Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Power Sources 157 (2006) 886–892
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

One kilowatt-class fuel cell system for the aerospace applications in a micro-gravitational and closed environment

Yoshitsugu Sone [a,*], Mitsushi Ueno [b], Hitoshi Naito [b], Saburo Kuwajima [b]

[a] *Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan*
[b] *Institute of Space Technology and Aeronautics (ISTA), Japan Aerospace Exploration Agency (JAXA), 2-1-1 Sengen, Tsukuba, Ibaraki 305-8505, Japan*

Received 26 December 2005; received in revised form 3 March 2006; accepted 3 March 2006
Available online 2 May 2006

Abstract

The Japan Aerospace Exploration Agency (JAXA) is developing polymer-electrolyte fuel cell (PEFC) systems that can operate under isolated low-gravity and closed environments. Subsystems and operating methods such as the closed gas operation subsystem, the working gases counter-flow method, and a dehydrator using wicking material were developed to simplify assembly of the fuel cell system. We combined these subsystems with the 1 kW-class fuel cell stack and simulated the operations of a spacecraft in Earth orbit. The system performed stably for 1100 h under various operational conditions.

Keywords: PEFC; Humidification; Dehydrator; Gas circulation; Aerospace; Closed environment

1. Introduction

Fuel cells have been applied in the field of space engineering to spacecraft since the 1960s. A fuel cell produces water as a by-product of generating electricity, making it attractive for manned operations in a closed environment. Furthermore, the fuel cell generates energy using hydrogen and oxygen, both of which have high energy density. This important potential continues to make fuel cells advantageous for application to large spacecraft with short-term missions [1–4].

The first practical application of fuel cell was started in space for GEMINI project, and the first fuel cell to travel in space was the polymer-electrolyte fuel cell (PEFC). However, the membrane for the fuel cell was polystyrene, not perfluoro-membrane, and high power supply, which is commonly achievable today, was not realized. When the APOLLO and Space Shuttle missions started, PEFC was replaced by an alkaline fuel cell system. After decades, the research and development of PEFC is gathering much attention again due to its applicability to ground facilities, but little data about the operation with high-power generation in a closed environment have been reported [5–8]. These situations encouraged us to develop a fuel cell system with the above concept using the latest technology like reinforced perfluoro-membrane and graphite separator.

PEFCs are presently receiving considerable renewed attention for aerospace applications. One example is the stratospheric platform project [5–10]. A lightweight, long-duration generating system is required to maintain the altitude and position of an aircraft or airships in the stratosphere.

The Japan Aerospace Exploration Agency (JAXA) is developing fuel cell systems for aerospace and planetary missions, including high-altitude balloons, transfer vehicles, and reusable spacecraft. For space applications, the simplest system will be requested to enhance the reliability of the component. We will further need lighter-weight, higher-output electrical power systems for the advanced designs of future spacecraft [5–12].

We prepared 100 W [13] and 1 kW-class [14,15] polymer-electrolyte fuel cell stacks. Our previous study using these stacks revealed that the polymer-electrolyte fuel cells could operate without humidification using a combination of pure hydrogen and oxygen. Hydrogen and oxygen supplied from opposite directions to realize the counter flow of the gases inside the fuel cell

* Corresponding author. Tel.: +81 42 759 8472; fax: +81 42 759 8472.
E-mail address: sone.yoshitsugu@jaxa.jp (Y. Sone).

0378-7753/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2006.03.042

could generate electricity continuously. This is possible even when the hydrogen outlet port is dead-ended and oxygen gas is recycled to increase consumption of the reactants.

We then designed a fuel cell stack using a catalyst with a larger effective surface area and a dehydrator that could remove water from the reactant gas using wicking material. We incorporated these elements with a gas-circulation pump and used this fuel cell system model to generate electricity using pure hydrogen and oxygen with no extra humidification [13–15]. Based on these prototype designs, we prepared a fuel cell system that can be operated automatically in a closed environment.

For the current study, we renewed the designs for the subsystems needed in a fuel cell system for space applications. In this system, water is trapped by the wicking material installed on the cylinder so that the water can be separated from gaseous materials even under micro-gravity conditions. The amount of water that will be generated is calculated using the sequence controller, and the extracted water is ejected automatically using the piston attached to the cylinder. Both oxygen and hydrogen are circulated to minimize the amount of exhaust materials. We did not install a humidifier in this system. The counter flow of high purity hydrogen and oxygen resulted in self-humidification of the system with no degradation in performance. In this report, we describe the performance of the autonomously operating fuel cell system.

