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Design, fabrication and performance analysis of a 200 W PEM fuel cell short stack

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Abstract

A PEM fuel cell short stack of 200 W capacity, with an active area of 100 cm^2 has been designed and fabricated in-house. The status of unit cell performance was 0.55 W cm^{-2}. Based on the unit cell technology, a short stack has been developed. The proper design of uniform flow distribution, cooling plate and compressed end plate were important to achieve the best performance of the short stack. The performance of four cells stack was analyzed in static and dynamic modes. In the static mode of polarization curve, the stack has peak power density of 0.55 W cm^{-2} (220 W) at 0.5 V per cell, when the voltage was scanning from low to high voltage (1.5–3.5 V), and resulted in minimum water flooding inside the stack. In this study a series of dynamic loadings were tested to simulate the vehicle acceleration. The fuel cell performances respond to dynamic loading influenced by the hydrogen/air stoichiometric, back pressure, and dynamic-loading time. It was needed high hydrogen stoichiometric and back pressure to maintain high dynamic performance. In the long-time stable power testing, the stack was difficult to maintain at high performance, due to the water flooding at high output power. An adjusting cathode back-pressure method for purging water was proposed to prevent the water flooding at flow channels and maintain the stable output power at 170 W (0.42 W cm^{-2}).

Keywords: PEM fuel cell; Stack design; Dynamic performance; Hysteresis effect

1. Introduction

Fuel cell stack development is a key technology for the fuel cell commercialization. Characteristics of the fuel cell stack performance could be different from combustion engine and batteries. It required operational experience for optimal design of the fuel cell system. Stability and performance of the polymer electrolyte membrane fuel cell (PEMFC) has significantly affected by the operating conditions such as temperature, humidity of reactant gases, flow rates and pressure. In order to achieve a better performance, several parameters in a fuel cell must be optimized. In addition to, the distribution of steam, moisture in the membrane electrolyte, liquid water in the channels and porous layers have a significant influence on the cell performance and their long-term stability. The key issue of successful fuel cell stack development involved on the identical distribution of flow rate, reactant gases, water, temperature, and uniform compression of the stack. However, most of the mechanisms and phenomena for the fuel cell design and operation are not well understood. There are limited literature to address the fuel cell stack design and operation to relate the stack performance and stability.

Weng et al. [1] reported the reasons for the compression of fuel cell hardware to minimize the contact resistance, and to optimize the gas permeability. Before real MEA performance testing, a metal foil was placed to measure the contact resistance and gas permeability of the cell. A relationship between water flooding, ohmic resistance and pressure drop was reported by Barbir et al. [2]. An increase in pressure drop, particularly on the cathode side is a reliable indicator of PEMFC flooding and increase in cell resistance is a reliable indicator of fuel cell drying.

In the development of stack, Knobbe et al. [3] employed solenoid valve to control the inlet and outlet of each cell individually and achieved a 30% increase in power output of a PEMFC stack. Nguyen and Knobbe [4] used stators to exhaust O_2 or H_2 and two sequential exhausting devices were tested, one based on a rotating device and another using electromechanical valves.

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Both showed dramatic improvement in performance associated with equalization of flow rate. Z. Qi and A. Kaufman [5] also employed a double-path-type counter-current flow-field design for better utilization of the water produced by the fuel cell to hydrate dry reactants and it could run stably at a current density up to 0.33 A cm^{-2} using dry hydrogen and dry air. Giddey et al. [6] examined that the stack has undergone small degradation in its performance after undergoing more than 40 cold start/shut down thermal cycles over an accumulated operation of ∼300 h as indicated by increase in the average ohmic resistance. Possible causes for increase in the ohmic resistance and degradation in the electrical output of the stack are: membrane degradation, increase in the contact resistance between various stack components and the deterioration of the catalyst.

In the present study, PEM fuel cell short stack of 200 W electric power output was designed and fabricated a large unit cell to achieve the best stack performance. It performance and stability related to stack design and operation were studied. The short stack is operated under dynamic-loading mode to simulate the vehicle acceleration. We are also discussed a better operating condition and procedure to improve the stack performance and stability.

