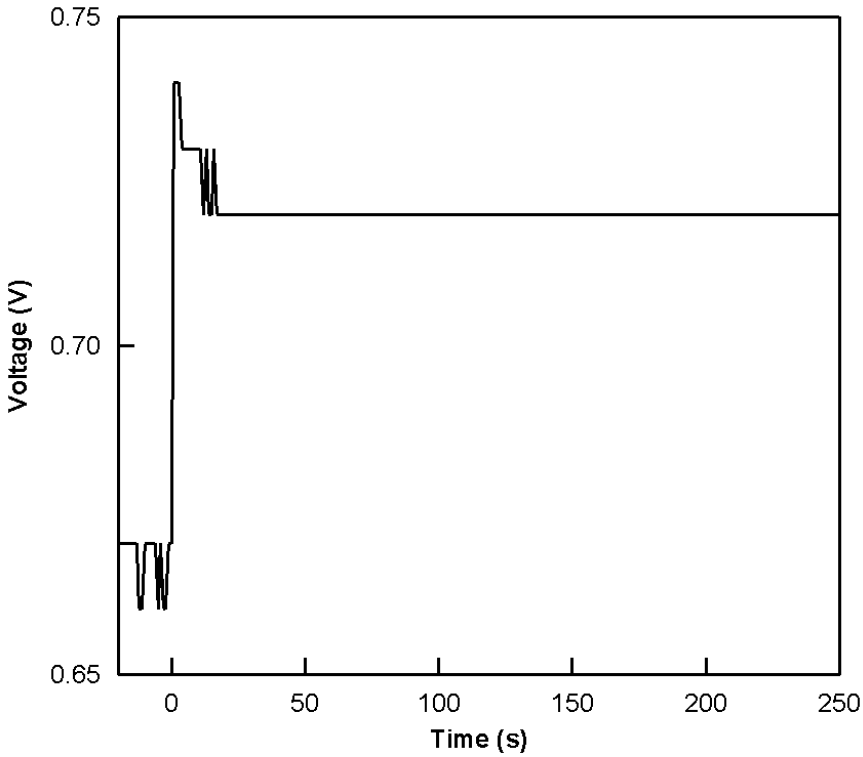


Fig. 4.10 Dynamic response of fuel cell with metal foam at 60℃, Step current change from 25 A to 18 A

4.4 Analysis

In many dynamic response studies, the explanations about the transient behavior of fuel cell under various conditions have done. Usually researchers have used theories and equations based on the gas diffusion and membrane hydration. In this chapter, the basic theories and equations about dynamic response are introduced. And these are connected to the experiment results.

4.4.1 Transient response analysis

Transient response consists of two parts. The first part is reactant gas distribution part. If the current value is changed that is loaded to the fuel cell, the necessary quantity of hydrogen and air will also be changed. Moreover, the more quickly the needed reactant gas is diffused evenly over the whole active area, the more power is produced. For example, when the current that is loaded to the fuel cell changes from low to high, the quantity of reactant gas which is needed is also increases. If the reactant gas is supplied to the MEA rapidly, and adequately, the undershoot or overshoot value will be decreased and the time taken to the steady state will also be shorter. The equation for the reactant gas distribution is followed:

$$\boldsymbol{\tau_k} = \frac{\boldsymbol{\delta_{GDL}}^{\mathbf{2}}}{\mathbf{D_g^{eff}}}$$

In this equation, $\boldsymbol{\tau_k}$ indicates the diffusion time and δ_{GDL} is the thickness of GDL. D_g^{eff} is the diffusivity of reactant gas. From this simple equation, We can conclude that the diffusion time depends on the diffusivity, because the thickness of GDL is constant.

The second part is membrane hydration part. Hydration of membrane is important because it decides the resistance of the membrane. If the membrane is not enough to be hydrated, in other words the membrane is dry, the resistance increases. As a result, the voltage level becomes lower. At each current level, the optimal hydration level exist. Lack of liquid water makes the membrane dried, however, too much amount of liquid water leads flooding phenomenon. Adequate quantity of liquid water reduced resistance and also makes reactant gas diffused well.

The equation related to the membrane hydration is followed:

$$\boldsymbol{\tau_m} = \frac{(\boldsymbol{\rho\delta_m\Delta\lambda})/\mathbf{EW}}{\mathbf{I/2F}}$$

$\boldsymbol{\tau_m}$ is membrane hydration time, and ρ means the density of membrane. EW is the equivalent weight of dry membrane (kg/mol), δ_m is the thickness of membrane. λ is the membrane water content, I is the current density. F is the Faraday constant. According to the membrane hydration time equation, the water content is important factor. Water content λ is the water molecules per

sulfonic acid group. Water content equation is followed:

$$\boldsymbol{\lambda = 0.043 + 17.81a_w - 39.85{a_w}^2 + 36.0{a_w}^3 \qquad \text{for} \quad 0 < a \leq 1}$$

$$\boldsymbol{\lambda = 14 + 1.4(a - 1) \qquad \text{for} \quad 1 < a \leq 3}$$

To summarize, the dynamic response of the fuel cell is closely related to the gas diffusion and membrane hydration. Above equations are the basic equations to understand the transient response.