2. PEFC system design

2.1. Design concept

A fuel cell for space application has special system requirements, operational conditions, and designs due to its isolated low-gravity environment, which significantly differs from the environment for terrestrial applications [11–15].

Proton conduction in the membrane requires water; the reactant gas is humidified before being supplied to the fuel cell. In contrast, water is produced from the fuel reaction, and excess water must be carried away, since water remaining on the path in the separator may block the stream of reactant gas. Thus, a fuel cell requires humidification of the supplied gas and dehydration in the separator in order to balance the complex humidity conditions inside it.

Air is used as the cathode gas and hydrogen (or reformed gas) as the anode gas for terrestrial applications; they are humidified before being supplied to the fuel cell. Compressed air is used for the cathode gas. The stream of air removes the excess water produced by the fuel cell reaction.

It is most important to prepare the simplest system when using fuel cells in space. In addition, all reactant materials must be carried inside the spacecraft, since a spacecraft is isolated in Earth orbit. Pure anode and cathode materials must be used to minimize the weight, and those materials must be consumed completely. We thus assumed the following system concepts, and proceeded with our research:

(1) pure hydrogen and oxygen are used as reactants;
(2) reactant gases are not humidified before being supplied to the fuel cell;
(3) as much of the reactants as possible must be consumed, and the amount of exhaust material must be minimal;
(4) the produced water must be collected.

Concept 2 is best realized if the fuel cell can be operated using only the produced water, so we designed the fuel cell system without a humidifier. The cathode gas (in this case, oxygen) must be exhausted from the fuel cell to prevent blocking the gas flow through the separators. We elected to circulate the flow of reactant gases and return oxygen and hydrogen to the fuel cell after dehydration to realize concepts 3 and 4. This also enabled us to control the humidity inside the fuel cell stack by the thermal condition of the dehydrator.

Fig. 1 illustrates the concept of proton and water movement inside the fuel cell. Protons move through the membrane electrode assembly (MEA) or proton conducting membrane via water. Because of this migration mechanism, water is essential for proton movement. Furthermore, migrating protons carry water due to electro-osmotic drag [16–18]. As a result of these proton migration mechanisms, the anode usually lacks water.

In contrast, the fuel cell produces water on the cathode side due to its electrochemical reaction. The produced water is diffused by the concentration gradient inside the membrane.

Fig. 2 depicts a conventional fuel cell system for ground applications. Hydrogen is usually used as the anode gas and is supplied directly from a high-pressure vessel or after being reformed from hydrocarbon. Air is conventionally used as a cathode gas because of its practical applicability.

If the reformed gas is used as the anode reactant and air is used as the cathode gas, the reactant gas is humidified through

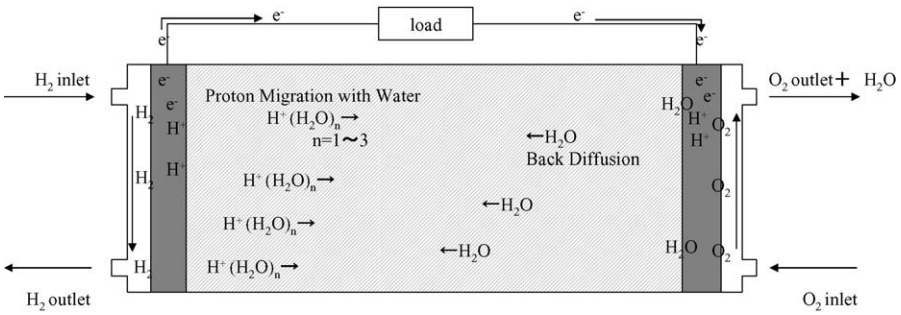

Fig. 1. Concept of proton and water movement inside the fuel cell.