2. Experimental

2.1. Design of the short stack

A self-developed short stack was designed and fabricated for the following experiments; a schematic representation of the stack arrangement can be seen in Fig. 1(a) and (b). The specifications of short stack were shown in Table 1. The end plates were made with gold-coated brass and they also have a function to conduct the electron. The stack was built from graphite composite bipolar plates. Sixteen serpentines type flow fields were used for uniform gas distribution on anode and cathode sides. The design converged of inlet channel to maintain the flow rate and pressure in the whole flow field at one side, as shown in Fig. 2(a). The flow-field channels of rib, ditch and depth are 0.83, 1.25 and 1 mm, respectively, and the bipolar plate's size is 130 mm × 130 mm. The gas flow field of bipolar plates are shown in Fig. 2(a). In every manifold of each cell, a special design is maintained where as the gas flow occurs through the back side than turn around to the front side. The special design of back-sealing can improve the efficiency of gas flow and reduce

Table 1
Specification of 200 W short stack

Item	Illustration
Active area	100 cm^2
Bipolar-plate area	169 cm^2
MEA manufacturer/type	Gore/PRIMEA® Series 5510 MEAs
Catalyst loading	0.8 mg cm^{-2}
Cell number	4
Flow-field type	16 serpentines
Fuel	H_2, Air
Peak power	200 W
Cooling type	Water cooling

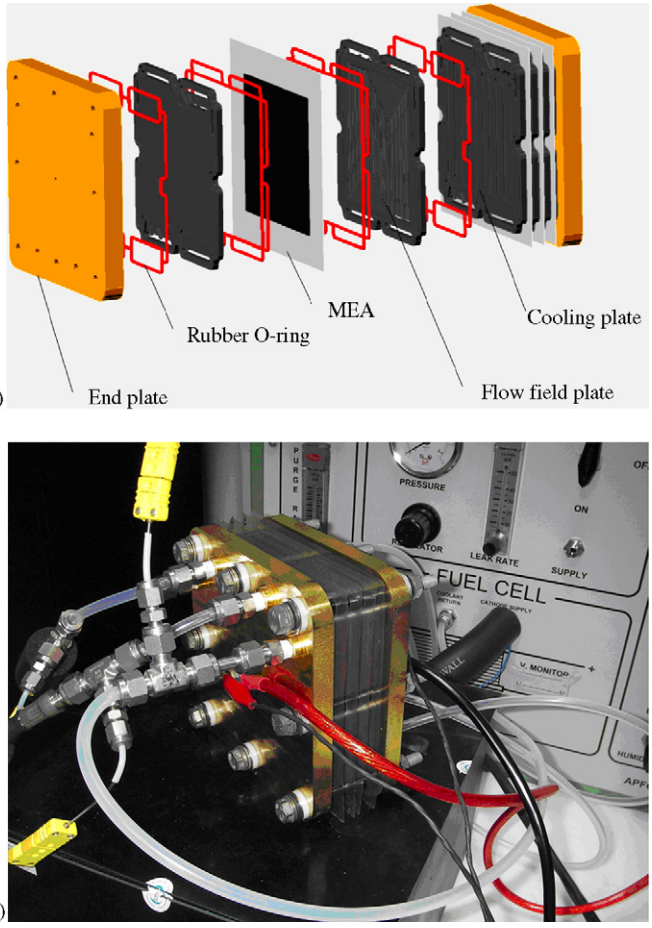

Fig. 1. (a) Schematics of fabricated PEM fuel cell short stack. (b) Picture of short stack under operation.

the gas flow through back side to front side, as shown in Fig. 2(c). The gas manifold has back-side inlet, and there is a water cooling plate between two cells in each bipolar plate at back side, can be seen in Fig. 2(b). This assembly included the flow-field plates, gasket layer, carbon cloth and the MEA was clamped between two enclosure plates by eight M8 screw joints and each having a torque of about 35 kgf cm.

2.2. Fabrication and measurement

Before testing the stack performance, ohmic resistance [7] and gas permeability were measured to obtain the optimal compressed condition of stack assembly, is shown in Fig. 3. In the part of gas diffusion layers maintained the uniform compressed ratio and its value is around 40%. The detailed procedure described elsewhere [1]. The MEA was made by Gore Fuel Cell Tech., which is using Gore 5600 series, catalyst reaction area 100 cm^2 and it was conditioned as suggested by Gore Fuel Cell Tech., 0.6 V for 1800 s, then 0.4 V for 1800 s and last return to open circuit voltage for 60 s. The MEA conditioning was repeated about five to six times or more until the performances reached a relatively steady state and it is reported in Table 2. Experiments were started after MEA conditioning. Waste heat was used to increase the cell temperature and cooling water

