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Experimental Analyses of Cell Voltages for a Two-cell PEM Stack Under Various Operating Conditions

Sang-Kyun Park[1] · Jae-Hyuk Choi†

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Abstract : Analyses of performance and behavior of the individual PEM fuel cells (PEMFC) under different operating conditions are of importance optimally to design and efficiently to operate the stack. The paper focuses on experimental analyses of a two-cell stack under different operating conditions, which performance and behavior are measured by the voltage of a cell as well as the stack. Experimental parameters include stoichiometric ratio, temperature of the air supplied under different working stack temperatures and loads. Results showed that the cell voltages are dominantly influenced by the temperature of the air supplied among others. In addition, an inherent difference between the first and the second cell voltage exists because of the tolerances of the cell components and the resulting different over-potentials at different equilibrium states. Furthermore, it is shown that the proton conductivity in the membranes conditioned by the humidity in the cathode channel highly affects the voltage differences of the two cells.

Key words : PEMFC, Stack, Cell voltages, Humidity

1. Introduction

Polymer Electrolyte Membrane Fuel cell (PEMFC) has the highest potential as a candidate for a power source of future because of the low operating temperature, a relatively short start-up time and a high power density.

The fuel cell stack is constructed by assembling different component layers in series that serve to provide pathways for reactants, charges and byproducts. The complexity of this reaction and transport mechanism of the mass and charges exposed in a varying temperature environment has not been fully investigated, even though experimental and theoretical analyses have been published. Particularly, most of the experimental research conducted in the past years has been based on analyses of the performance of either the single cell or the whole stack simply by measuring the single or whole stack voltage under various operation conditions[1-20].

In reality, the performance of the individual cells in a stack is different each other, even though the same technologies are used. The cell voltages can vary with design, locations, and operating conditions, to name a few. Thus, the cell voltages of a single cell or stack are experimentally investigated to find out physical laws subject to various operating conditions. The key parameters considered include the working temperature, humidity on the air stream, pressure and the stochiometric numbers.

The temperature in a stack is not uniformly

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† Corresponding Author(Division of Marine System Engineering, Korea Maritime University, E-mail: choi_jh@hhu.ac.kr, Tel. 051-410-4257)
1 Korean Register of Shipping

distributed and changes continuously because of different heat source terms in the layers. At the same time, the resulting temperature influences the exchange current density, gas diffusivity, membrane conductivity and water condensation as well as evaporation. The higher the working temperature in the stack is, the more reactive the chemical reaction becomes and consequently the cell performance is improved. In contrast, the high temperature can potentially decrease proton conductivity in the membrane by possible dehydration and subsequently the performance can drop[1,2].

The dew point temperature of the supplied gas influences the partial pressure of the vapor. When the dew point temperature of the supplied gas gets increased, the vapor mass flux tends to follow, which affects dehydration of the membrane or water flooding dependent upon the temperature of the cell operating[5].

The operating pressure directly influences the partial pressure of the reactant. When the operating pressure gets increased, the performance of a cell gets improved. Particularly, a high pressure at the high current load enables a safe operation[9].

In addition, the air stoichiometric ratio influences not only oxygen available for the reaction, but also removal of water produced, which subsequently affects water content in the membrane. Specifically, an increase of the flow rate at a high current load can potentially repel more water than the produced. As a result, the water in the membrane can be imbalanced and the membrane is likely to be dehydrated, even though the availability of oxygen increases the reaction rate in the catalyst[1, 3, 6-8].

Effects of the operating conditions on the performance of an individual cell of the stack have been investigated by measuring ohmic voltage losses, impedance of a stack, individual cell voltages or a combination of them. However, the measured quantities do not provide a clear causality between the operating conditions and the performance. Thus, it is hard for performance of a stack to get standardized.

The air stream should be properly humidified to balance between water produced, taken up by protons in the membranes and exited. Specifically, the balance of water content in the membrane is of importance for protons to keep high conductivity and consequently increase the efficiency and reduce the heat produced[14-16].