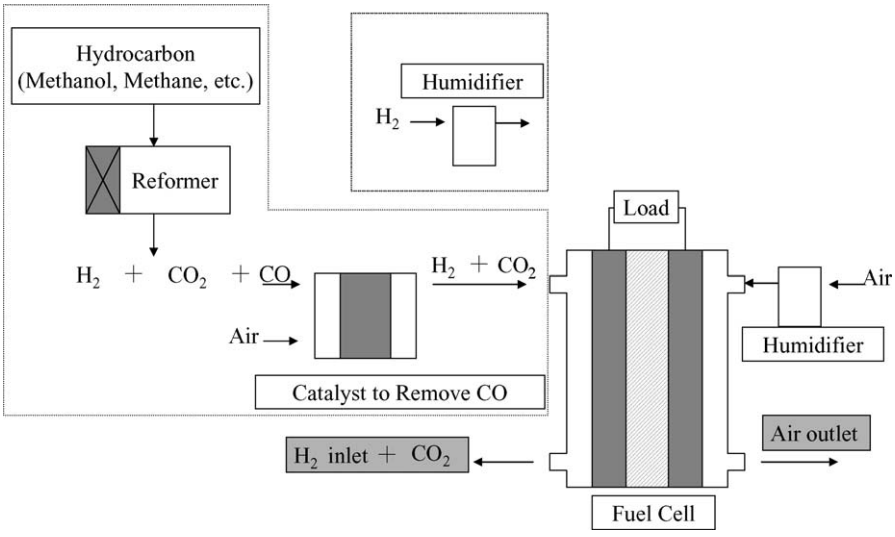

Fig. 2. Conventional fuel cell system for ground applications.

the reformation process and the humidity inside the fuel cell is maintained. If we use hydrogen as the anode gas and air as the cathode gas, it is necessary to exhaust gases continuously to maintain fuel cell performance because inert gas like N_2 degrades fuel cell performance. In addition, the exhausted gas removes humidity from the fuel cell and tends to dry the membrane, so we need to humidify the reactant gases before supplying them to the fuel cell stack.

Fig. 3 depicts the fuel cell system we prepared for our applications. In contrast to ground applications, we need to carry both anode and cathode gases inside the space vehicle, so we can only use pure hydrogen and oxygen. In our case, we used high-grade hydrogen (99.99999%, G1 grade) and oxygen (99.999%, G2 grade) when we specifically simulated closed-environment conditions to minimize the degradation of fuel cell performance.

In addition, we tried to eliminate the humidifier to simplify the system. One of our main targets was to demonstrate stable operation of the fuel cell system using its own product water without extra humidification. Previously, we demonstrated that the counter flow of the pure hydrogen and oxygen provided constant and stable generation of electricity without external humidification [13–15]. We applied the same type of gas-flow channel in our current system to realize self-humidification of the fuel cell stack.

2.2. Preparation of the fuel cell stack

We prepared a separator with a serpentine gas-flow channel on both sides of a graphite carbon plate to prevent gas leakage in the oxidant and fuel gas flow. The serpentine channel was 1.25 mm wide and 1.20 mm deep. The MEA was sandwiched between the separators. The effective surface area of the Pt catalyst layer on the MEA was 162 cm^2.

The MEA was PRIMEA5510® produced by GORETECHS Ltd. The membrane for the MEA was 30-μm-thick GORE-SELECT®.

Fig. 4 depicts the 18-cell stack fuel cell. In the stack, two cells shared a separator with water coolant to keep the fuel cell temperature at 60–65 °C.

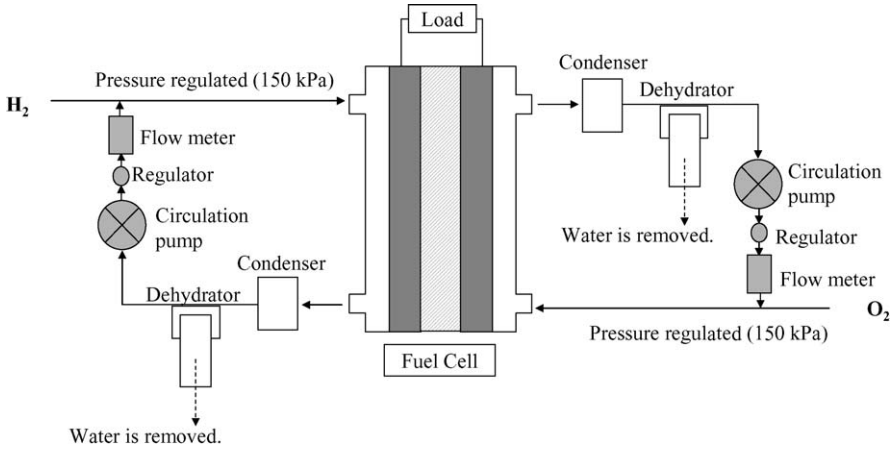

Fig. 3. Concept design of our fuel cell system for space applications.