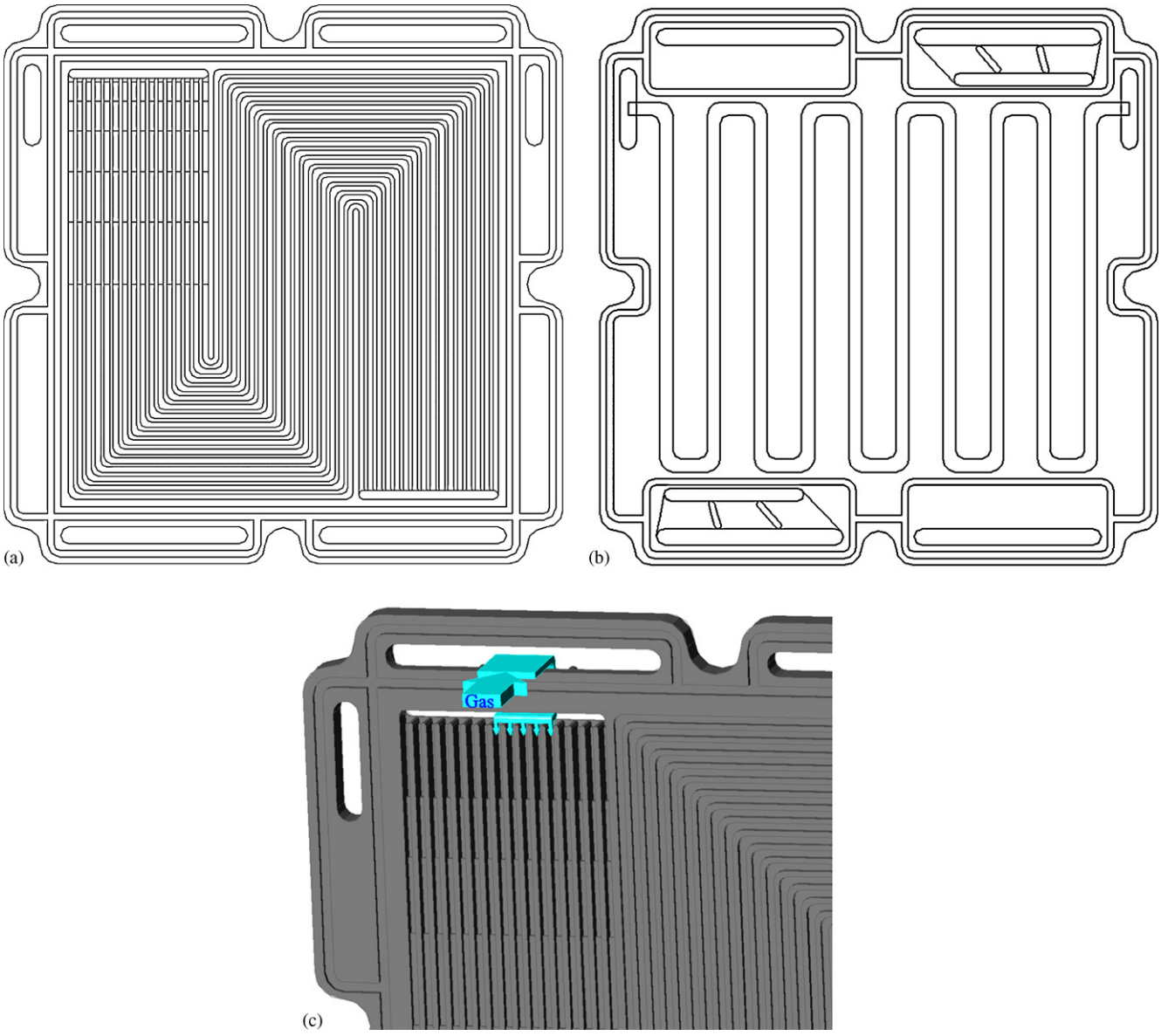

Fig. 2. Special design of bipolar plate: (a) front side of bipolar plate, (b) back side of bipolar plate, and (c) manifold sealing for gas inlet.

used to decrease the cell temperature. The gas was humidified in a bubbler and it was mixed with dry gas to set the desired dew point temperature. A Scribner 890 B Fuel Cell Test Loads is available for various series of experiments, such as scan voltage, constant voltage, constant current, and dynamic load response. The cell was tested under constant voltage and constant current mode, to generate the polarization curve and to stabilize the stack performance, respectively. To simulate the vehicle acceleration, a series of dynamic loading were operated for developing response of the stack performance.