The ohmic voltage loss in the individual cells measured by Tuomas et al[17]. uses the method of the current interruption under two limited air supply conditions and assesses performance of the cells. Conductivities of the individual cells are estimated by the ohmic losses. However, extensive investigations of the operating conditions on the performance have not completed. Xiaozi et al. [18] measures ohmic resistances of the individual cells by the impedances by the EIS. However, the only one operating condition varied is the load current. Paul et al[19]. explained effects of four design and operating factors on cell voltage distributions across the stack. It is shown that the I-V characteristics of individual cells are influenced by temperature distribution, degradation and tolerance of the components as well as design parameters of the flow patterns. The only operating condition considered for the experiment is the load current.

Studies conducted in the paper focuses on experimental analyses of a two-cell stack by measuring the individual cell voltages under three different operating conditions. These are the working temperature of the stack, the temperature of the air at the inlet and the stoichiometric ratio at different load currents. In fact, distributions of the cell voltages in a stack are not explicitly. The understanding of the dependence of individual cell voltages on operating conditions benefits the one to fit the stack to the conditions and maximizes the performance.

2. Experimental apparatus and method

2.1 Apparatus

The schematic of the experimental set-up is depicted in Figure 1. The test station consists of a two-cell stack and the balance-of-the-plant that includes an air supply, a humidification, a hydrogen delivery system, a coolant circuit and a control system. In addition, instrumentations and an electric load connected to the stack are included.

The air at the inlet of the stack is supplied by two air blowers. The air and humidification system mixes a dry air stream and a humidified air stream together to achieve a target relative humidity and temperature prior to entering the fuel cell. The hydrogen was automatically supplied through the mass flow meter proportional to the load current produced. The coolant is controlled by an electrical pump to keep the temperature of the coolant channel outlet of the stack. Thus, the working temperature can be assumed to be the same as to the temperature of the coolant water outlet.

The stack is constructed with two cells separated by a thermally conductive plate in order to minimize potential influences of the coolants on the working temperature. Except the separator, other components are the same as those in a typical assembly, which is shown in the Figure 2.

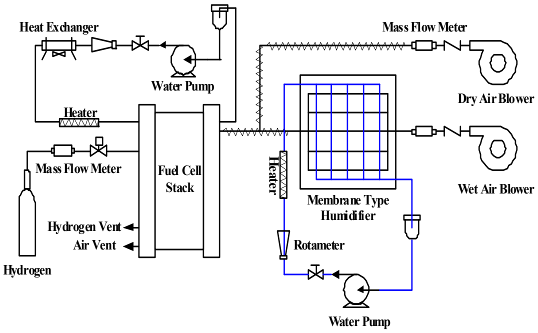
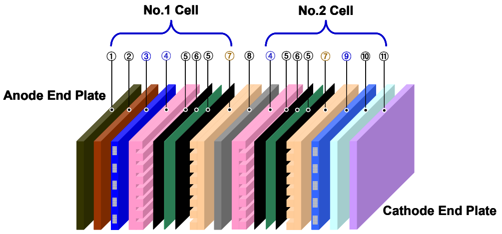


Figure 1: Schematic of experimental apparatus



①	Anode End Plate	⑦	Cathode Gas Channel Plate
②	Anode Bus Plate (Current collector)	⑧	Separator (No coolant channel)
③	Anode Cooling Plate	⑨	Cathode Cooling Plate
④	Anode Gas Channel Plate	⑩	Cathode Bus Plate (Current collector)
⑤	Gas Diffusion Layer	⑪	Cathode End Plate
⑥	MEA		

Figure 2: A two -cell stack

In addition, a wire lead is connected to the separator, so that the voltages are measured across the separator and the bus plates. The cell fabricated has an active area of 140 cm^2. The membrane (Series 5510) and the GDL (ELAT v3.0) have a thickness of 0.035 mm and 0.4 mm. The plate for the gas flow channel is 1.5 mm thick and made of TM graphite. The plates for the coolant channels and the separator are made of graphite (AXF-5Q-PYC), which thickness is 3 mm and 1.5 mm. The thickness of the endplate (G-10 Garolite) and the bus plate (Gold-plated 316 stainless steel) is 28.5 mm and 1.5 mm, respectively. The maximum electric power of the stack is 80 W.