4.4.2 Experiment results explanation

The experiment results showed that the fuel cell with metal foam has better transient response. The undershoot and overshoot values of fuel cell with metal foam were smaller than that of conventional fuel cell, and the time consumed to reach the steady state point was shorter in fuel cell with metal foam. From these phenomena, we can concluded that both of the diffusion time and membrane hydration time are able to be reduced if porous media is used as a flow distributor. These results verified that porous media enhances the gas distribution and keeps optimal quantity of liquid water inside the channels, and can be the strong evidence which shows the porous media is the promising material to improve fuel cell performance.

4.5 Summary

In this chapter, dynamic response of the fuel cell with metal foam was evaluated. While changing the current values, voltage level changes were observed. Consequently, the magnitude of voltage undershoot and overshoot was smaller in fuel cell with metal foam compared to the conventional fuel cell. In addition to that, it took less time to reach steady state when fuel cell with metal foam was used. Because the dynamic response is related to the gas diffusion time and the membrane hydration time, the fact that fuel cell with metal foam has better dynamic response means that porous media is useful to diffuse reactant gas evenly over the whole active area and manage liquid water well.

As a result of the experiments, we concluded that porous media is adequate to apply to fuel cells which are used in transportation. Also, the experiment results will encourage many researchers to continue to study on porous media as an effective flow distributor.

Chapter 5. Fuel cell with inclined channel

5.1 Introduction

In this chapter, we tried to create inclined serpentine flow field and conducted experiments to verify how much the performance is enhanced. Inclined channels have several advantages. At first, it can give momentum of upward direction to the reactant gases, in other words, it is easy for reactant gases to distribute toward catalyst layer and MEA, since channel height is reduced gradually. Second, the velocity of the reactant gases increases as it flows through the channels due to the decreased height. The accelerated gas flow pushes produced water much easier, as a result, water management characteristics can be improved.

Some papers made an attempt at simulations for sloped channels applied fuel cell. Mancusi *et al*. [24] studied tapered channels installed PEM fuel cell through the numerical analysis. They observed performance differences when slope angle changes. Meanwhile, Fontana *et al*. [25] focused on how produced water moves through the channels until it goes out from the fuel cell. They showed the process of the water removal depending on the time relatively well.

In this experiment, we made inclined channel applied fuel cell and evaluated the performance. Lastly, we compared the results with conventional fuel cell.

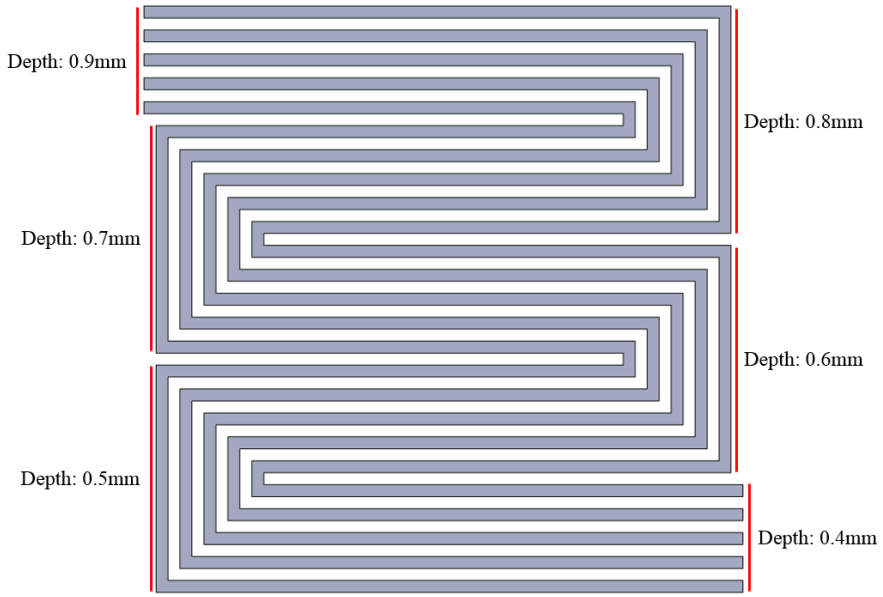
5.2 Experimental conditions

The performances of the conventional fuel cell and the fuel cell with inclined channel were compared each other. New channel structure will be introduced, and experimental conditions will be mentioned. In addition, the factors which were considered to calculate the performance are going to be shown.

5.2.1 Novel bipolar plate

In this experiment, only cathode side channel was modified. Fig. 5.1 shows the structure of the inclined channel which was used in this research. The inclined channel is basically serpentine channel structure. It is square shape and the active area is 25 cm^2 (width and height length are 5 cm). The inlet depth is 0.9 mm, and the depth is decreasing by 0.1 mm according to its length in horizontal direction. In case of vertical flow path, the channel depth was kept as the final depth of the horizontal flow path. Under this rule, the channel depth reduced as the reactant gases reach the outlet, finally, the outlet depth becomes 0.4 mm.

