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Journal of Power Sources 145 (2005) 604–609
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Short communication

Operating characteristics of an air-cooling PEMFC for portable applications

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Accepted 1 February 2005
Available online 28 July 2005

Abstract

Optimal design and proper operation is important to get designed output power of a polymer electrolyte membrane fuel cell (PEMFC) stack. The air-cooling fuel cell stack is widely used in sub kW PEMFC systems. The purpose of this study is to analyze the operating conditions affecting the performance of an air-cooling PEMFC which is designed for portable applications. It is difficult to maintain well balanced operating conditions. These parameters are the relative humidity, the temperature of the stack, the utility ratio of the reactant gas and so on. In this study a 500 W rate air-cooling PEMFC was fabricated and tested to evaluate the design performance and to determine optimal operating conditions. Moreover, basic modeling also is carried out. These results can be used as design criteria and optimal operating conditions for portable PEMFCs.

Keywords: Air-cooling; Portable; Design parameter; PEMFC

1. Introduction

The design of a fuel cell stack is highly complicated. A lot of parameters affect the performance of the system and these parameters are tightly related each other. Contrary to a single cell, a stack must be considered as a manifold design to well distribute flow rate at each cell. Pressure drop is also important to operate complete a system with an air compressor.

When it comes to operating a fuel cell stack, in many applications of polymer electrolyte membrane fuel cells (PEMFC), a portable power module should be operated under a variety of environments. The performance of the fuel cell system can alter with the ambient humidity and temperature. The portable power system should be able to adapt to these environments by itself through the water and heat balance of the system.

The power of the PEMFC is closely dependent on the relative humidity of the reactant air in the stack. The relative humidity is determined by the humidity and temperature of the input reactant air and the stack. The air-cooled fuel cell stack is widely used in sub kW PEM fuel cell systems because it is a simple and easy method. However, as the power density of stack is increased, it is harder to get enough balanced humidity of the input fuel air and stack cooling by ambient air. To design a portable power fuel cell system, it is crucial to know the boundary of possible operating input fuel air humidity and controllable air-cooled stack temperature to maintain stable and high power output.

There has been much research about the water and heat balance of PEMFC or DMFC [1,2]. However, it is hard to find the data for real PEMFC adapted air-cooled system at the several hundred watt size.

Water balance is coupled with the water produced in the MEA, the stack temperature and the fuel air humidity. Therefore, a parametric experiment with a real system is a useful

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doi:10.1016/j.jpowsour.2005.02.062

approach. Design aspects, such as pressure drop on the cathode channels and flow distribution of each cell, are studied. This paper is also focused on the relationship between the power of the stack and the relative humidity through the control of the air-cooled system.

2. Test apparatus and experiment model

The stacks (Fig. 1) consisted of 16 and 21 cells separated from each other by corrugated plates for forced air-cooling. The active area of the each cell is 100 cm^2. The dimensions of the 21-cell stack are 23 cm (width) × 7.2 cm (height) × 22 cm (length), 3.64 l. The MEA is made up from Nafion® 112 membrane with SGL carbon paper as the gas diffusion layer, while catalyst blending and assembly procedures of each component were freshly prepared. The four and six axial fans control each stack temperature. K type thermocouples were used to get the temperature data at the four locations in the stack.

Fig. 2 shows the schematic diagram of the experiment. The reactant air is humidified 100% through the heated water reservoir that is controlled at the set temperature. The temperature of the water reservoir is set at 30, 40 and 50 °C according to the capacity of the possible heat and water exchanger. Several axial fans control the stack temperature for reflecting the real system control condition. Therefore, there is some variation of the stack temperature as the current of the stack is modified from low to high although the temperature of 60 °C is hold stable as possible. The relative humidity can be calculated by the following equation [3]:

$$\phi = \frac{P_w}{P_{sat}} \tag{1}$$

P_w and P_{sat} is the saturated vapor pressure at the temperature of the reactant air inlet and the stack, respectively. The tube that is connected from the water reservoir to the reactant air inlet is kept isothermal by the insulating material. The temperature deviation from the water reservoir to the reactant air inlet is 2° or 3°. Therefore, it can be assumed that the temperature for the P_w is that of the reactant inlet air.