Table 2
MEA started procedures of MEA conditioning

Conditions	Procedure
Cell number: 1 cell	(1) Constant 0.6 V for 30 min
H_2 stoichiometric flow rate: 1.2×, air stoichiometric flow rate: 2.5×	(2) Constant 0.4 V for 30 min
Gas humidified temperature 75 °C	(3) OCV for 1 min
Cell temperature 70 °C	Repeat (1)–(3) for six times

3. Results and discussion

3.1. Performance of polarization curve

The performance results of 100 cm^2 single cell at different temperatures are shown in Fig. 4. The cell was operated at gas humidified temperature 75 °C and anode/cathode (A/C) stoichiometric: 1.2/2.5. As can be seen from Fig. 4, the performance of the cell is increasing with increase of temperature. *I–V* polarized curve and power density of per cell from respective unit cell, two cells, and four cells are given in Fig. 5. The utmost performance of the single cell achieved at operating condition of 0.5 V with power density of 0.55 W cm^{-2} and provides the power of 55 W. However, the maximum performance of two

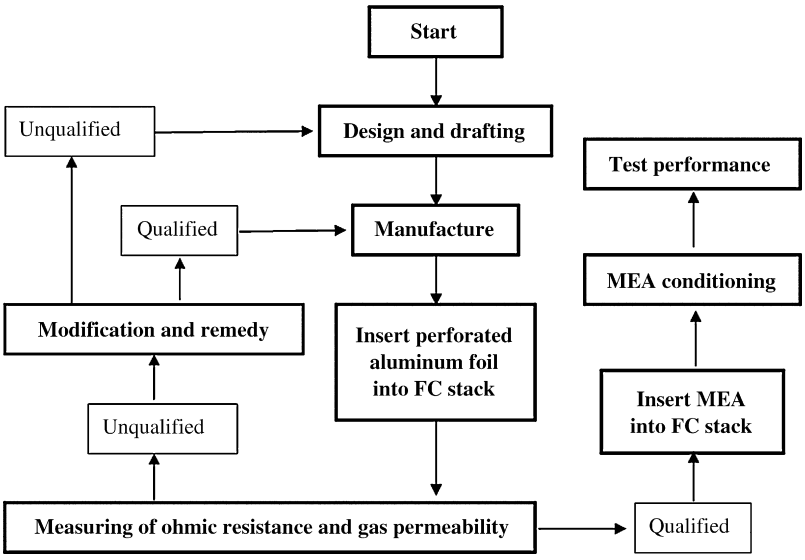

Fig. 3. Design, fabrication and experimental procedure.

cells is attained at 0.98 V with power density of 0.48 W cm^{-2} and the power reaches to 91.6 W. On the other hand, the fulfilment of four cells is accomplished at 2 V with power density of 0.38 W cm^{-2}, and the power reaches up to 156 W. As the cell number increases, the uniform distribution of humidified gases, optimal moisture of membrane and gas diffusion layer to avoid the water flooding is become significant.

Accordingly, it is evident that operating conditions of single cell provides the better polarization curve and power density among the performance of other cells. The observation illustrates that the performance decay not only for the increase of ohmic resistance but also for the worsening of the water flooding. In addition, the aggravating uneven distribution of fuel result in increase the number of cells or flow-field design and gas flow control may leads to decay of the whole performance. On that reason, the eventual part of the polarized curve in four cells abruptly drops due to the insufficient supply of the fuel. On the other hand, it is evident that ultimate portion of the polarization curve of single cell and two cells is not decreasing owing to the satisfactory amount of fuel supply and less water flooding.

The hysteresis effect in the polarization curve of four cell stack, and with different initial cathode flow rate are shown in Fig. 6. Thick line: the voltage is scanning from low to high voltages (1.6–3.6 V) or high to low current densities. Dashed line: the voltage is scanning from high to low voltages (3.6–1.6 V). The stack operating conditions are same as previous cases. The results show that the thick line has better performance than dashed line. The thick line has almost same as unit cell maximum performance of 0.55 W cm^{-2} (Fig. 4). The hysteresis effect in polarization curve is due to the water flooding at cathode gas diffusion layer and gas channels. Furthermore, the stack is operating at constant gases stoichiometric. The thick line has initial low voltage and high current, and resulted in initial high flow rate to avoid the water flooding of the fuel cell stack and obtain a bet-

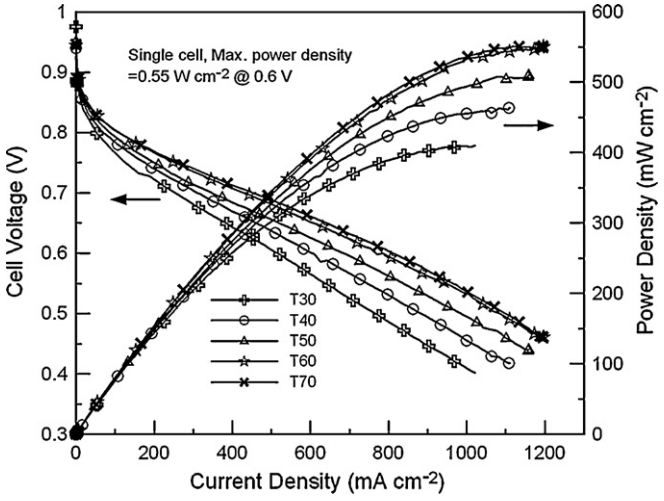

Fig. 4. Effect of cell temperature on unit cell performance, A/C stoichiometric: 1.2/2.5, cell temperature 70 °C, humidified gas temperature 75 °C, and back pressure 0 psig.