In case of the anode channel structure, the depth is 0.6 mm and width is 1 mm.



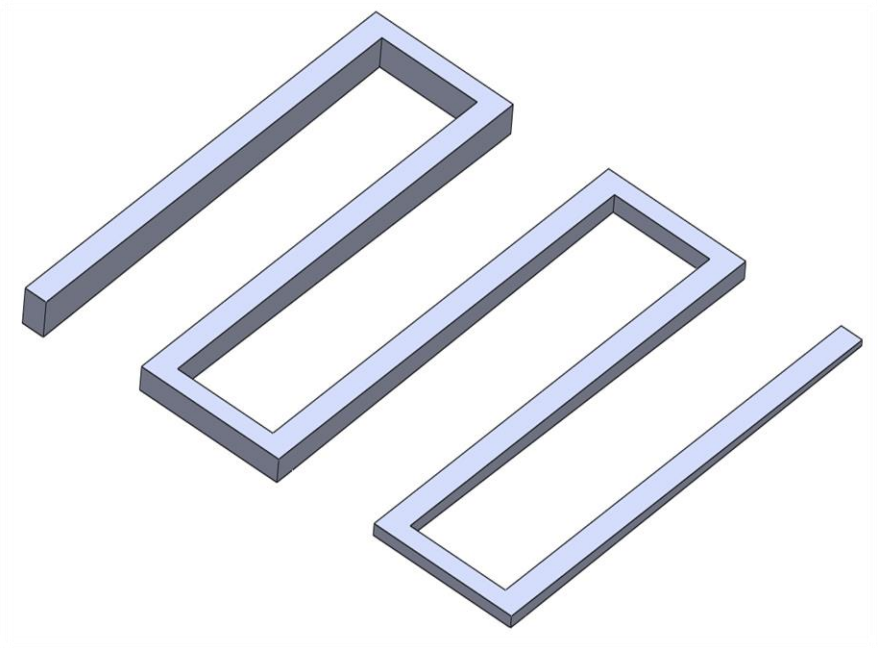


Fig. 5.1 Schematic of inclined channel structure

The bipolar plate is made of graphite and it has five channels. Each channel width is 1 mm.

The specifications of the conventional fuel cell, the control group, are same as the inclined fuel cell, except channel depth. The depth of the conventional PEMFC channel is 0.9 mm.

5.2.2 Experimental conditions

Table 5.1 shows the experimental conditions. In this experiment, we used conventional fuel cell and fuel cell with inclined channel. I-V performance and power density were measured. The operating temperature was 60℃ and relative humidity was 100% at both anode and cathode side. In case of the stoichiometry number, the stoichiometry number of the anode side was kept as 1.5 and the stoichiometry number of the cathode side was 2. Operating pressure was standard atmosphere pressure (1 atm).

5.2.3 Compressor power consumption calculation

Since the size of the inclined channel outlet is smaller than that of inlet, the pressure difference between inlet and outlet of fuel cell with inclined channel is higher. So, the pressure difference must be considered when the performance was calculated. Usually, many areas where the fuel cells are used need air compressor to supply air into cathode side at appropriate pressure. So, we

Table 5.1 Experimental conditions

Parameter	**Value**
T_{cell} (℃)	60
SR_a	1.5
SR_c	2
RH_a (%)	100
RH_c (%)	100

calibrated power values, generated from the fuel cell, by subtracting compressor power consumption. In this experiment, we deducted compressor work from an energy balance of an air compressor. If the required work to compress air is W, inlet temperature is T_1, outlet temperature is T_2, specific heat at constant pressure is C_p, mass flow rate is m, and air supplied to the cathode is assumed as ideal gas, compressor work can be written as:

$$W = \dot{m}C_p(T_2 - T_1)$$

And also, If this process is polytropic compression, following relation can be established:

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

In addition, in consideration of the compressor efficiency, compressor work can be calculated as follow:

$$W = \frac{1}{\eta_c}[\dot{m}C_pT_1\left\{\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1\right\}]$$

Table 5.2 shows parameter values at 60℃, fuel cell operation temperature.

5.2.4 Pressure difference measurement

As mentioned previous section (5.2.3), pressure difference between channel inlet and outlet was dissimilar depending on the channel types. Especially because the depth of the channels of fuel cell with inclined channel was shallow, pressure drop occurred much. Therefore, if the air compressor is used to supply air, the fuel cell with inclined channel consumes more electrical power. It is the reason why pressure difference should be considered to deduce effective power generation quantity. In order to measure pressure difference between cathode inlet and outlet, the differential pressure gauge was installed at the cathode side. Fig 5.2 presents the differential pressure gauge that was used in this experiment. Talking of the specification of the pressure gauge, the range of measurement is 0 to 10 kPa, and the accuracy is ±0.5%. Pressure difference was fluctuated a lot, since the phenomenon that the produced water gathered and moved out occurred frequently. So, we observed enough time and measured the values when the values reached the steady state.