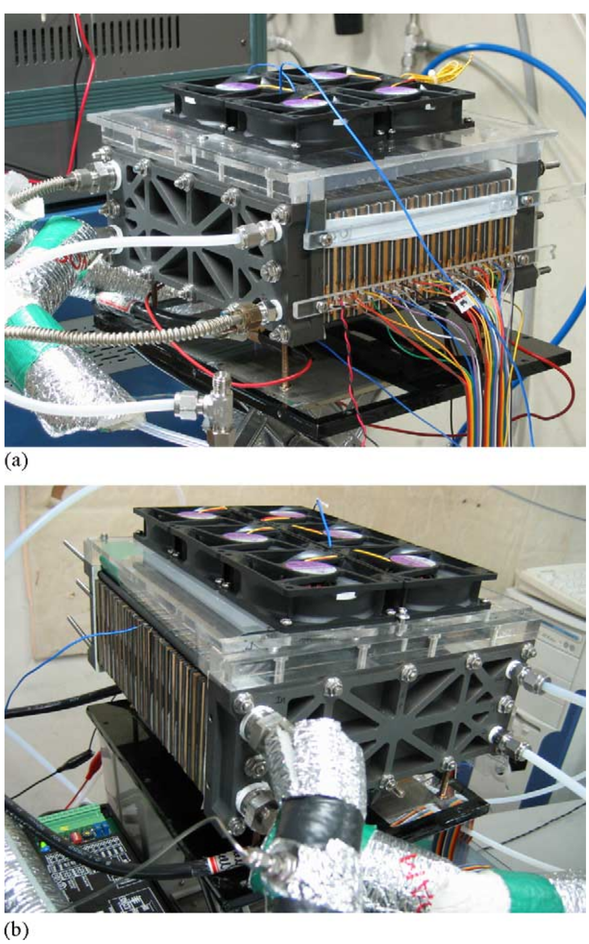

Fig. 1. The experimented stacks (a) 16-cell stack and (b) 21-cell stack.

3. Results and discussion

3.1. Pressure drop

Pressure drop is one of the parameters to be considered when a fuel cell stack is designed. The difference in the water exhausting property from cell to cell can be raised, even if the geometry of each bipolar plate is identical. There can be a disparity of the alignment of each cell or surface condition between water and the channel walls or gas diffusion layer. If the pressure drop is high enough, the difference of water exhausting can be unaffected. From this point of view, increasing the pressure drop gives an advantage to the operation of the fuel cell stack. However, the pressure drop should be optimised because the power and performance of the air supplier is limited in respect of a portable system. An appropriate difference of pressure is estimated from the above considerations.

Pressure difference between the inlet and the outlet of the cathode side is measured and is shown in Fig. 3. The cell temperature is 22 °C. Dry air is supplied into the cathode channels but some moisture exists in the channels because of previous operations. Hydrogen is supplied into the anode channels and an open circuit voltage is maintained during the experiment.

In addition, the pressure drop is calculated by a theoretical equation. The reynolds number of the channel flow is below 1000 in every operating case. Therefore, the flow in the channels can be assumed laminar and the flow friction is calculated by using the Hagen–Poiseuille equation as follows:

$$f = \frac{64}{Re}, \quad Re < 2300 \tag{2}$$

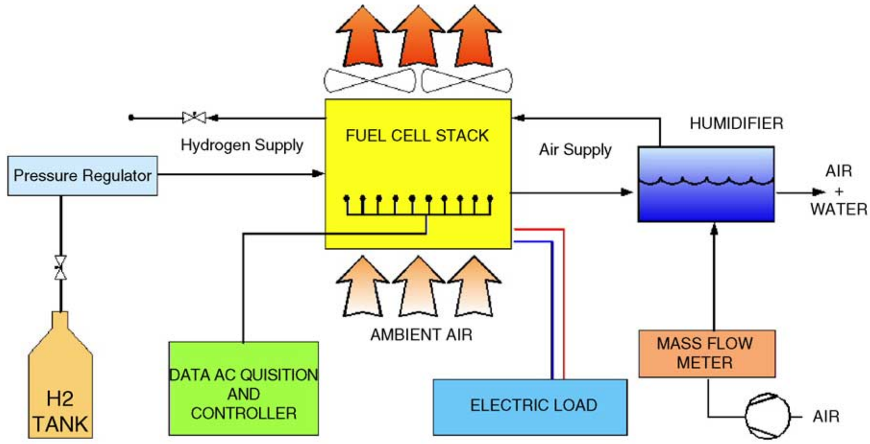

Fig. 2. Schematic diagram of the PEMFC experiment system.