Fig. 4. Photograph of a 1 kW-class fuel cell stack.

2.3. Design of the dehydrator

In the low-gravity of Earth orbit, we cannot separate water from humid gas using water's "weight," even if we chill the humid gas and increase the density of water.

In the GEMINI project, the water produced by the PEFC was absorbed by the wicking material installed along the gas-flow channel inside the PEFC stack. It was effective in the GEMINI fuel cell where high power with high current density was not generated.

To supply high power, we needed to remove the large amount of water produced by the PEFC operation. Thus, we designed a dehydrator that could be installed along the gas-circulation line.

Fig. 5 displays the concept design, which consists of a condenser and cylinders. Each cylinder has an outer coolant jacket to maintain the same temperature as the condenser. A wick is installed inside the cylinder to absorb water from humid gas. The wick has holes that pass through the cylinder and circulate the dehumidified gas. The dehydrator includes a piston that can squeeze the water to the outside. The wick is squeezed by the piston when it absorbs water. Humid gas is introduced to another piston to enable continuous operation of the fuel cell. In our case, we installed a wick inside the dehydrator. Gas passing through the dehydrator is cooled to 5 °C, and the humidity in the gas is absorbed by the wick to produce the low humidity gas for circulation.

2.4. System packing

Fig. 6 illustrates the fuel cell system. The 18-cell stack covered with an insulator is installed at the top of the system.

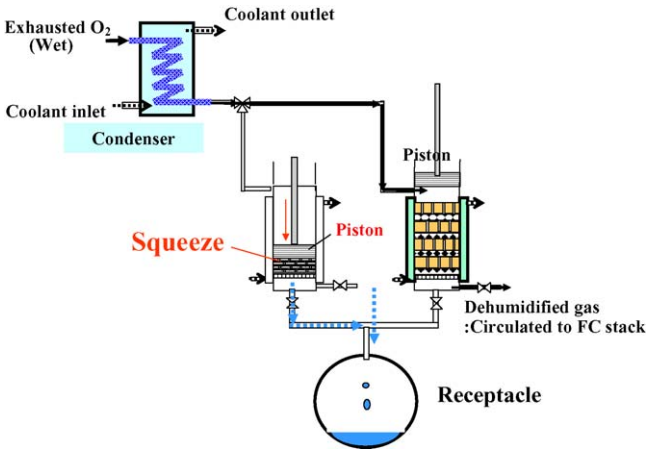

Fig. 5. Concept design of condenser and dehydrator.

Both hydrogen and oxygen were supplied to the fuel cell stack without extra humidification. The excess gases were first introduced to the condenser at the point where the 5 °C coolant is circulated to chill the humid gas and condense the water. The chilled gas/water was introduced to the dehydrator, and the water was trapped by the wicking material inside the dehydrator. The pump then increased the pressure of the dehumidified gases, and the gases were recycled to the fuel cell stack to generate the power. The water produced from the fuel cell was ejected automatically using the piston installed in the dehydrator. The dehydrator was installed along each hydrogen and oxygen line. The piston movement interval was calculated automatically by the sequence controller inside the system, which predicted the amount of water that would be produced based on the current and the number of cells.

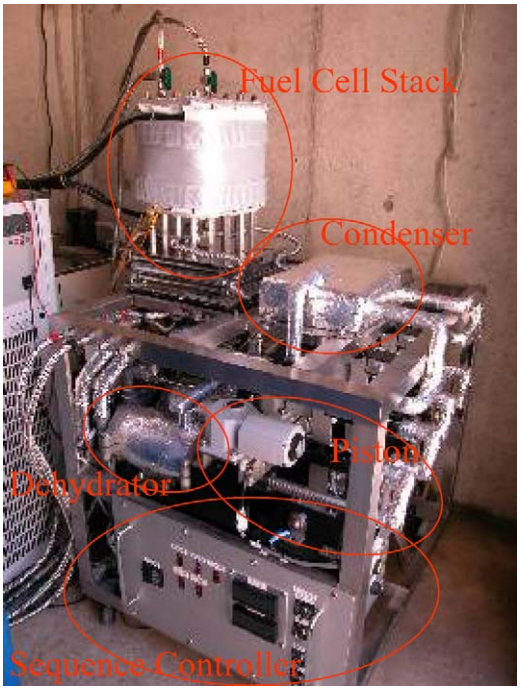

Fig. 6. Fuel cell system combining PEFC stack, gas circulator, and dehydrator.