Table 5.2 Parameters used in the compressor power consumption calculation

Parameter	**Value**
T_1 (℃)	60
$\dot{m}$	Flow rate at each current value
C_p	1.007
P_1 (atm)	1
P_2 (atm)	1+ΔP
k	1.399
η_c	80

Fig. 5.2 Differential pressure gauge

Fig. 5.3 indicates the pressure difference of the conventional fuel cell and the fuel cell with inclined channel. Of course, the pressure difference of the fuel cell with inclined channel was higher than that of the conventional fuel cell. At the low current density region, the pressure drops were almost unchanged, because the quantity of the reactant gas was small and the liquid water was merely produced at this region. On the other hand, at the high current density region, the pressure drop increased linearly, and the gap of the two cases was widening, because the chemical reaction rate increases and flooding phenomenon is observed at this region.

However, the important point that we have to focus on is the value of the pressure difference. According to the Fig. 5.3, the pressure difference of the fuel cell with inclined channel was just less than 6 kPa even at 1.68 A/cm^2 current density. Therefore, we can tell that the pressure drop gave minor effect to the performance calculation.

5.3 Experiment results

Fig. 5.4 and Fig 5.5 present the polarization curve and power density curve respectively. According to Fig. 5.4, voltage level of the fuel cell with inclined channel and conventional fuel cell was similar at the low current density region. However, the fuel cell with inclined channel kept relatively high voltage level even at the high current density region. It verified that the accelerated gas flow removed liquid water effectively, and it is consistent with the assumption.

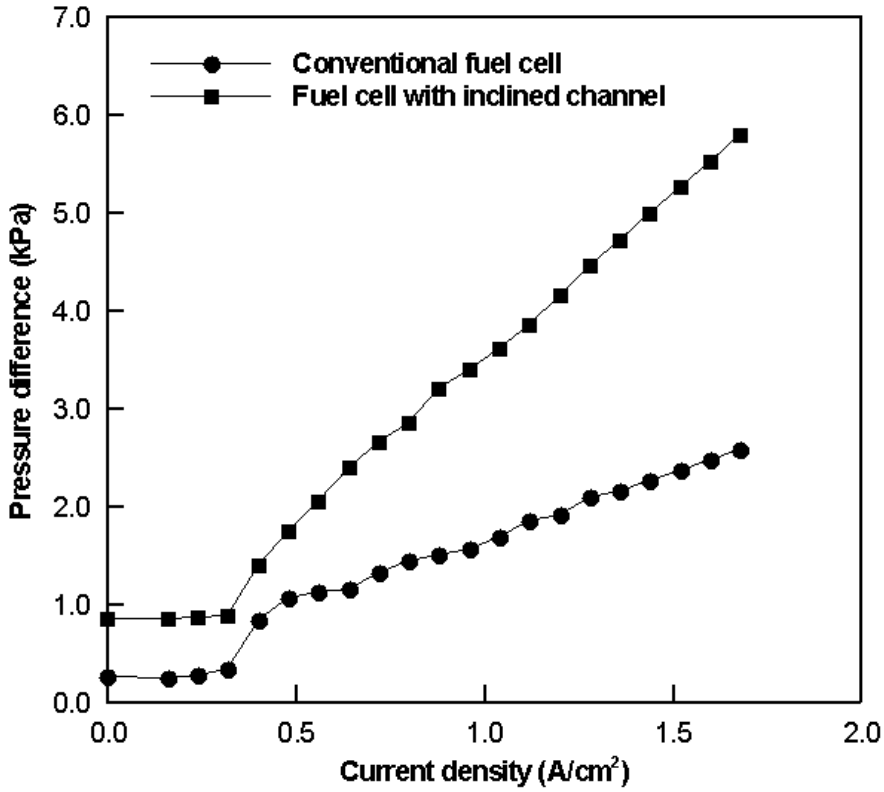


Fig. 5.3 Pressure difference between cathode inlet and outlet of conventional fuel cell and fuel cell with inclined channel