Assuming single phase air flow because dry air is supplied into the channels, the pressure drop can be obtained from:

$$\Delta p = \frac{32 v \mu L}{D_{\mathrm{h}}^2} \quad (3)$$

where v is the mean flow velocity in a channel, μ the viscosity, L the length of a channel and D_{h} the hydraulic diameter.

The solid line in Fig. 3 is the result of calculation. However, the theoretical result is only about 30% of the measurement over the whole volume flow rate region. There are several possible explanations for this inconsistency. First of all, the channel cross-section can decrease due to swelling of the gas diffusion layer between flow channels [4]. Second, the dry air might actually be two-phase flow because of moisture that already exists in the channels. Finally, manifold pressure loss and the effect of the channel bending can also affect this result. To estimate accurate pressure drop, theoretical analysis as well as experiment have to be carried out.

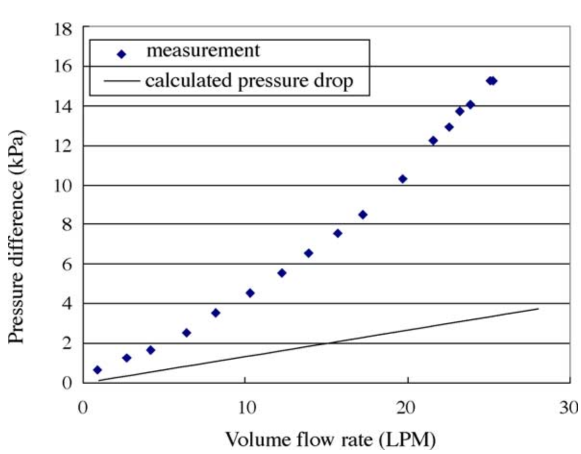

Fig. 3. Measured and calculated pressure drops of the cathode side in to 21-cell stack.

3.2. Flow rate distribution

Uniform flow rate distribution exercises a direct influence on cell voltage and performance. If an uneven amount of air is provided into the channels then the voltage of a cell decreases due to air shortage or water flooding within the cell. In a serious case, the voltage of a cell centre reversed and then water is electrolysed in the cell. Because the impact force is considerable when a bubble forms by electrolysis, physical destruction can take place on the high stress region of membrane, for example the edge by channels. It is then possible that hydrogen can spread into the cathode channel

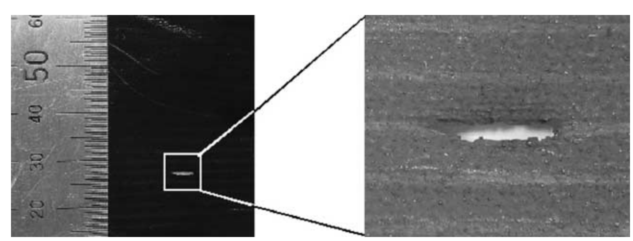

Fig. 4. Example photograph of membrane failure.

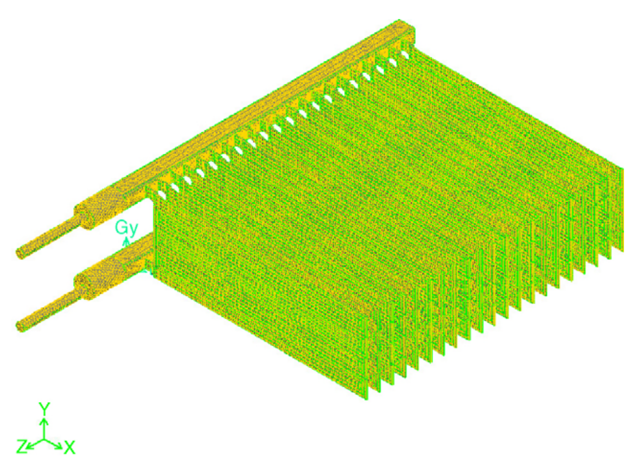

Fig. 5. Three-dimensional mesh for numerical analysis.