2.2 Experimental conditions and measurement

The I-V characteristics of the cells were obtained by measuring the voltage of individual cells and the stack current at three different parameters under different load current; working stack temperature (T_{st}), air temperature (T_{air}), and air stoichiometric

Table 1: Experimental conditions

Supply air temperature (℃)	30 (a1), 40(a2), 50 (a3), 60(a4)
Stack operating temperature (℃)	40 (b1), 50(b2), 60(b3)
Air stoichiometric ratio (-)	2 (c1), 3(c2), 4(c3)
Relative humidity of air (%)	100

ratio (Air_{stoich}), which is summarized in the Table 1.

The hydrogen was supplied as a dry gas under a room temperature. The stoichiometric ratio for the hydrogen is set to being 1.2 over the whole range of the load current. The air is fully humidified and the stoichiometric ratio is set according to the load current.

Experiments have been carried out in following steps. Firstly, the coolants are heated up and then circulated through the stack until the outlet temperature of the stack takes a stable and constant temperature that is assumed as initial working temperature of the stack. The experiments are started by applying a load current, after the temperature, the flow rate and the relative humidity of the air setby the blowers gets stabilized. In addition, the anodic side is purged for 1 sec in every three minutes to avoid the back diffusion of water from the cathode side and minimize the subsequent voltage drops.

Figure 3 shows voltage and current of the two cells with respect to the time (Left) and the I-V characteristic (Right) at a load current. The operating conditions are T_{st} = T_{air} = 60℃, Air_{stoich} = 3 and the RH=100%. The load is a multiple step current, whose magnitude varies from 0 to 60 A with duration of 1 minute.

The output voltage is an average of two values at the positive and negative edges of each current step.

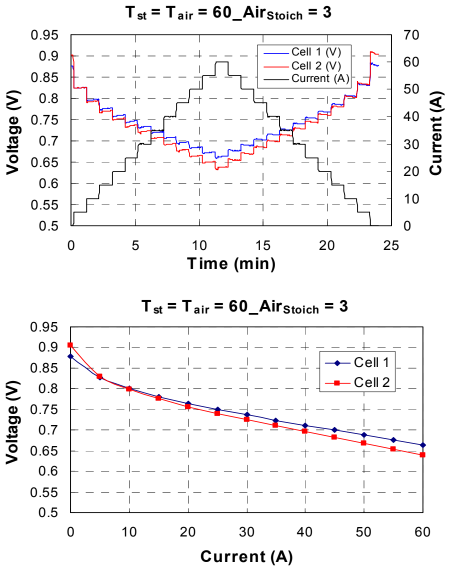


Figure 3: Voltages with respect to time and I-V curves of the two cells

The results clearly illustrate the voltage difference of the cells results from the physical background aforementioned.

3. Results and analyses

3.1 Case for Tst=Tair

In the following, the temperature of the air supplied is set to be identical with the working temperature of the stack. Figure 4(a), (b) and (c) show the I-V curve dependent upon the changes of the temperature and the stoichiometric ratio. Fig. 4(d) shows the voltage differences of the two cells at different air stoichiometric ratios.

The I-V curves show that the cell voltages increase when the temperature is elevated from 40℃ to 60℃ regardless of the stoichiometric ratios. In fact, an elevated working temperature of the stack increases the thermal energy of reactant molecules and subsequently the gas diffusivity. In addition, the ionic conductivity in the membrane is affected by the temperature and the water content in the membrane [15]. The ionic conductivity in the membrane gets increases with increasing the working temperature of the stack as long as hydration of the membrane remains constant. On the other hand, the water content in the membrane tends to increase when the water concentration in the cathode gas channel gets increased by a higher saturation temperature of the supply air. As a result, the ionic conductivity in the membrane gets increased and the associated ohmic losses decreased.