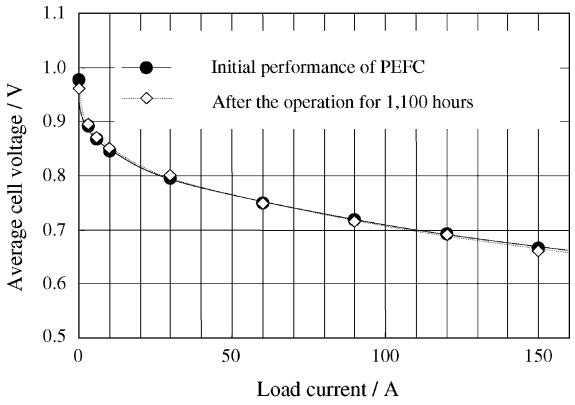

Fig. 7. *I–V* characteristics of an 18-cell stack PEFC. The fuel cell was operated at 65 °C without humidification. Both hydrogen and oxygen were exhausted. (●) Initial performance of the PEFC; (□) after the operation for 1100 h.

3. Results and discussion

3.1. Burn-in procedure of the fuel cell stack

We first increased the temperature of the fuel cell stack to 40 °C. We operated the fuel cell with a 1.00 A (6.17×10^{-3} A cm^{-2}) current flow for 1 min, followed by 3.00 A (1.85×10^{-2} A cm^{-2}) for an additional minute. We then operated the fuel cell at 20.0 A (1.25×10^{-1} A cm^{-2}) for 10 min, and subsequently increased the current in steps of 10.0 A (6.17×10^{-2} A cm^{-2}). The operation continued for 10 min at each step. The temperature of the fuel cell increased with the current. We controlled the circulation of the coolant (water) so that it took more than 30 min to raise the temperature to 60 °C. The consumption of hydrogen and oxygen was limited to 30% during the procedure.

Fig. 7 illustrates the *I–V* relationship of an 18-cell stack. During the *I–V* measurement, the excess gas for the fuel cell reaction was exhausted to the air, while the reactant gas was not humidified before being supplied to the fuel cell stack. The power generated from the stack was 810 W at 60 A and 1.8 kW at 150 A. Thus, we prepared a 1 kW-class fuel cell stack.

3.2. Simulation of closed environments

After measuring its *I–V* performance, we initiated constant operation of the fuel cell stack without external humidification. The important point for the operation here was the direction of gas flow. As previously reported, the fuel cell performance degraded immediately if the gases were supplied in the same direction to realize the concurrent flow across the MEA without humidification [11–15]. The amount of water produced inside the fuel cell can be low in the upper part and high in the lower part of the gas stream. This gradient accelerated the heterogeneous distribution of water in the cell.

In order to obtain stable performance of the fuel cell, water must be homogeneously distributed, so we supplied hydrogen and oxygen from opposite directions across the MEA. In this case, the water produced on the cathode side is carried to the lower stream of oxygen and migrates to the anode side. This migrating water humidifies the counter flow of dry hydrogen across the MEA and carries the humidity to its lower stream. Furthermore, the humidity carried by the hydrogen stream migrates through the MEA in the upper stream of cathode gas where the membrane is rather dry. As a result, we can realize a favorable distribution of water inside the fuel cell.

In this case, the gas-flow channel was serpentine, but we observed the same effect of gas-flow directions even in a interdigitated flow field [11,12].

Fig. 8 presents the results of continuous operation of an 18-cell stack for 1100 h. Cathode and anode gases were fed from opposite directions to realize the counter flow without humidification. During the whole operation, the stack was continuously operated at an average cell voltage of 0.75 V for 60 A (0.37 A cm^{-2}), and we could successfully demonstrate stable fuel cell performance for hours without humidification.

