Journal of Power Sources 196 (2011) 9076–9080

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Short communication

A 100-W class regenerative fuel cell system for lunar and planetary missions

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ARTICLE INFO

Article history:
Received 6 November 2010
Received in revised form 13 January 2011
Accepted 26 January 2011
Available online 3 February 2011

Keywords:
PEFC
Electrolysis
Regenerative fuel cell
Aerospace
Closed environment
System design

ABSTRACT

The Japan Aerospace Exploration Agency (JAXA) is developing polymer electrolyte fuel cell (PEFC) systems that can be operated under isolated low-gravity and closed environments. In the present study, we combine the PEFC with an electrolyzer in order to realize a regenerative fuel cell. Ideally, if a single cell can be operated as a fuel cell and the cell can be made reversible through the electrolysis reaction, then compact, lightweight regenerative fuel cell systems can be realized. A unitized regenerative fuel cell was prepared, and its operability was demonstrated. During 100-W class operations, a stable fuel cell and electrolysis reaction was observed.

1. Introduction

Recently, lithium-ion secondary cells/batteries have received significant attention because of their higher energy densities compared to Ni–Cd, Ni–MH, and Ni–H_2 batteries. In the field of space technology, a number of studies are focusing on applying lithium-ion battery systems in spacecraft [1–7]. The Japan Aerospace Exploration Agency (JAXA) has also been developing lithium-ion secondary cells for aerospace applications [3–7]. One example is the HAYABUSA spacecraft, which used 13.2 Ah lithium-ion secondary cells. Based on the above experience, JAXA used lithium-ion secondary batteries for the Venus and Mercury missions.

Lithium-ion secondary cells are attractive for use in lunar and planetary missions because the energy density realized by the cell is 100–160 Wh kg^{-1}. The energy density is approximately two or three times higher than that of the conventional Ni–Cd, Ni–MH, and Ni–H_2. However, higher energy densities that exceed those of current lithium-ion secondary cells are desired for future lunar and planetary missions. In order to satisfy these demands, research into regenerative fuel cells must be accelerated.

A major disadvantage of conventional battery systems is the coupling between their capacity and rated power. For fuel cell systems these parameters are decoupled, since their capacity is rated to the fuel storage while the rated power depends on the electrode area. Furthermore, the combination of hydrogen and oxygen is very promising in order to realize the energy storage device with high energy density exceeding conventional battery systems. Fuel cells have been applied to spacecraft since the 1960s. When hydrogen and oxygen are used for the reaction, a fuel cell can produce water as a by-product of generating electricity, making this attractive as an option for manned operations in a closed environment [8–17]. At present, we use the produced water for the electrolysis reaction and reproduce the hydrogen and oxygen in order to realize a regenerative fuel cell system.

For space missions, the regenerative fuel cell systems have been receiving much attention targeting the application to earth orbit missions, the solar electric aircraft, and lunar and planetary surface installations [18–21]. We also prepared a 1-kW class regenerative fuel cell to demonstrate its applicability to the stratospheric platform project of Japan. A fuel cell and an electrolysis reaction were tested to simulate the material balance using the system. Furthermore, a 100-W class demonstration system was also prepared in order to confirm the realization of a compact regenerative fuel cell system. All of these activities were based on the separated regenerative fuel cell concept, where two different stacks were individually used for the electrolysis and the fuel cell.

Ideally, we can realize a lightweight, compact regenerative fuel cell system if the fuel cell and the electrolysis reaction can be realized using the same stack. As a result, the unitized regenerative fuel cell (URFC) has been investigated. The design of electrode for URFCs requires a delicate balancing of transporting media. The transportation of gases, electrons and protons must be carefully optimized to provide efficient electrochemical reactions using the bi-functional electro-catalyst for the fuel cell and the electrolysis reaction [22].

