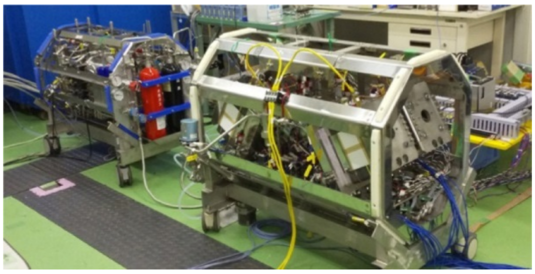
Development of Scalable Regenerative Fuel Cell System as Completely Isolated Power Supply



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Power sources and electric power sources are one of the major issues in promoting the use of the ocean. In order to solve this issue, during the three years from FY2018 to FY2020, as a project selected by the Japan Aerospace Exploration Agency (JAXA) for their request for proposals for the space exploration innovation hub, Mitsubishi Heavy Industries, Ltd. (MHI) developed a completely isolated scalable fuel cell system that can be designed in a scalable manner according to the output scale of the application. In this development, we prototyped a fuel cell device with improved operational reliability and a water electrolysis device that performs electrolysis at high pressure, which realized a repeated cycle of electrolysis and power generation in a completely closed system.

1. Introduction

In Japan, which is surrounded by the sea, it is required to promote the use of the ocean (surface, underwater and deep sea) to create new industries. However, on the sea surface it has been difficult to use conventional internal combustion engines due to recent strict environmental regulations and under the sea and in the deep sea, internal combustion engines have never been usable because there is no air underwater. In this way, power sources and electric power sources are one of the major issues for the use of the ocean. As a technology that can solve this issue, MHI has been developing a regenerative fuel cell system that combines a water electrolysis device and a fuel cell device and during the three years from FY2018 to FY2020 we developed a completely isolated scalable fuel cell system as a project selected by the Japan Aerospace Exploration Agency (JAXA) after their request for proposals for the space exploration innovation hub. This report describes on the development process.

The completely isolated scalable fuel cell system is a regenerative fuel cell system that can be designed in a scalable manner according to the output scale of the application. **Figure 1** describes its configuration. In the system depicted in this figure, the water electrolysis device powered by electrical energy from the solar cell produces hydrogen and oxygen and the fuel cell device generates electricity to establish a completely isolated power supply. In order to reduce the storage volume of hydrogen and oxygen, the water electrolysis device is operated at high pressure.

In this system, it is necessary to seal the piping and completely circulate hydrogen and oxygen, which are active materials, as well as water, which is a product thereof, between the water electrolysis device and the fuel cell device in order to prevent their dissipation. In this research and development project, we prototyped a fuel cell device and a water electrolysis device, aiming for complete circulating operation of hydrogen, oxygen and water.