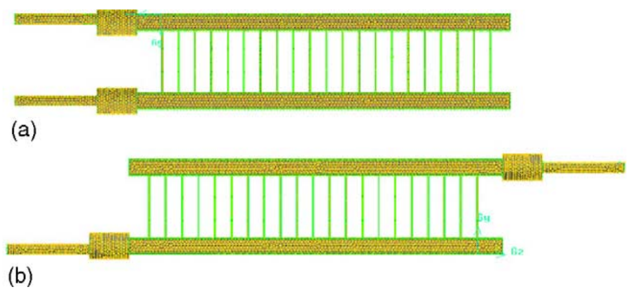

Fig. 6. Manifold configuration (a) u shape and (b) z shape.

through the tiny destruction point. This leads to a thermal combustion of hydrogen by direct mixing with oxygen. Fig. 4 shows this failure.

To prevent the failure, the volume flow rate distribution of the cathode side is estimated by a three-dimensional numerical analysis. The commercial program, FLUENT® 6.0 is used. Mesh created by using GAMBIT® 2.0 is shown in Fig. 5. Air is assumed to be single phase and the electrochemical reaction is not considered.

The manifold design is important to make the distribution of the volume flow rate uniform. The flow pattern is changed sensitively according to the shape of the air inlet. In addition, the inlet and outlet configurations (Fig. 6) also affect the flow distribution. Fig. 7 shows the results. On the whole, the u shaped configuration is more uniform then the z shape. The deviation of distribution in the u shape case is under 1%.

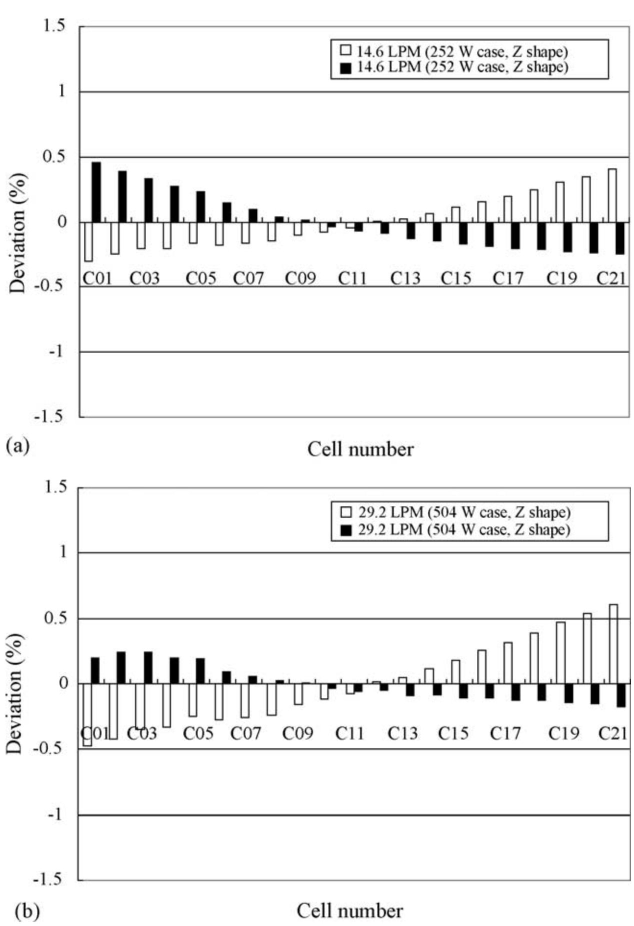

Fig. 7. The deviation of the volume flow rate of each cell at (a) 14.6 litres per minute and (b) 29.2 litres per minute.