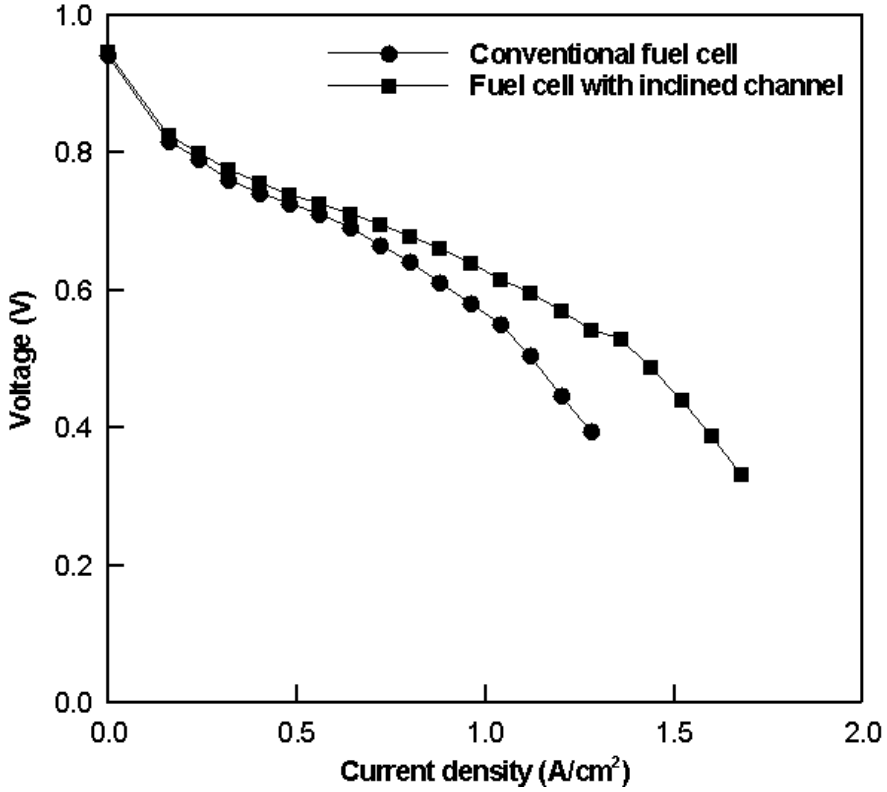


Fig. 5.4 I-V polarization curve comparison between conventional fuel cell and fuel cell with inclined channel

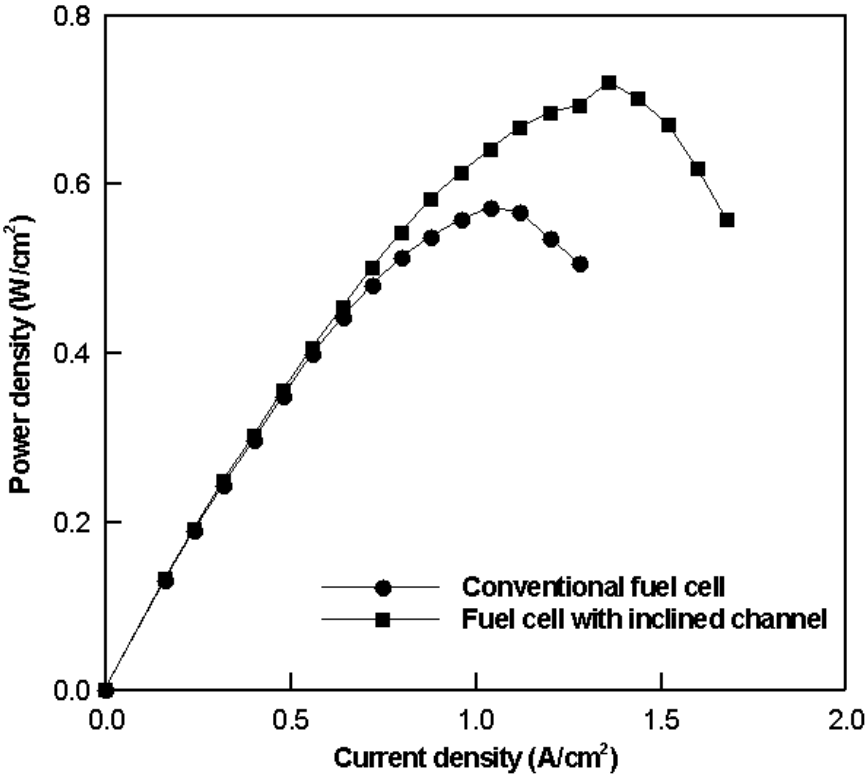


Fig. 5.5 Power density comparison between conventional fuel cell and fuel cell with inclined channel

Fig. 5.5 indicates the power density comparison. As mentioned at section 5.2.4, since the inclined channels have shallow depth, large pressure drop is inevitable. Therefore, the pressure drop must be considered when the power density is evaluated. At first, we measured the power and subtracted compressor power consumption. By doing so, effective power density values were deducted. Also, in order to compare the maximum power density of conventional fuel cell and fuel cell with inclined channel, peak power densities were assessed. In conclusion, the peak power density of the fuel cell with inclined channel was about 25.7% higher than that of conventional fuel cell.

5.4 Analysis

We analyzed why the fuel cell with inclined channel showed better performance. We focused on the velocity changes of the reactant gas in the inclined channels. In this chapter, the velocity of the gas flow was considered and we observed the movement of the fluid flow by using ANSYS FLUENT program.

5.4.1 Simplify the channel structure

In real experiments, the number of channels was five, but the only single serpentine channel was considered here in order to simplify the simulation. And we assumed that the channel is the rectangular pipe, and only air flows inside.

Air entered the inlet with 1.39×10^{-5} kg/s that is the mass flow rate at the $1A/cm^2$ current density. We used only fluid flow model and set k-epsilon model as viscous model.