Recently, the URFC performance is very much enhanced based on the development of electro-catalyst and gas diffusion back-

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doi:10.1016/j.jpowsour.2011.01.085

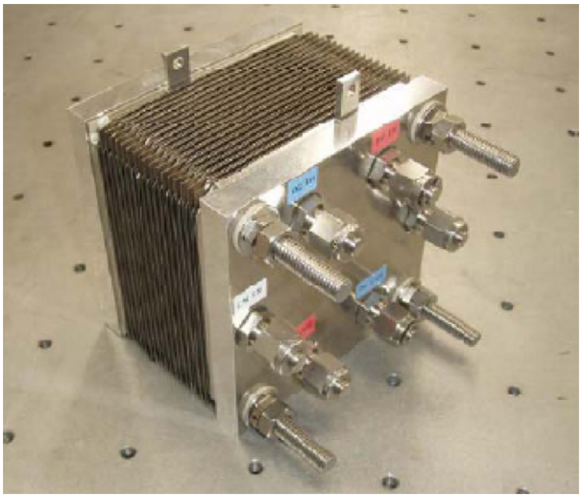

Fig. 1. Photograph of a 100-W class regenerative fuel cell stack.

Table 1
Specifications of the unitized regenerative fuel cell.

Fuel cell mode	
Power	100-W class
Output voltage	12-V class
Water electrolysis mode	
Input voltage	28-V class
Operational conditions	
Temperature	Above 25 °C
Current	Less than 30 A for electrolysis Less than 15 A for the fuel cell
Stack design	
Stack number	17 cells in series
Electrode area of the MEA	28.5 cm^2 $cell^{-1}$

ings, which encouraged us to develop the URFC system which can demonstrate its applicability to our lunar and planetary missions [23–25]. The 100-W URFC stack was prepared, and its performance was tested in order to realize an autonomous system in the future.

2. Experimental

Fig. 1 shows the photograph of the unitized regenerative fuel cell (URFC) stack. The URFC was prepared by Takasago Thermal Engineering Co., Ltd. The original specifications of the stack are shown in Table 1. The IrO_X over Pt-black was adhered as the catalyst to the perfluorinated proton-conducting membrane to form the membrane electrode assembly (MEA). The platinum-coated titanium separator was used for the gas flow channel. A total of 17 cells were stacked together to realize 28-V class operation of water electrolysis and 12-V class fuel cell reactions. Each cell had a separator for the coolant. The temperature of the stack was controlled by water circulation during the reactions. The water circulation rate was 2 l min^{-1}.

After the electrolysis reaction, the stack was purged by the dry nitrogen gas before the fuel cell reaction. For the fuel cell reaction, the nominal temperature for the operation was less than 80 °C. The gas flow rate during the reaction was constant at 4 l min^{-1}. During the fuel cell reaction, the coolant water was circulated to maintain the constant thermal condition of the stack. The nominal current level was 15 A for 12-V class operation of the fuel cell reaction. During the fuel cell operation, the hydrogen and oxygen were not circulated and were exhausted after the fuel cell reaction.

For the electrolysis, the nominal current supplied to the URFC was less than 30 A for 28-V class electrolysis operation. The flow rate of the water supplied to the stack was 1.8–1.9 l min^{-1} under the open circuit condition and 1.4 l min^{-1} for the nominal electrolysis procedure. For electrolysis, the prepared stack was designed to be operated under atmospheric conditions. The gas output line was open to the atmosphere during the electrolysis operation. Thus, the hydrogen and oxygen produced from the cell were released into the atmosphere.

During operation, the distributions of temperature and voltage among the cells were monitored. Three separators were installed inside the stack. Thermocouples were inserted into the separator in order to measure the temperature distribution along the surface of the separator.

3. Results and discussion

Fig. 2 shows the concept design of the regenerative fuel cell. In the case of the separated regenerative fuel cell, the water electrolyzer is connected to the water supply unit and gas storage tanks. For the fuel-cell reaction, oxygen and hydrogen are supplied from the gas tank after proper regulation of the pressure. The advantage of the separated regenerative fuel cell is the efficiency of each stack. The electrolyzer and fuel cell can be designed for specific applications to realize the proper efficiency. However, the weight loss due to the separated stack cannot be neglected if the compact regenerative fuel cell is required.