As shown in Fig. 1, conduction of protons inside the membrane requires water. In ground applications, the conventional cathode gas is air, and about 79% of the cathode gas is inert nitrogen. Due to this inert gas, the humidity of the cathode gas remains low if water is not supplied through the humidifier. Furthermore, the inert gas must be purged continuously from the fuel cell, which also decreases the humidity. Therefore, air cannot be

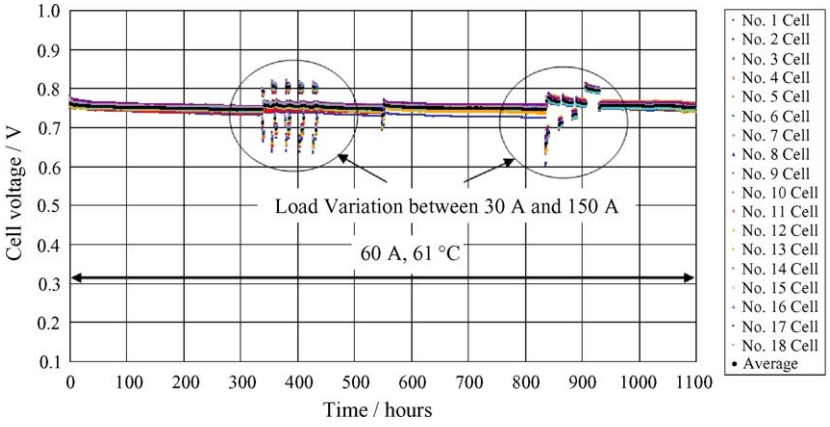

Fig. 8. Continuous operation of a 1 kW-class fuel cell. The fuel cell was operated at 65 °C without humidification. Both hydrogen and oxygen were circulated.

used as the oxidant in a closed system. However, when the cathode gas is pure oxygen, the cathode humidity can be increased by the change in oxygen utilization. The high humidity supported the performance of our fuel cell.

Our test also demonstrated the PEFC operation of closed gas conditions. All reactants must be carried inside the vehicle for space applications. Ideally, then, reactant gases must be fully consumed with no exhaust. This environmental restriction caused us to test the fuel cell performance under closed conditions, and we tried to circulate hydrogen and oxygen.

The water produced by the use of oxygen must constantly be removed from the catalyst layer of the MEA. We therefore installed a dehydrator along the gas recycling line together with a gas-circulation pump. The dehydrator can remove water by condensation. The removed water was wicked up and reapplied to humidify the fuel cell by controlling the temperature of the dehydrator. Gas circulation also plays an important role in inhibiting flooding on the cathode side. In this operation, the gas-circulation rate was four times greater than the theoretically required mass [13–15]. The appropriate circulation rate resulted in constant fuel cell performance.

Ideally, if the hydrogen outlet at the anode were to be closed, the simplest system could be realized. To do this, we must prevent condensation and accumulation of unvaporized water in hydrogen with subsequent flooding on the anode side. In our previous report, we demonstrated that the hydrogen outlet port could be dead-ended [13–15]. However, we installed the gas-circulation system and dehydrator along the hydrogen gas-flow line as well as the oxygen line to maintain a continued stable performance under the microgravity conditions of the system. In our previous system, we dead-ended the hydrogen outlet port, so that the slow hydrogen stream might maintain the humidity inside the fuel cell. However, the results of continuous operation of the current system confirmed that stable performance of the PEFC system could be maintained by the hydrogen gas circulation even without external humidification.

The purity of reactant gas is also important for gas circulation or closed gas operation. When we used low purity gases, we observed degraded fuel cell performance. Impurities such as nitrogen inside the fuel cell might also gradually decrease performance. Specifically, we used 99.99999% pure hydrogen and 99.999% pure oxygen for continuous operation. Even though we use such pure gases, we need to purge at regular time intervals to operate a fuel cell in a closed environment. In our system, the water that accumulated inside the dehydrator cylinder was ejected by the movement of the piston at regular time intervals. The gas inside the cylinder was also ejected by the piston movement, which plays the same role as the purge system for the impurities. The piston movement interval is automatically controlled by the sequencer installed in the system. The results shown in Fig. 8 also demonstrated that automatic operation of the dehydrator facilitates constant operation of our system.