5.4.2 Simulation results

Fig. 5.6 shows the simulation results. The velocity contours over the whole channel. Overall, the velocity scale of the inclined channel was larger than that of conventional channel. Over the whole channel area, the velocity values were almost same in conventional channel, on the other hand, the velocity gradient was clear in inclined channel. Through this simulation results, we can predict that the flow will be accelerated along the flow path. Especially, if there are water droplets, the effect of pushing them might be larger in fuel cell with inclined channel. If we consider the small pressure drops of fuel cell with inclined channel, it can be concluded that the inclined channel is very effective structure.

5.5 Summary

In this chapter, inclined channel structure was adopted to raise the fuel cell performance. The channel depth was gradually decreased, the outlet depth became just 4/9 of the inlet depth. By using this kind of channel structure, the velocity of the reactant gas was able to be increased, consequently, the

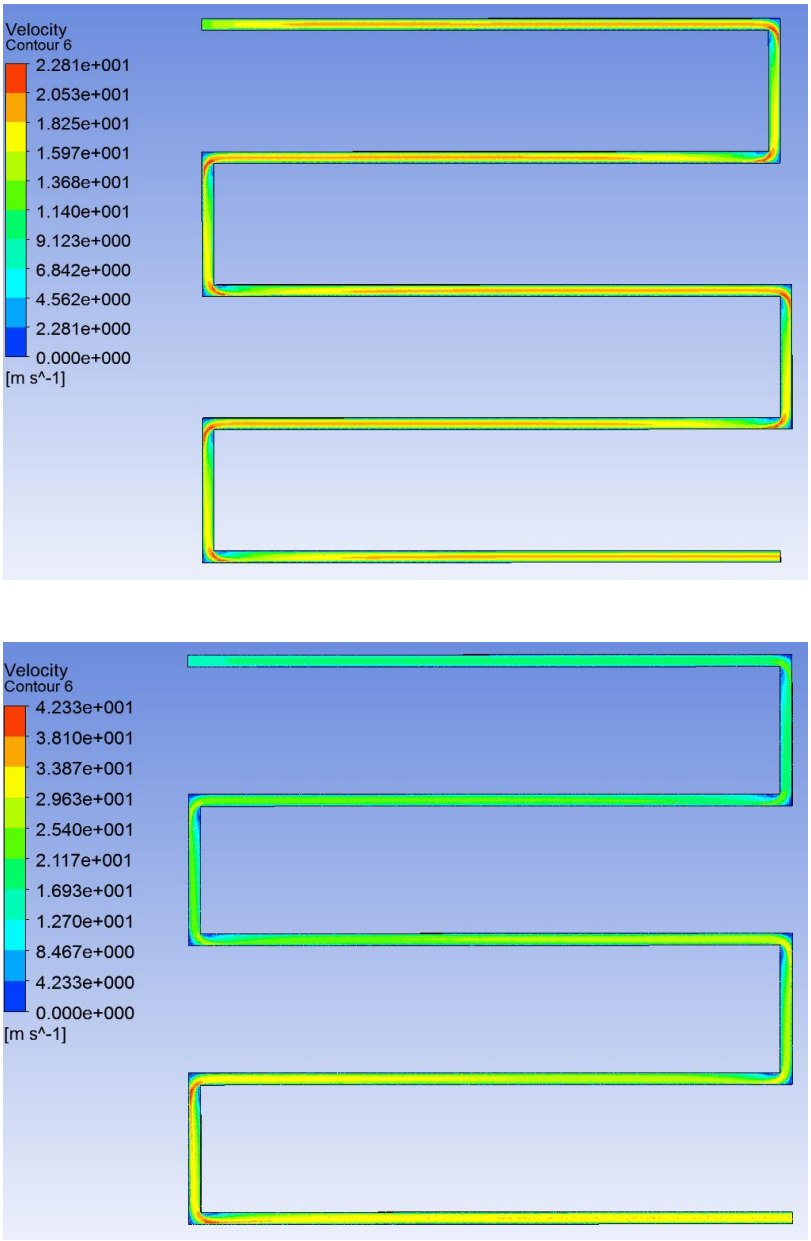


Fig. 5.6 Velocity contour of single conventional channel (up) and inclined channel (down)

accelerated reactant gas flow removed produced liquid water much easily. Like the assumption, the fuel cell with inclined channel kept relatively high voltage at the high current density, and showed higher power density. Although the pressure drops of the fuel cell with inclined channel was larger than that of conventional fuel cell, pressure drop range was very small. Therefore, even though pressure drops were considered, the performance was enhanced a lot compared to the conventional fuel cell. Also, by using ANSYS FLUENT, fluid velocity was simulated. The simulation results were also consistent with the experiment results.

Chapter 6. Conclusion

In this study, two different types of novel fuel cells were suggested. First, the performance of the fuel cell with porous media (metal foam) was evaluated. All channel structures of cathode side were removed and metal foam was inserted in the flow field. Fuel cell with metal foam showed better performance compared to the conventional fuel cell and tended to keep higher voltage levels even at the high current density region. It is because metal foam makes even pressure distribution over the whole active area, and gives freedom of flow to reactant gas. Also, since produced water is not condensed at specific region, it is easy to move out through the outlet.