Figure 4(d) shows, the voltage difference between the two cells gets larger regardless of the air stoichiometric ratio at a working temperature set as the load current increases. It turns out that the voltage drop at the cell 2 is larger than the one at the cell 1, even though both cells constructed have the same geometry and material properties. In fact, the ionic conductivity in the membrane is the most dominant factors in determining the voltage drops in the cells, which magnitude depends upon the water content in the membrane, the thickness of membrane and the cell working temperature. It showed that the difference of the cells voltages drop amounts to 0.01 V at a load current 60 A and Air_{stoich} = 2 when the temperature of the stack and air is raised from 40℃ to 60℃. However, the average value of the voltage difference has not changed at the same load current, even though the Air_{stoich} has been varied. As a result, it can be concluded that the voltage drop in the cell 2 is not affected by the temperature variation. In addition, the variation of the cell voltages by different Air_{stoich} remains identical at different working temperature.

When the temperature of the air supplied is identical with the one of the stack, it can be presumed that membranes of both cells are fully humidified, which implies no direct influence of the air flow rate on the voltage drop of the cell 2. Therefore, the difference of the ohmic over-potentials in the cell 2 is regarded as results from fabrication tolerances of the two cells, even though two cells have the same thickness of membrane. These are inherent and basic I-V characteristics that should be taken into account for optimal operations of a stack. The maximum deviation between the two cell voltages has been identified with 0.032 V at 60 A.

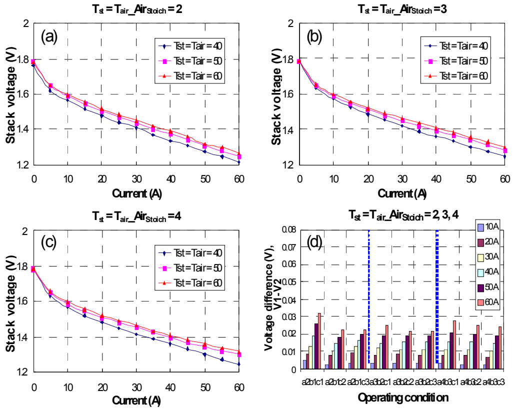


Figure 4: I-V characteristics of a two cell stack and voltage difference under various air stoichiometric ratios at T_{st} = T_{air}

3.2 Air temperature

In this session, effects of the temperature of the air supplied on the difference of the cell voltages have been studied. Experimental results of the polarization curves and voltage difference in the individual cell of the stack is presented in Fig. 5.

It should be noted that no difference in the cell voltages by variation of air temperature regardless of the Air_{stoich} at T_{st} = 40℃ and 50℃. As matter of fact, the relative humidity at the outlet can be maintained at higher than 80 % because of water produced on the cathode side, when the working temperature of the stack is below 50℃ and the pressure for the cells is operated with 1 atm [6, 20]. Thus, the water content in the membrane is not affected by the air temperature, even though the air supplied is humidified with a lower temperature than the one of the stack. Under these operating conditions, the humidity on the cathode side is sufficient to maintain the water content in the membrane.

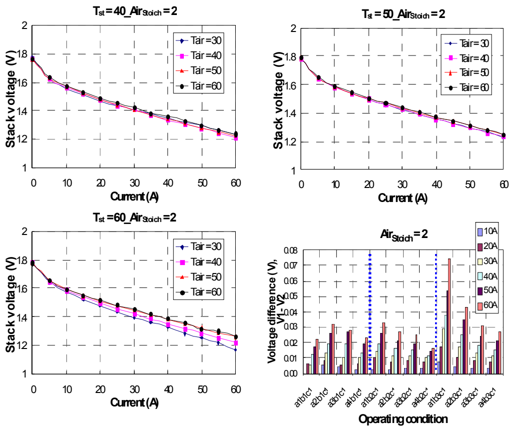
However, it is observed that the voltages of the cells tend to be lower when the temperature of the air is set to 30℃ and 40℃ at T_{st} = 60℃.It indicates that the humidity in the channel cannot be maintained as before when the working stack temperature is higher than 60℃ and requires an additional humidification. In addition, when air with a low vapor pressure is supplied to a stack working at a higher temperature than the one of the air, the amount of the water vapor becomes much less than before and the exiting air takes up more water vapor. Subsequently, the membrane might be dehydrated that leads to a high ohmic over-potential. Due to the lower current density, the flooding effects are negligible.