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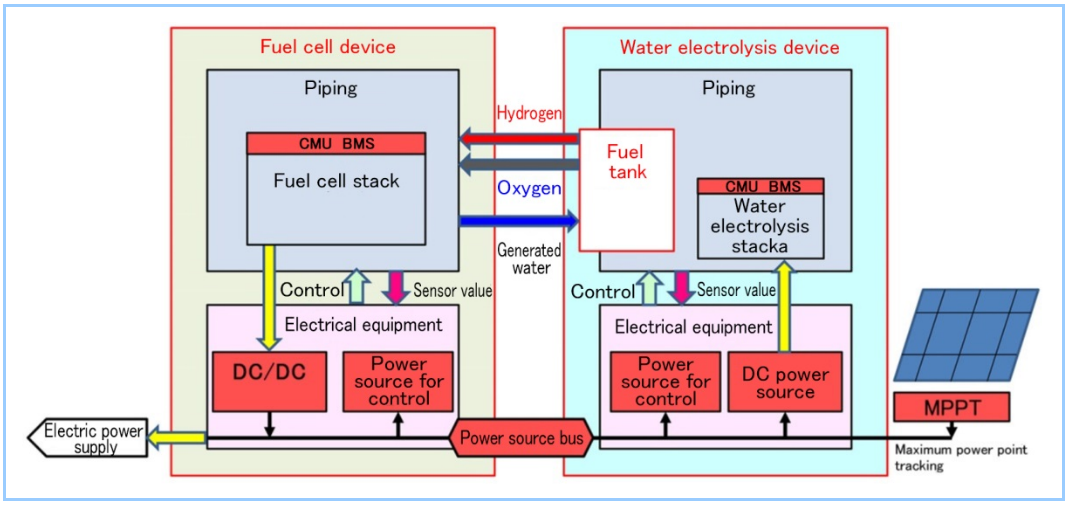
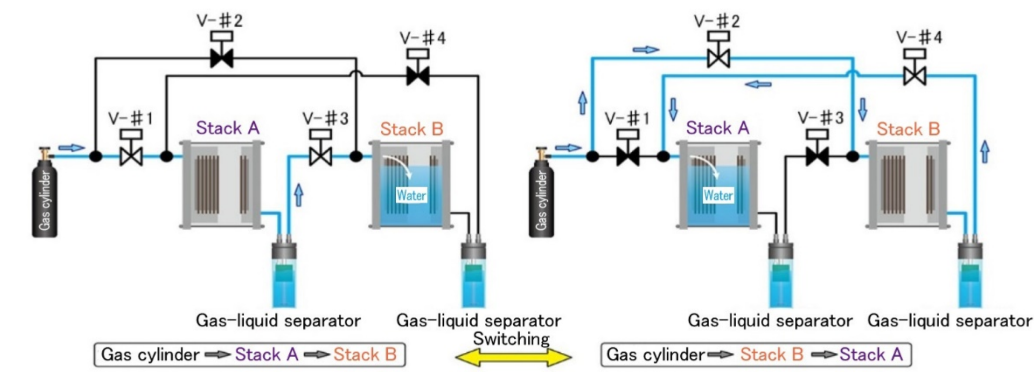


Figure 1　Configuration of completely isolated scalable fuel cell system

2. Examination of prototype fuel cell device and water electrolysis device as system elements

2.1 Examination of prototype fuel cell device

For the fuel cell device that makes up the completely isolated scalable fuel cell system, the HEML (High Efficiency Multi Less) method(1), which Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and MHI have been studying and developing for application to electrical power sources of marine equipment, was adopted. **Figure 2** gives an outline of this method. This method consists of two stacks and multiple valves in which gas passes through one stack—called the upstream stack—and then flows into the other stack, called the downstream stack. The upstream stack and the downstream stack are switched by operating the valves at certain time intervals during operation. Since the gas to be consumed by the two stacks (the upstream and downstream stacks) is supplied to the upstream stack, there is a gas flow at the outlet of upstream stack to the downstream stack, which exhausts the generated water. The downstream stack accumulates the generated water inside because there is no gas flow, but when the upstream and downstream stacks are switched, it turns to be the upstream stack and exhausts the generated water. The power generation stability is ensured by appropriately selecting the time interval for switching the upstream and downstream stacks.



				Stack A				Stack B			
V-#1	V-#2	V-#3	V-#4	Location	Reaction gas	Excess gas	Generated water	Location	Reaction gas	Excess gas	Generated water
Opened	Closed	Opened	Closed	Upstream	Supplied from gas cylinder (RH0%)	Exhausted	Exhausted	Downstream	Humidified gas is supplied (humidified to about RH100% at upstream stack)	None (consumed fully)	Accumulated in stack
Closed	Opened	Closed	Opened	Downstream	Humidified gas is supplied (humidified to about RH100% at upstream stack)	None (consumed fully)	Accumulated in stack	Upstream	Supplied from gas cylinder (RH0%)	Exhausted	Exhausted

RH% = Relative Humidity %

Figure 2　Operation of HEML method

This time, aiming at higher operational reliability of the completely isolated scalable fuel cell system, we decided to consider increasing the number of stacks in which gas flows in series to improve the generated water exhausts capacity.