Recently, discussion focused on staying overnight on the moon has received a great deal of attention. The energy required for unmanned spacecraft, such as rovers and seismometers, is approximately 100 W, and the amount of time required for a night landing at the lunar equator is 350 h. Furthermore, the size and mass of the spacecraft are severely restricted by the launcher. Thus, the most lightweight, compact design must be realized. In order to satisfy this requirement, unitized design of the regenerative fuel cell is investigated.

Science missions in space often use 28-V class bus systems in the spacecraft. During the period of sunshine, the battery is charged to 28 V, and the battery is discharged during nighttime.

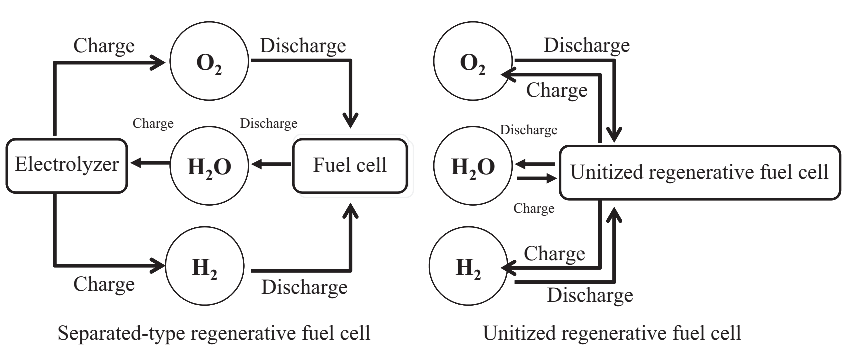

Fig. 2. Concept of the regenerative fuel cell.

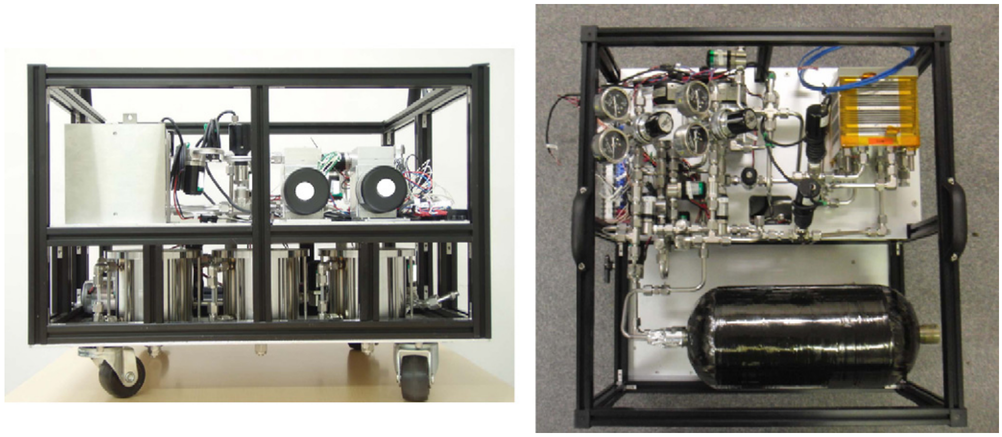

Fig. 3. Photograph of the demonstration model of the 100-W class URFC system.