We simulated operation of an energy-generating system for space applications. Although we varied the load current between 30 and 150 A, we observed no drastic degradation of the generating voltage of the PEFC stack. Fig. 7 also displays the *I–V* performance of the PEFC stack after continuous operation of the fuel cell system for 1100 h. We observed almost the same *I–V* characteristics for the stack even after the extended operation, verifying the system concept and the subsystem component function in our system.

In a Space Shuttle, the operation period for one flight is about 250 h (10 days), and the maintenance interval for its alkaline fuel cell is every 2500 h. Our test results demonstrated the applicability of the PEFC system to the closed environment inside a spacecraft in which an alkaline-type-fuel cell system might typically have been applied.

4. Conclusion

JAXA is now developing a PEFC system for the future operation of transfer vehicles and larger spacecraft.

We tested PEFC performance without external humidification for a 1 kW-class PEFC system in a closed environment. Our experiments confirmed that the fuel cells did not need a humidifier if they were operated with pure hydrogen and oxygen supplied from opposite directions. We also simulated closed gas operations to demonstrate the applicability of this fuel cell system to a closed environment in which both hydrogen and oxygen are circulated and the extracted water is removed.

The results of our constant operation of a PEFC system for approximately 1100 h in a closed gas system should provide information and guidance for future design and operation in space applications.

Acknowledgement

This research was partially supported by the New Energy and Industrial Technology Development Organization (NEDO) of Japan.

References

[1] W.E. Simon, D.L. Nored, Proc. IEEE 75 (3) (1987) 277.
[2] M. Warshay, P.R. Prokopius, J. Power Sources 29 (1990) 193.
[3] W.E. Simon, Proceedings of the Space Shuttle Technical Conference, NASA CP-2342, 1985, p. 702.
[4] S. Kuwajima, in: Z. Takehara (Ed.), Fuel Cell Technology and Its Applications, vol. III, Technosystem, Tokyo, 2000, p. 293 (in Japanese).
[5] P.L. Loyselle, T.M. Maloney, H.M. Cathey Jr., Proceedings of the 34th Intersociety Energy Conversion Engineering Conference, Paper No. 1999-01-2588, 1999.
[6] M.L. Davis, R.K. Allgeier Jr., T.G. Rogers, G. Rysavy, The Development of Cryogenic Storage Systems for Space Flight, NASA SP-247, 1970.
[7] O.A. Velev, Proceedings of the 35th Intersociety Energy Conversion Engineering Conference, Paper No. AIAA-2000-2873, 2000.
[8] H. Naito, K. Eguchi, T. Hoshino, S. Okaya, American Institute of Aeronautics and Astronautics, Paper No. 99-3913, 1999.
[9] J.P. Fellner, Z.A. Johnson, D.F. Pickett, Proceedings of the 35th Intersociety Energy Conversion Engineering Conference, AIAA 2000-2871, 2000.
[10] H. Itagaki, Y. Kaneko, T. Yokoyama, Y. Nakamura, T. Oka, Y. Hamada, T. Yamaguchi, Proceedings of the Symposium of Next Moon Exploration, Sagamihara, Japan, 1999, p. 100 (in Japanese).
[11] Y. Sone, M. Ueno, S. Kuwajima, Proceedings of the 41st Electrochemistry Seminar, Kobe, Japan, 2001, p. 65 (in Japanese).

[12] Y. Sone, M. Ueno, S. Kuwajima, Electrochemistry 70 (2002) 705 (in Japanese).
[13] Y. Sone, M. Ueno, S. Kuwajima, J. Power Sources 137 (2004) 269.
[14] Y. Sone, M. Ueno, S. Kuwajima, Electrochemistry 71 (2003) 938 (in Japanese).
[15] Y. Sone, M. Ueno, H. Naito, S. Kuwajima, Electrochemistry (submitted for publication).
[16] T.A. Zawodzinski Jr., T.E. Springer, J. Davey, R. Jestel, C. Lopez, J. Valerio, S. Gottesfeld, J. Electrochem. Soc. 140 (1993) 1981.
[17] Y. Sone, P. Ekdunge, D. Simonsson, J. Electrochem. Soc. 143 (1996) 1254.
[18] R.S. Yeo, H.L. Yeager, B.E. Conway, R.E. White, in: J.O'M. Bockris (Ed.), Modern Aspects of Electrochemistry, vol. 16, Plenum Press, New York, 1985, p. 437.