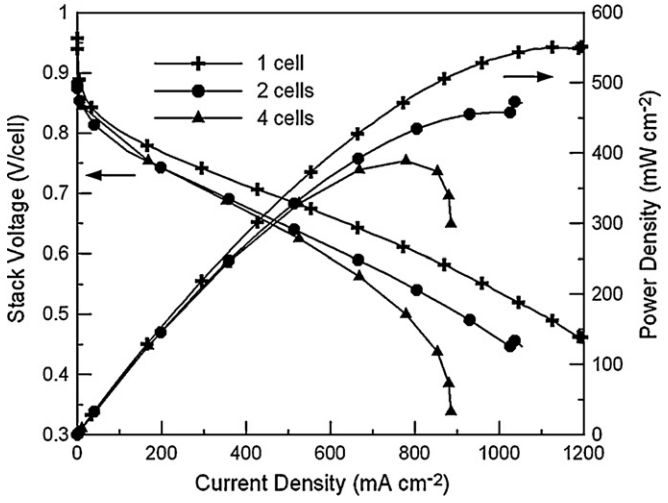

Fig. 5. Polarization and power density curve per cell at unit, 2 and 4 cells, A/C stoichiometric: 1.2/2.5, cell temperature 70 °C, humidified gas temperature 75 °C, and back pressure 0 psig.

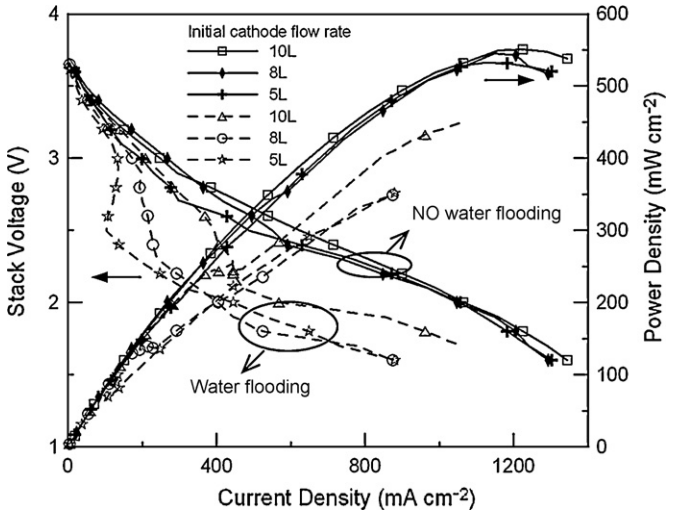

Fig. 6. The hysteresis effect of the stack performance. Thick line (—): the voltage is scanning from low to high voltages. Dashed line (- - -): the voltage is scanning from high to low voltages. A/C stoichiometric: 1.2/2.5, cell temperature 70 °C, humidified temperature 75 °C, and back pressure 0 psig.

ter power density. On the other hand, as the result of dashed line, the stack represents the initial high voltage and resulted in low current density with the low flow rate at constant cathode stoichiometric. The water gradually blocks the part of gas channels and gas diffusion layer, and it decreases the maximum power density 0.4–0.2 W cm^{-2}. Moreover, the performance could be improved by increase of cathode initial flow rate, and result in decrease the water flooding in stack. Therefore, as the cell number increases in stack, it needs to increase the gas stoichiometric to reduce the water flooding for maintaining stack performance.

Air flow at the cathode side with different stoichiometric rates is included with 2.5, 3.0, 3.5 and 4.0, respectively, as shown in Fig. 7. The stack at high current output needs a high flow rate of air, to prevent the water flooding. At the region of ohmic resistance, a polarization loss is very different from the stoichiometric air flow rate at 4.0 and 2.5. The high air flow rate is convenient to remove the water flooding and provides the better performance.