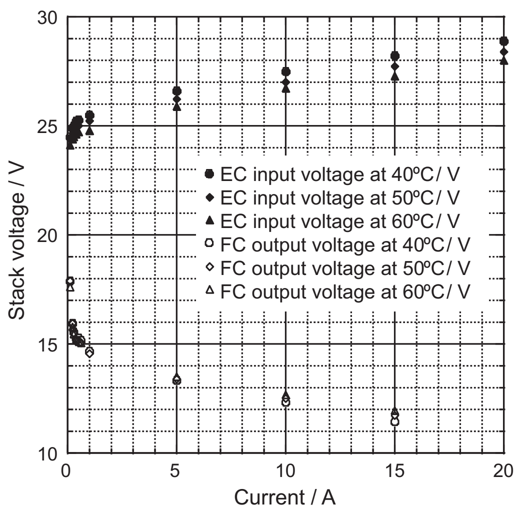

Fig. 4. *I–V* characteristics of a seventeen-cell stack URFC. The regenerative fuel cell (RFC) was operated at 40 °C, 50 °C and 60 °C.

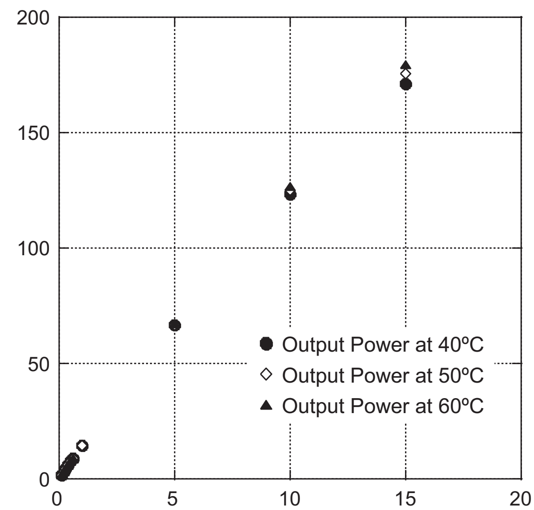

Fig. 5. Power generated during the fuel cell reaction of the URFC stack.

Japanese spacecrafts are operated by unregulated power from the battery. European spacecrafts are normally operated by regulated power at 28 V. In order to satisfy both of these operations, a 28-V class unitized regenerative fuel cell system, which can generate 100-W class electricity by the fuel cell reaction, was designed.

Fig. 3 shows a 100-W class demonstration model of the URFC system. Water is decomposed into hydrogen and oxygen by 28-V electrolysis, and the hydrogen and oxygen are then stored inside the tank. Water produced by the 12-V fuel cell reaction is stored inside a container. This water can be circulated for the electrolysis reaction. In order to determine the automatic operational condition of the system, the basic performance of the URFC stack was investigated.

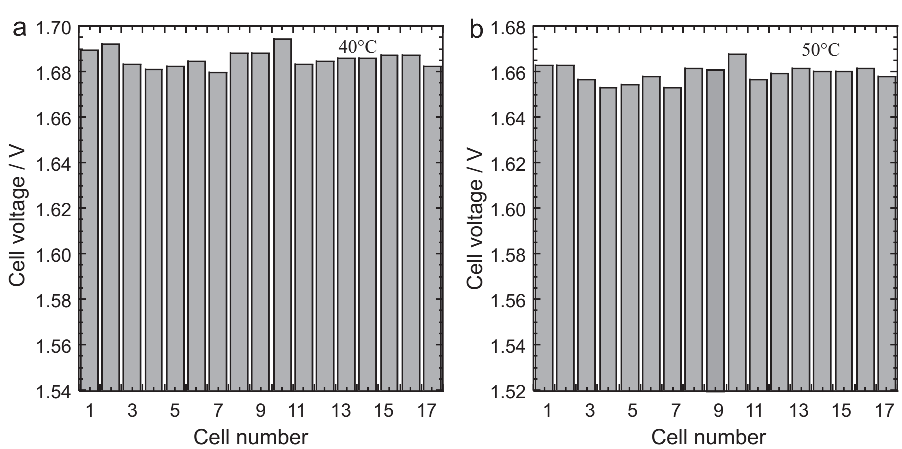

Fig. 6. Cell performance during the electrolysis reaction of the URFC stack. The regenerative fuel cell (URFC) was operated at (a) 40 °C and (b) 50 °C.