As seen the voltage difference in the Figure 5(a), (b) and (c), the difference of the cell voltages gets narrow regardless of the air $_{stoich}$ as the temperature of the air increases. In fact, the elevated temperature of the air results in a higher saturation vapor pressure of the air than the one of the stack channel and subsequently increases water content in the membrane. Particularly, the voltage drop of the cell 2 is strongly influenced by the amount of the vapor in the air supplied. At T_{st} = 60℃ and T_{air} = 30℃, the voltage drop has been reached with 0.074 V at the load current, 60 A.

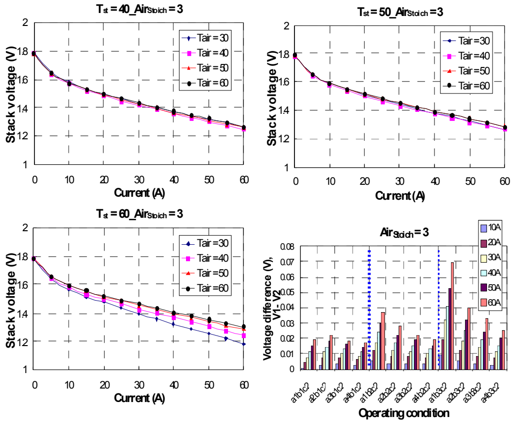
3.3 Working temperature

Figure 6 shows effects of the working temperature on the difference of the cell voltages.

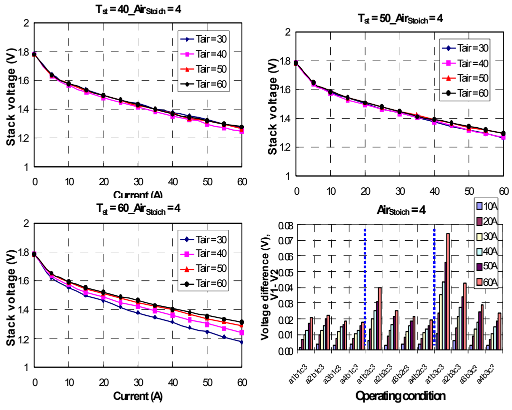
In general, it is anticipated that the voltages of the cells get higher at an elevated temperature. However, the result shows a reversed phenomena in the voltage regardless of the Air_{stoich} at T_{air} = 30℃ and 40℃. Specifically, the voltage at T_{air} = 30℃



(a) T_{st} = 40℃, 50℃ and 60℃, and Air_{stoich} = 2



(b) T_{st}=40℃, 50℃ and 60℃, and Air_{stoich} =3



(c) T_{st} = 40℃, 50℃ and 60℃, and Air_{stoich} = 4

Figure 5: I-V characteristics of the cells and the voltage difference at various T_{air},T_{st} and Air_{stoich}.

and T_{st} = 60℃ shows the lowest amplitude, which indicates that the performance of the cell is dominantly influenced by the humidity level in the channel on the cathode side rather than the working temperature.

As shown the voltage difference in the Figure 6(a), (b) and (c), the voltage of the cell 2 drops heavily and the voltage of the stack gets lower at T_{air} = 30℃ and T_{st} = 60℃. It implies that the performance of the cell 2 shown a lower performance than the cell 1 drops further as the low humidity in the cathode gas channel gets lower.

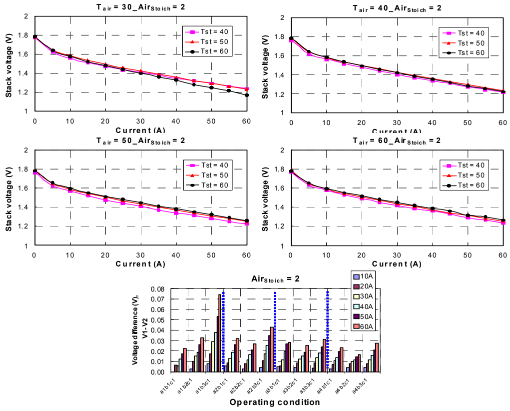
3.4 Air stoichiometric ratio

In this session, effects of the air stoichiometric ratio on the difference of the cell voltages are studied. The experimental results are shown in the Figure 7.