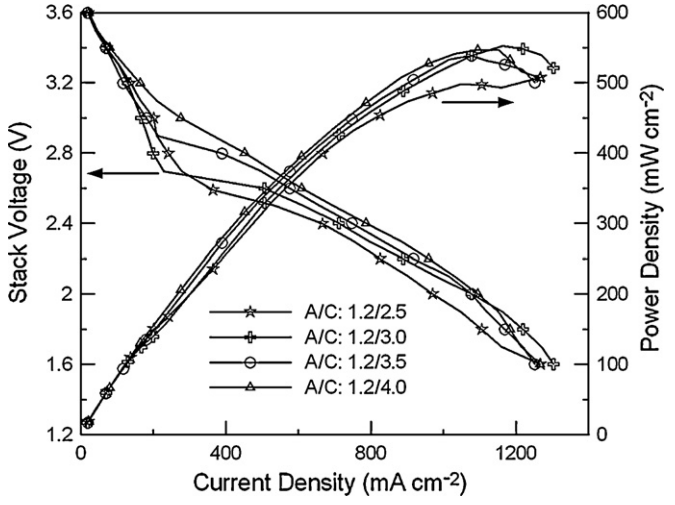

Fig. 7. Effect of cathode stoichiometric rates on the stack performance, cell temperature 60 °C, humidified gas temperature 60 °C, and back pressure 15 psig.

3.2. Dynamic load response of the short stack

The dynamic load response with the triangular wave of step-constant current change is shown in Fig. 8(a). This experiment can simulate the vehicle acceleration situation. In order to simulate the acceleration, constant different current (different step-constant current) shows the different power and the flow rate under different stoichiometric. Each step is fixed with the current correspondingly at 70, 90, 110 and 130 A for 60 s. Fig. 8(a) indicates the current is responses immediately at this operating condition. However, the generation of power output is not observed high enough with higher current output. Therefore, higher current output generates the lower voltage and then resemble the power output is uncertain. As the anode stoichiometric increases to 1.5, the output power may be response the third cycle of dynamic loading without fuel starvation. For the understanding of better performance of the simulated vehicle acceleration, the loading time is changed from 60 to 5 s, as represented in Fig. 8(b). This study considers the three series of condition: (1) A/C stoichiometric 1.2/3.0, back pressure 0 psig, (2) A/C stoichiometric 1.5/4.0, back pressure 0 psig, (3) A/C stoichiometric 1.2/3.0, back pressure 15 psig. According to the condition (1), in the lower stoichiometric and at shorter response time, the current may not generate completely in time and consequently the current setting is frequently moving onward. Therefore, comparison between conditions (1) and (2), it is evident that only condition (2) with increasing gases stoichiometric can follow the current setting in the first cycle. The total output power is very low at the higher current region as the fuel cell operating at this high frequency dynamic loading.

As mentioned above, the gas flow rate cannot satisfy the fuel cell to generate enough current response in very short time. In order to solve this problem, the back pressure in fuel cell operated at 15 psig, as condition (3). It is easy to observe that the condition (3) is only one, which generates the corresponsive current without operating at high fuel flow rate. On that regards, fuel cell immediately generate extremely high current for the acceleration of motor and back pressure is effective to handle out at the above situation.

To compare the effect of constant loading time at 60, 20 and 5 s, respectively, on power generating, is shown in Fig. 8(c). The flow rate at high stoichiometric generate the higher performance of the total power around 200 W at 60 s of loading time. However, the performance of total power is decreasing with decrease of loading time. It cannot maintain the higher current output at loading time 20 s and it is unpredictable for sustain the higher current at 5 s. These results indicate the shorter time of power generation in the fuel cell is more difficult for the current response. Consequently, high current output in very short time may result the total power output unstable and decreased.

3.3. Stability of the short stack

Fig. 9 shows the long-term operating stability of fuel cell at constant voltage 1.9 V and also illustrates the measurement of high frequency cell resistance, in the current interrupt method. The meaning of resistance (R) is related to the proton conduc-