Second, the fuel cell with inclined channel was suggested. It had basically serpentine structure, but the depth of the channels were becoming shallow along the flow path. The inlet depth was 0.9 mm and the outlet depth was 0.4 mm. Due to the depth changes, the velocity of the reactant flow became faster, this accelerated gas flow was able to remove produced water well. Improved water management characteristics helped to enhance the performance of the fuel cell.

From these results, we concluded that just by modifying channel and bipolar plate structures, the performance can be improved a lot, and the studies on this field are worth doing continuously in order to develop high performance, next generation fuel cell.

References

[1] Xianguo Li, Imran Sabir. Review of bipolar plates in PEM fuel cells: Flow-field designs. International Journal of Hydrogen Energy 2005;30:359-371

[2] Shiro Tanaka, Toshio Shudo. Significant performance improvement in terms of reduced cathode flooding in polymer electrolyte fuel cell using a stainless-steel microcoil gas flow field. Journal of Power Sources 2014;248:524-532

[3] Shiro Tanaka, Toshio Shudo. Corrugated mesh flow channel and novel microporous layers for reducing flooding and resistance in gas diffusion layer-less polymer electrolyte fuel cells. Journal of Power Sources 2014;268:183-193

[4] Chung-Jen Tseng, Bin Tsang Tsai, Zhong-Sheng Liu, Tien-Chun Cheng, Wen-Chen Chang, Shih-Kun Lo. A PEM fuel cell with metal foam as flow distributor. Energy Conversion and Management 2012;62:14-21

[5] Bin-Tsang Tsai, Chung-Jen Tseng, Zhong-Sheng Liu, Chih-Hao Wang, Chun-I Lee, Chang-Chng Yang, Shih-Kun Lo. Effect of flow field design on the performance of a PEM fuel cell with metal foam as the flow distributor. International Journal of Hydrogen Energy 2012;37:13060-13066

[6] Tetsuro Kariya, Tomoki Hirono, Hiroshi Funakubo, Toshio Shudo. Effect of the porous structures in the porous flow field type separators on fuel cell performances. International Journal of Hydrogen Energy 2014;39:15072-15080

[7] P. Karthikeyan, R.J. Vasanth, M. Muthukumar. Experimental investigation on uniform and zigzag positioned porous inserts on the rib surface of cathode flow channel for performance enhancement in PEMFC. International Journal of Hydrogen Energy 2015;40:4641-4648

[8] Ryo Koresawa, Yoshio Utaka. Water control by employing microgrooves inside gas channel for performance improvement in polymer electrolyte fuel cells. International Journal of Hydrogen Energy 2015;40:8172-8181

[9] Seong Ho Han, Nam Hyeon Choi, Young Don Choi. Study on the flooding phenomena and performance enhancement of PEM fuel cell applying a Concus-Finn condition. Renewable Energy 2012;44:88-98

[10] Natthawoot Bunmark, Sunun Limtrakul, Michael W. Fowler, Terdthai Vatanatham, Jeff Gostick. Assisted water management in a PEMFC with a modified flow field and its effect on performance. International Journal of Hydrogen Energy 2010;35:6887-6896

[11] F. Tiss, R. Chouikh, A. Guizani. A numerical investigation of reactant transport in a PEM fuel cell with partially blocked gas channels. Energy Conversion and Management 2014;32-38

[12] Shiang-Wuu Perng, Horng-Wen Wu. A three-dimensional numerical investigation of trapezoid baffles effect on non-isothermal reactant transport and cell net power in a PEMFC. Applied Energy 2015;143:81-95

[13] A. Ghanbarian, M.J. Kermani. Enhancement of PEM fuel cell performance by flow channel indentation. Energy Conversion and Management

2016;110:356-366

[14] Jenn-Kun Kuo, Cha'o-Kuang Chen. Evaluating the enhanced performance of a novel wave-like form gas flow channel in the PEMFC using the field synergy principle. Journal of Power Sources 2006;162:1122-1129

[15] R. Roshandel, F. Arbabi, G. Karimi Moghaddam. Simulation of an innovative flow-field design based on a bio-inspired pattern for PEM fuel cells. Renewable Energy 2012;41:86-95

[16] Jason P. Kloess, Xia Wang, Joan Liu, Zhongying Shi, Laila Guessous. Investigation of bio-inspired flow channel designs for bipolar plates in proton exchange membrane fuel cells. Journal of Power Sources 2009;188:132-140

[17] Fu-Pin Ting, Chung-Wei Hsieh, Wei-Heng Weng, Jing-Chie Lin. Effect of operational parameters on the performance of PEMFC assembled with Au-coated Ni foam. International Journal of Hydrogen Energy 2012;37:13696-13703