3.3. Cell voltage distribution and relative humidity

Considering the general relation of several parameters, the more the relative humidity increases, the more the ion conductivity of the membrane improves but the deactivated area of the catalyst layer also enlarges because water flood-

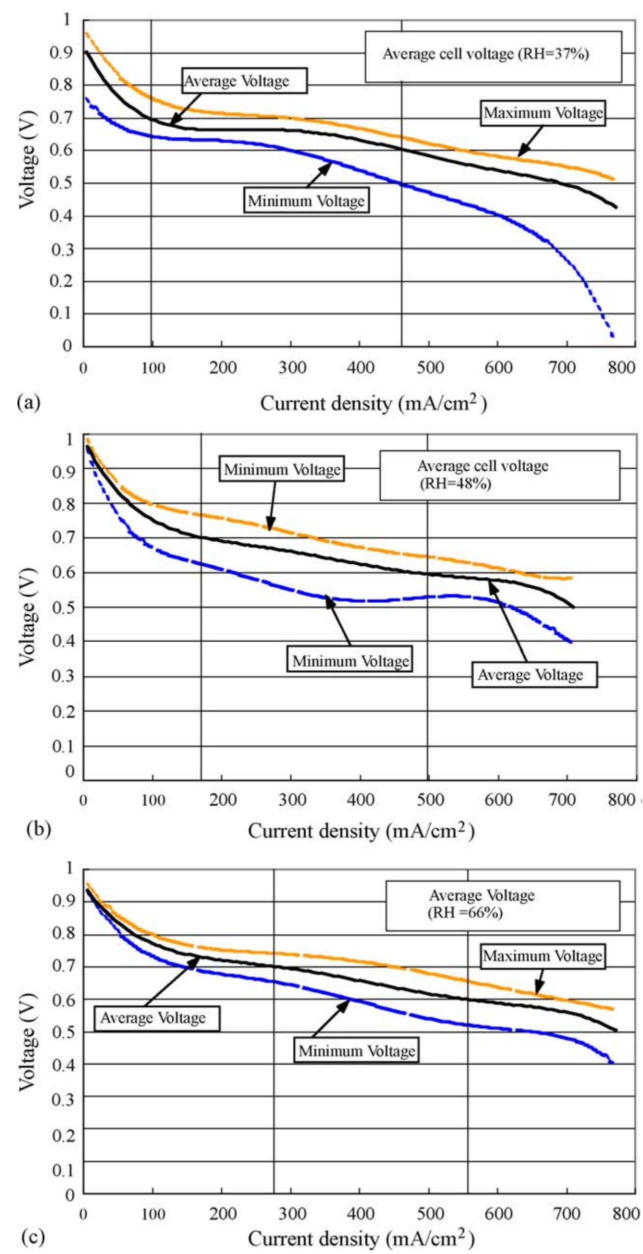

Fig. 8. The average and the distribution of cell voltage with respect to the relative humidity (a) relative humidity = 37%, (b) relative humidity = 48% and (c) relative humidity = 66%.

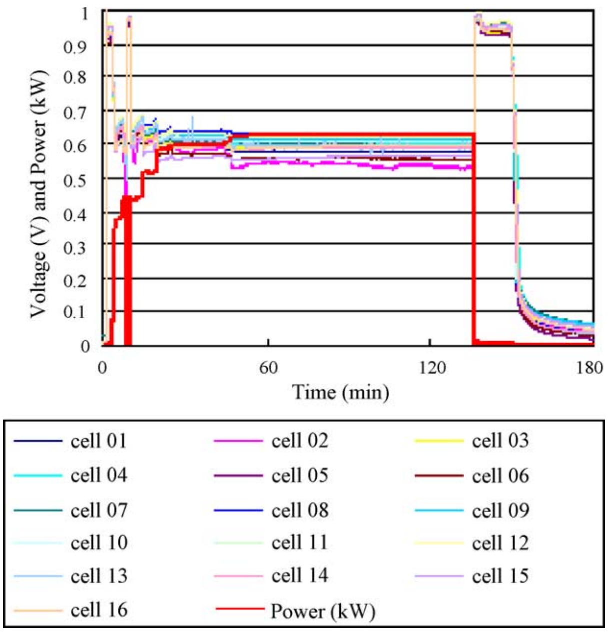

Fig. 9. The voltages of the cells and the stack power graph.

ing appears in the channels. Therefore the uniformity of each cell's voltage or the stability of stack performance can be deteriorated under low as well as high relative humidity. Moreover, the MEA is optimised for gas and water transport in the specific condition by treatment of PTFE at the gas diffusion layer and design of the structure of the micro layer. As a result of the MEA specification, the operating condition can be restricted for getting an appropriate cell voltage and performance [5]. In addition, the humidifier of the air is bound to be limited for the application of portable power systems. With these circumstances in mind, it is important to determine the proper relative humidity within the designed parameters such as the pressure drop through the channel, the MEA properties, the performance of the humidifier and the cooling fans.