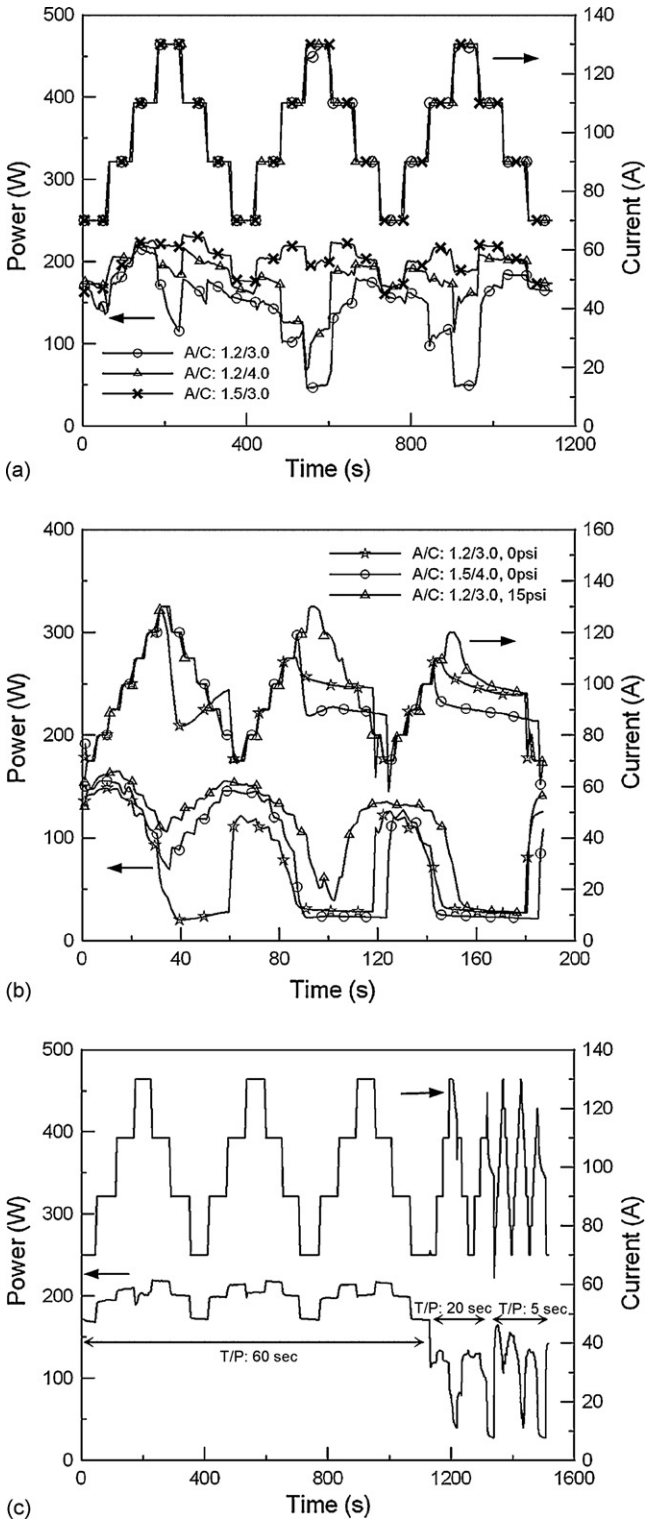

Fig. 8. (a) Dynamic load response at low frequency step-triangle wave constant current, 60 s of each step current with variation of A/C stoichiometric, cell temperature 60 °C, humidified gas temperature 60 °C, back pressure 0 psig. (b) Dynamic load response at high frequency step-triangle wave constant current, 5 s for each step current with variation of A/C stoichiometric, cell temperature 60 °C, humidified gas temperature 60 °C. (c) Dynamic load response with variable frequency step-triangle wave constant current at 60, 20, and 5 s of each step current (T/P = time/point), cell temperature 60 °C, humidified temperature 60 °C, back pressure 0 psig, A/C/stoichiometric: 1.5/4.0.

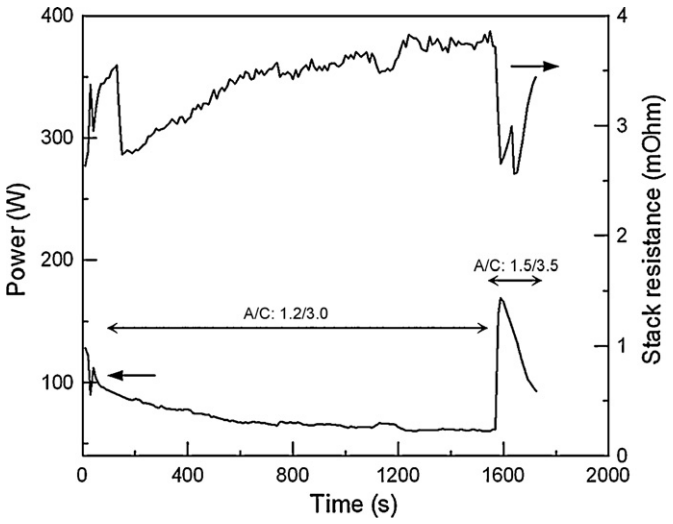

Fig. 9. Stability of constant voltage at 1.9 V, without water purging, cell temperature 60 °C, humidified gas temperature 60 °C, back pressure 15 psig.