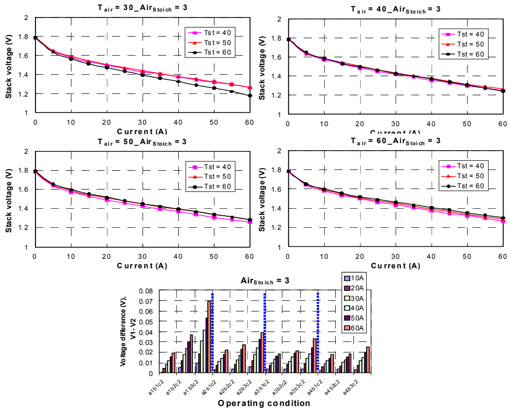
Air_{stoich} can influence partial pressure of the oxygen in the cathode gas channel, water balance in the membrane and water flooding. The voltages of the cells are identical at Air_{stoich} =3, 4, while the voltages gets lower at the Air_{stoich} = 2.

It indicates that the low Air_{stoich} slow down the removal rate of water and raises the level of the water content in the membrane. In fact, more oxygen is consumed as the load current increases. At the Air_{stoich} = 2, the cell performance is mainly affected by the partial pressure of the oxygen rather than the water content in the membrane. As a result, the cell voltages drop. However, it is to recognize that the voltage becomes lower at T_{st} = 60℃, T_{air} = 30℃ and Air_{stoich} = 4. It indicates that the increased flow rate of the air with a low saturation pressure raises the removal rate of water vapor that can dehydrate the membrane, even though the partial pressure of the oxygen in cathode gas channel is sufficiently .

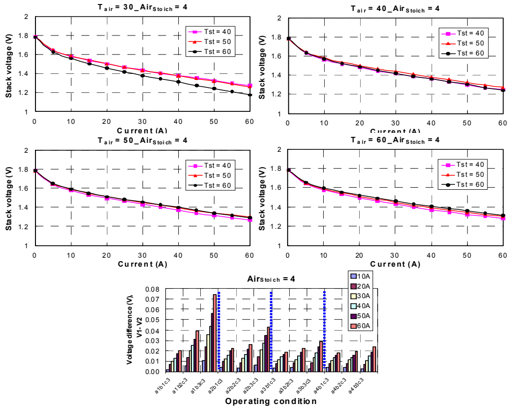
As shown the voltage difference in the Figure 7(a), (b) and (c), the maximum voltage difference



(a) T_{air}=40℃, 50℃ and 60℃, and Air_{stoich}=2.

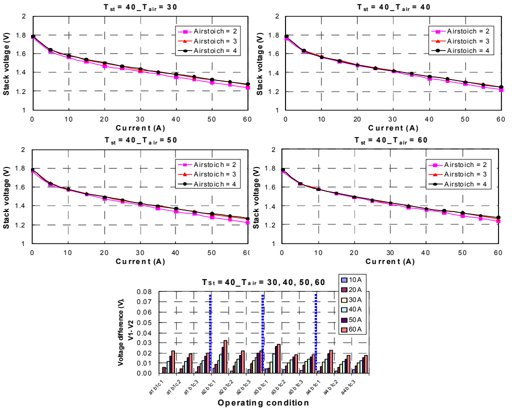


(b) T_{air}=40℃, 50℃ and 60℃, and Air_{stoich}=3.