Fig. 8 shows the average cell voltage and the deviation of the maximum and minimum for each relative humidity case. In the 37% relative humidity case, minimum voltage steeply decreases above 550 mA cm^{-2} region although the average voltage still has a moderate value. On the contrary, the I–V performance and the deviation between minimum and maximum voltage of the other cases appear acceptable. This result indicates two facts. The one is that the designed pressure drop is enough to clear water in the channel below the 50–70% relative humidity condition. The other is that low relative humidity can be the dominant reason for cell voltage distribution instability caused by the deterioration of ion conductivity. As a result, about 65% relative humidity operating condition is proper if this condition is controllable by the humidifier and the axial fans.

3.4. 600 W operating results by air-cooled PEMFC stack

Fig. 9 shows the operating data. The relative humidity keeps about 64% in the stable operating region. The operating

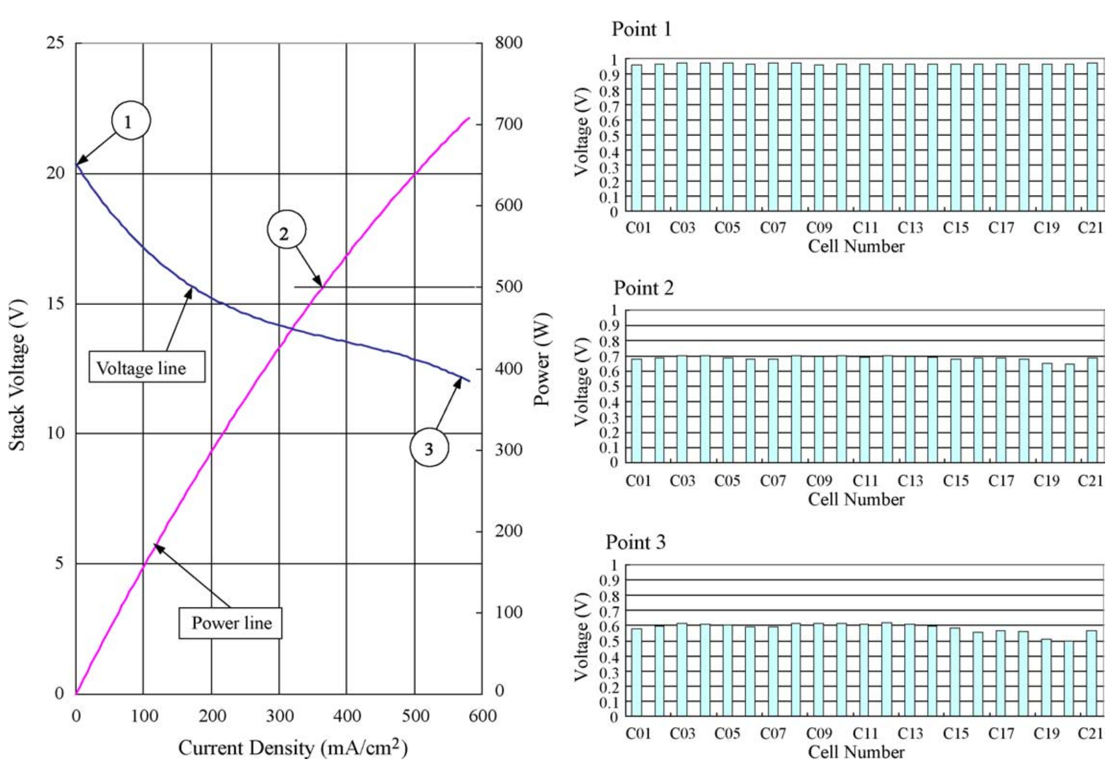

Fig. 10. I–V performance curve of the 21-cell stack and the voltage distribution at various current levels.