[18] Atul Kumar, Ramana G. Reddy. Polymer electrolyte membrane fuel cell with metal foam in the gas flow field of bipolar/end plates. Journal of New Materials for Electrochemical Systems 2003;6:231-236

[19] K.H. Loo, K.H. Wong, S.C. Tan, Y.M. Lai, Chi K. Tse. Characterization of the dynamic response of proton exchange membrane fuel cells – A numerical study. International Journal of Hydrogen Energy 2010;35:11861-11877

[20] Sunhoe Kim, S. Shimpalee, J.W. Van Zee. The effect of stoichiometry on

dynamic behavior of a proton exchange membrane fuel cell (PEMFC) during load change. Journal of Power Sources 2004;135:110-121

[21] Qiangu Yan, H. Toghiani, Heath Causey. Steady state and dynamic performance of proton exchange membrane fuel cells (PEMFCs) under various operating conditions and load changes. Journal of Power Sources 2006;161:492-502

[22] Bosung Kim, Dowon Cha, Yongchan Kim. The effect of air stoichiometry and air excess ratio on the transient response of a PEMFC under load change conditions. Applied Energy 2015;138:143-149

[23] Atul Kumar, Ramana G. Reddy. Effect of gas flow-field design in the bipolar/end plates on the steady and transient state performance of polymer electrolyte membrane fuel cells. Journal of Power Sources 2006;155:264-271

[24] Erasmo Mancusi, Eliton Fontana, Antonio Augusto Ulson de Souza, Selene M.A. Guelli Ulson de Souza. Numerical study of two-phase flow patterns in the gas channel of PEM fuel cells with tapered flow field design. International Journal of Hydrogen Energy 2014;39:2261-2273

[25] Eliton Fontana, Erasmo Mancusi, Antonio Augusto Ulson de Souza, Selene M.A. Guelli Ulson de Souza. Flow regimes for liquid water transport in a tapered flow channel of proton exchange membrane fuel cells. Journal of Power Sources 2013;234:260-271

국 문 초 록

수소연료전지는 수소와 산소의 화학반응을 이용해 전기에너지를 생산해 내는 기관으로 부산물로 물만이 발생되는 환경 친화적인 에너지원이다. 오늘날 화석연료 사용에 따른 환경오염문제, 화석연료 고갈에 따른 신 에너지원 개발의 필요성에 따라 수소연료전지는 친환경-신재생 에너지원으로 각광받고 있다.

하지만 수소연료전지의 많은 장점들에도 불구하고 가격요인, 여러 기술적 제약으로 인해 널리 상용화 되지 못하고 있는 실정이다. 특히 높은 출력을 얻기 위해 반응면적을 넓히고 많은 분리판을 적층하는 과정에서 부피와 무게가 증가하여 상용화하는데 큰 어려움이 있다.

본 연구에서는 위와 같은 문제를 해결하기 위하여, 같은 단위면적에서 고출력을 발생시킬 수 있는 연료전지를 개발하고자 하였다. 그 방법으로 공기극 분리판의 유로구조를 변화시켜 반응기체의 확산을 개선하고, 생성수의 관리가 잘 이루어 질 수 있는 연료전지를 설계하였다. 본 연구에서는 크게 두 가지의 새로운 유로구조를 제안하였다.

첫 번째로, 공기극 유로구조를 모두 없애고 금속 다공체(메탈폼)를 삽입하였다. 기공크기가 서로 다른 다섯 가지의 금속 다공체를 사용하여 성능을 평가하였으며, 기존 사형유로구조와 비교하였다. 그리고 금속 다공체를 삽입한 연료전지의 동특성 분석 실험을

수행하여, 기존의 연료전지에 비해 빠른 반응성과 안정성을 나타냄을 보였다.

두 번째로, 기존의 사형유로구조를 유지하되, 유로의 깊이가 서서히 얕아지는 경사진 유로를 적용한 연료전지의 성능평가를 수행하였다. 유로의 깊이가 얕아짐에 따라 반응기체의 흐름속도가 증가되어 생성수를 효과적으로 제거하고, 점점 옅어지는 산소농도에도 불구하고 확산이 잘 이루어 질 수 있도록 고안되었다.

실험 결과, 새로운 유로구조를 적용한 두 가지의 연료전지 모두 기존의 사형유로구조를 적용한 연료전지보다 고성능을 나타내었으며, 반응기체의 고른 확산, 생성수의 효과적인 관리 측면에서 개선되었음을 확인 할 수 있었다. 이 같은 결과들은 유로구조의 개선만으로 같은 반응면적에서 획기적인 성능증가가 가능함을 보인 것으로, 유로구조 연구의 중요성을 시사하는 것이라 할 수 있다. 또한 유로, 분리판에 대한 지속적인 연구를 통해 연료전지의 소형화, 경량화를 이루어, 보다 많은 분야에서 연료전지가 적용될 수 있을 것이라 예상한다.

주요어: 고분자 전해질막 연료전지, 금속 다공체, 경사진 채널, 생성수 관리, 기체 확산, 동특성

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