tivity (σ) and the lower resistance provides the better membrane conductivity $I_H{}^+ = (\sigma A)\Delta V_R/l_m$. Therefore, the high frequency cell resistance is $\Delta V_R/I_H{}^+ = l_m/(\sigma A) = R$. In the long-term operating of the fuel cell at constant voltage, the power decreases slightly and consequently increases the resistance. After increasing the fuel flow rate as like as the A/C stoichiometric: 1.5/3.5 from the A/C stoichiometric: 1.2/3.0 then the power increases enormously and subsequently the resistance decreased in a greater value. The increase of membrane resistance might be due to the effect of water flooding, blocking of the proton conduct area (A), and resulting in the increase of cell resistance (R). The resistance is suddenly decreased with increase of A/C stoichiometric from 1.2/3.0 to 1.5/3.5 and it might be due to the high flow rate, remove the water flooding, re-opening of the blocking electrochemical process and increase the proton conducting area. However, the cell resistance is increased after 1600 s; it might be due to the water flooding at cathode electrode at constant voltage and constant stoichiometric, which is the condition of unstable decaying performance.

Especially in stack, the abundant amount of water generated frequently with the current output. Water removing from the fuel cell operation is a challenging for the flow-field system. In order to know the water removing from the fuel cell operation, we performed long-term fuel cell performance study at constant current. In fuel cell long-term study, the constant current is generated the constant water flooding, as shown in Fig. 10. Therefore, fuel cell operation is carried out at constant current 90 and 70 A, respectively for understanding the water flooding effect. In this period, the water flooding in higher current output results the decay of fuel cell performance. Initial performance of the fuel cell power output gradually decreased and overcome this performance loss in time being with the cathode outlet of the stack is opened momentarily, to apply the back-pressure release impulse in the cathode gas stream. This removes the liquid water from the gas channels and then the cell voltage jump to higher values for the impulse of back-pressure release and consequently maintains the trend to avoid decreasing of the power output. This

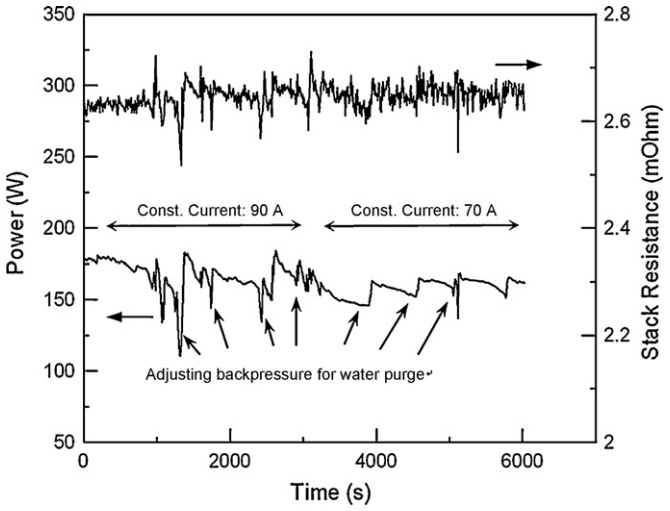

Fig. 10. Stability of constant current at 90 and 70 A, respectively, with water purging, cell temperature 60 °C, humidified gas temperature 60 °C, back pressure 15 psig, A/C stoichiometric: 2.0/3.5.

proves the long-term operation in stack and it required several times of water purging to maintain the stability of higher output power at 170 W (0.42 W cm^{-2}).

4. Conclusion

The intricate design of stack was used in this study and the flow-field design has capability to improve the smoothness of gas flowing into the fuel cell. The cell device of one, two and four cells have provided the best performance with 0.55, 0.47 and 0.39 W cm^{-2} of peak power density respectively at cell temperature 70 °C, and humidified temperature 75 °C.

The hysteresis effect in polarization curve might be due to the water flooding at cathode gas diffusion layer and gas channels at low gases stoichiometric condition. As the voltage scanning from low to high (1.6–3.6 V) or high to low current densities, the initial high current and gas flow rate condition is shown less water flooding on the cathode side and it provides the higher stack performance of 0.55 W cm^{-2}. On the other hand, the initial low current and gas flow rate condition is produced water and it is gradually blocks the part of gas channels, gas diffusion layer, and result in lower the stack performance.

Dynamic load response provides the information of stack operation under strict condition. High power output in the short loading time and simultaneously to generate the high current output of the stack is difficult to obtain, unless operating under high fuel flow rate or rising the back pressure. In the long-term stability experiments, the stack operation's is very important to maintain the fuel cell performance and stability. It needs some operating skill to maintain the performance in the stack operation, such as purged water is a significant way to maintain the stability of higher output of power at constant current and constant stoichiometric condition.

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