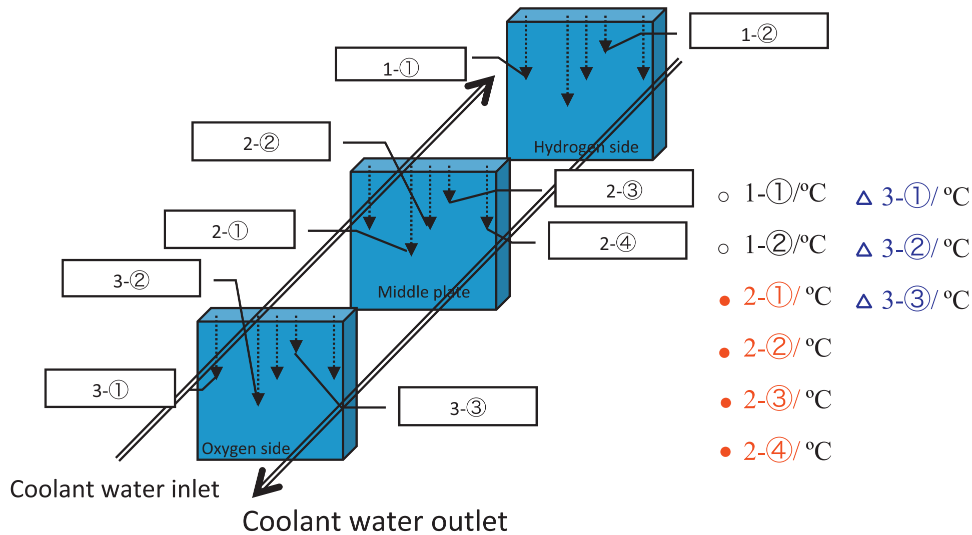

Fig. 7. Plates used to measure the temperature distribution inside the URFC stack. Thermocouples were installed in the plates.

The URFC stack was operated at 40 °C, 50 °C and 60 °C. The electrolysis performance of the stack was tested at less than 28 V, which simulates the operational conditions for the 28-V class bus system of spacecraft. In the case of the fuel cell reaction, the URFC was tested at above 12 V, because the DC/DC converter used to regulate the voltage for the loads can be easily selected for operations above the 12-V class.

Fig. 4 shows the *I–V* performance during electrolysis and fuel cell reaction. For the electrolysis, the *I–V* curve at a lower temperature exhibited a higher voltage for the electrolysis, whereas approximately the same voltage was monitored during the fuel cell reaction between 40 °C and 60 °C at lower current less than 5 A.

Fig. 5 shows the power curves during the fuel cell reaction. The output power was approximately 180 W at 15 A, which suggests that the performance of the URFC is sufficient. Above 15 A, output power at 60 °C was slightly higher than that at 40 °C, which might reflect the decrease in impedance at higher stack temperatures.

Fig. 6 shows the cell voltages during water electrolysis. The URFC was operated at 20 A. The cell voltage at 40 °C was 20 mV higher than that at 50 °C. The distribution of the cell voltages was less than 20 mV, and each cell appeared to maintain the same performance distribution at each temperature.

The temperature of the stack was monitored during the operations, as shown in Fig. 7. Three plates having thermocouples of different depths were installed inside the URFC stack in order to monitor the thermal distribution. Fig. 8 shows the temperature trend for the electrolysis at 40 °C. The coolant water circulating inside the URFC stack was controlled at 40 °C, whereas the temperature inside the stack has a gradient and the temperature difference depending on the position was less than 0.8 °C. Furthermore, the

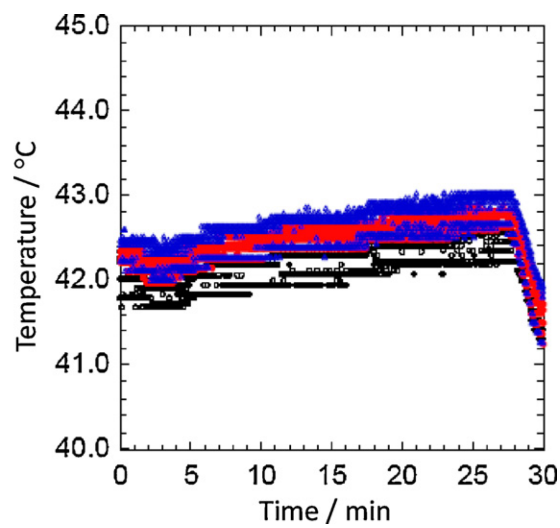

Fig. 8. Temperature distribution inside the URFC stack.