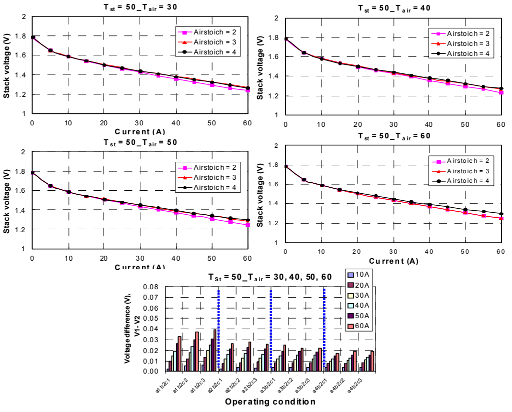


(c) T_{air}=40℃, 50℃ and 60℃, and Air_{stoich}=4.

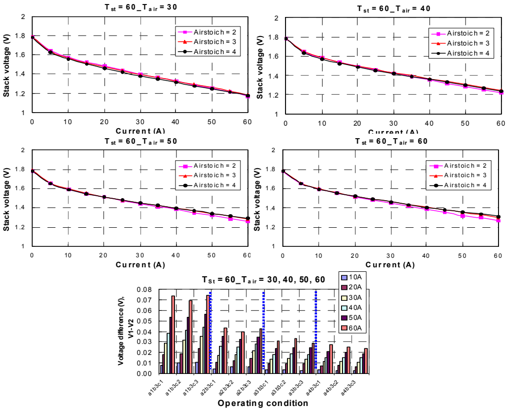
Figure 6: I-V characteristics of the cells and the voltage difference at various T_{air}, T_{st} and Air_{stoich}



(a) T_{st}=40℃ and T_{air}=30℃, 40℃, 50℃, 60℃



(b) T_{st}=50℃ and T_{air}=30℃, 40℃, 50℃ and 60℃



(c) T_{st}=60℃ and T_{air}=30℃, 40℃, 50℃ and 60℃

Figure 7: I-V characteristics of the cells and the voltage difference at various T_{air}, T_{st} and Air_{stoich}

reaches 0.01V by variation of Air_{stoich} at 60 A and the influence of the Air_{stoich} can be regarded as a minimum.

4. Conclusions

The paper presented focuses on experimental measurements and analyses of the individual cell voltages of a stack under different operating conditions. The conditions include the temperature of the air, stack and the stoichiometric ratio. The results can be summarized as follows;

1. Even at T_{st} = T_{air}, there exists a voltage difference between two cells, which can be regarded as ohmic over-potentials inherently given by different characteristics of the components used and tolerances occurring at fabrication of the stack. The voltage difference at the stack used amounts to 0.032 V at a load current of 60 A.

2. Due to the relatively low load current applied to the stack, no water flooding phenomena has been observed in the experiments. The temperature of the air supplied among other operating variables showed the most influential factor in manipulating the voltage of the cells. It shows that the difference of the cell voltages gets smaller when the working temperature of the stack is elevated, while the Air_{stoich} has the least influence. At T_{air} = 30℃ and T_{st} = 60℃, the difference of the cell voltages has been increased to 0.074 V at a load current of 60 A.

3. The stoichiometric ratio has not significantly influenced the overall voltage difference, even though the voltage difference reached 0.01 V at the load current of 60 A.

The experiments show that the voltage difference between the individual cells of the stack is basically dominated by inherent characteristics of the cell components and tolerances by assembling a stack. Particularly, the characteristic and its sensitivity on the humidity do play the most significant roles in determining the performance of the cells. For example, variation of the humidity in the cathode flow channel maximizes the difference in the cell voltages. Conversely, the difference in the voltages over all ranges except the water flooding area can be minimized if the temperature of the air supplied is higher than the one of the stack.

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Author Profile

Sang-Kyun Park

He received his B.S and M.S degrees from Korea Maritime University in 1996, 2001 and Ph.D. degree from Hokkaido University in 2005. He is currently a Principal Researcher in Korean Register of Shipping.

Jae-Hyuk Choi

He received his B.S and M.S degrees from Korea Maritime University in 1996, 2000 and Ph.D. degree from Hokkaido University in 2005. He is currently a professor in Korea Maritime University. Dr. Choi's research interests are reduction of pollutant emission (Soot and NOx), high temperature combustion, laser diagnostics, alternative fuel and hydrogen production with high temperature electrolysis steam (HTES)