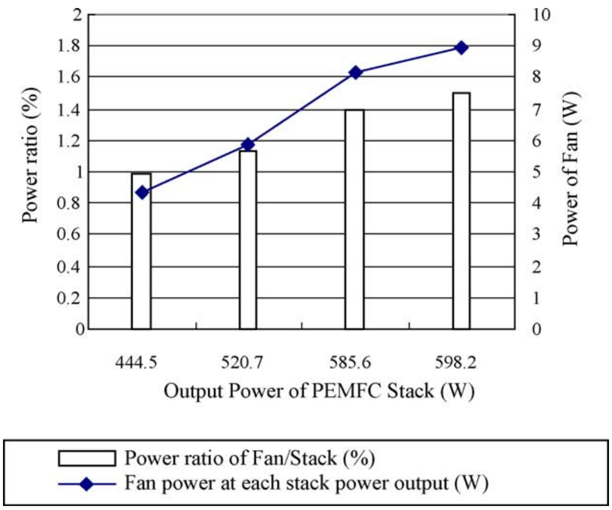

Fig. 11. The parasitic load associated with the forced cooling by axial fans.

pressure of air and hydrogen is atmospheric pressure. Average cell temperature is 60 °C and the air input temperature is 50 °C. Air stoichiometry is 2.3. The measurement shows that the stack performance has reasonable stability at the given relative humidity.

It is important that the voltage of each cell keep uniform at various current levels. The cell voltage distribution of the 21-cell stack at three selected points is shown in Fig. 10. Points 1–3 indicate the voltage variation at open circuit voltage, normal power output and 0.6 average voltage points, respectively. The uniformity of cell voltages is acceptable, despite the fact that the voltages of 2 or 3 cells which are opposite the manifold inlet appears over 18% lower than the average voltage above the region of current density of 550 mA cm^{-2}.

3.5. The parasitic load associated with the forced cooling by axial fans

The parasitic load associated with the forced cooling by axial fans is shown in Fig. 11. The operation is carried out under the identical condition of Fig. 9. Ambient temperature is typical room value, 20 °C. As shown in the graph, the heat control of the PEMFC stack is successfully carried out by axial fans with 2% consumption of the total power output of the stack.

4. Conclusion

PEMFC stacks are designed and manufactured with 16 or 21 cells, respectively, and 100 cm^2 active area. Appropriate pressure drop is investigated and estimated by experiment. The difference between the measurement and the basic theoretical calculation of pressure drop is over three times. A two-phase model and the swelling effect of the gas diffusion layer must be considered to obtain more reasonable estimation. The deviation of the distribution of volume flow rate is under 1% by optimal design and configuration of the manifold. Moreover, the deviation of the distribution is analyzed by the basic numerical calculation.

The experiment with the stack is carried out at three relative humidity conditions controlled by the temperature of the stack and the inlet reactant air. The air-cooling method is used to control the temperature of the stack. The stack power is improved at the 66% relative humidity case compared to other cases. In portable systems, the stack temperature is varied according to the current and the air flow rate. If the humidity and the temperature of the inlet reactant air was exchanged with the outlet reactant air, the condition also can be controlled according to the outlet reactant air. The relative humidity can be a useful operating indicator in this operating situation.

The air-cooled PEMFC stack that is designed for 500 W optimal operation works successfully in the 60% range of relative humidity. The parasitic load associated with the forced axial cooling fan consumes less than 2% of the overall power output at the room temperature. To estimate a more real situation, the parasitic load of the air compressor, actuators and control board should be considered.

References

[1] S. Ahmed, J. Kopasz, R. Kumar, M. Krumpelt, J. Power Sources 112 (2002) 519–530.
[2] M.G. Izenson, R.W. Hill, Proceedings of the First International Conference on Fuel Cell Science, Engineering and Technology, vol. 1, 2003, pp. 477–486.
[3] J. Larminie, A. Dicks, Fuel Cell Systems Explained, 2nd ed., John Wiley and Sons Ltd., England, 2000.
[4] P. Rodatz, F. Buchi, C. Onder, L. Guzzella, J. Power Sources 128 (2004) 208–217.
[5] G.-G. Park, Y.-J. Sohn, T.-H. Yang, Y.-G. Yoon, W.-Y. Lee, C.-S. Kim, J. Power Sources 131 (2004) 182–187.