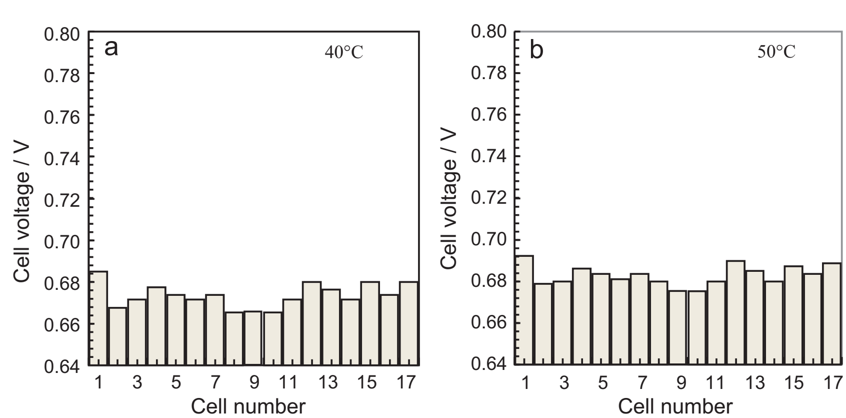

Fig. 9. Cell performance during the fuel cell reaction of the URFC stack. The regenerative fuel cell (RFC) was operated at (a) 40 °C, (b) 50 °C and (c) 60 °C.

difference did not increase during operation, which indicates that the thermal condition inside the stack was well controlled by the operation. After 28 min, the temperature of the stack decreased because of external thermal control using a chiller. Fuel cell is usually operated above 70 °C since the resistance of the membrane decreases with increasing temperature. However, when the fuel cell is operated above 70 °C, the fuel cell system must be equipped with the humidifier in order to avoid the dry-out of the membrane. Whereas, through our experience, the fuel cell can be operated without external humidification if the fuel cell is operated at lower temperature less than 60 °C [14–17]. Thus we tested our unitized stack at lower temperature less than 60 °C. The results obtained here demonstrated that the unitized regenerative fuel cell stack could be operated above 40 °C which will satisfy our requirements to realize the 12-V class fuel cell operation for 100-W class system.

Fig. 9 shows the cell voltages during the fuel cell reaction at 40 °C and 50 °C. Hydrogen and oxygen were humidified at the same temperature for the fuel cell operation. The difference in cell voltage in the case of the fuel cell reaction exhibited approximately the same tendency as in the case of electrolysis. The difference in cell voltage was less than 20 mV and did not vary with the operating temperature. The uniform performance of each cell suggests that the gas and water condition inside the cell were suitable for proper operation.

4. Summary

JAXA is developing the regenerative fuel cell (RFC) system based on the polymer electrolyte fuel cell (PEFC). In the present study, we combine the PEFC with an electrolyzer in order to realize a unitized regenerative fuel cell (URFC). A 100-W class URFC system was designed, and the basic performance of the stack, which should be reflected in the automatic system operation, was investigated.

During the fuel cell and electrolysis reaction, the difference in cell voltage was within 20 mV at the temperature range between 40 °C and 60 °C. The performance of the stack was confirmed to be sufficient.

Acknowledgements

The author would like to thank Atsushi Kato and Atsushi Takahashi of Takasago Thermal Engineering Co., Ltd. and Tetsuya Yoshida of Daiki Ataka Engineering Co., Ltd. for providing technical support.

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