When the number of stacks is increased to N, the time period during which a stack is located most downstream and the generated water accumulates in the stack is reduced to 1/N, which reduces the probability of deterioration of power generation performance. In addition, upstream stacks have a large gas flow at their outlet due to the large number of the downstream stacks, which improves the generated water exhaust capacity and the operational stability. On the other hand, there arises the issue that the number of pipes and valves increase and the system becomes complicated. Therefore, we decided to set the number of stacks to four, which is twice the minimum required number of two for the HEML method.

The four stacks were divided into two groups of two stacks and arranged so that the two groups face each other. Normally, the power generation is performed while switching the gas flow of the four stacks. However, when the inclination is large and the generated water cannot be exhausted from one of the stack groups, the valve control is changed so that the power generation is performed only by the other stack group that can exhaust the generated water. As a result, electric power can always be supplied. With this mechanism, restrictions on the posture of the fuel cell device are greatly reduced and the installation for applications in which the fuel cell device is mounted in a vertical posture, such as VLSs (Vertical Launching Systems), is made possible.

Figure 3 is the appearance of the fuel cell device. As described above, the four fuel cell stacks (stack A to stack D) are divided into two groups of two stacks and arranged in a V-shape so that the two groups face each other.

Figure 4 illustrates the change in the cell voltage of the stack A to represent the behavior of the cell voltage during power generation. In this figure, the six graphs, which indicate the voltage of the six cells in the stack, overlap. When the stack became the most downstream stack and the gas flow disappeared, the cell voltage dropped the most and when it became an upstream stack and the gas flow recovered, the cell voltage also recovered. (The voltage was recovered by switching the valves.)

The internal temperature of the pipes for both hydrogen and oxygen lines rose at the timing when the voltage recovered. Since the temperature inside the pipe rises when the water generated by power generation flows, it is examined that the cell voltage was restored due to the elimination of the water accumulation. From these data, it was confirmed that the operation was as planned as a prototype, although fine adjustments were necessary.

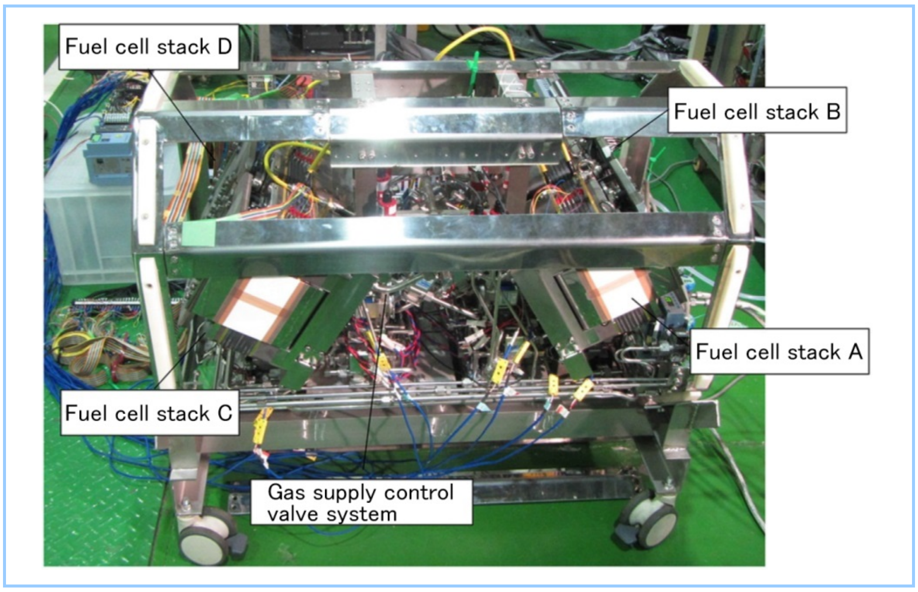


Figure 3 Prototyped fuel cell device

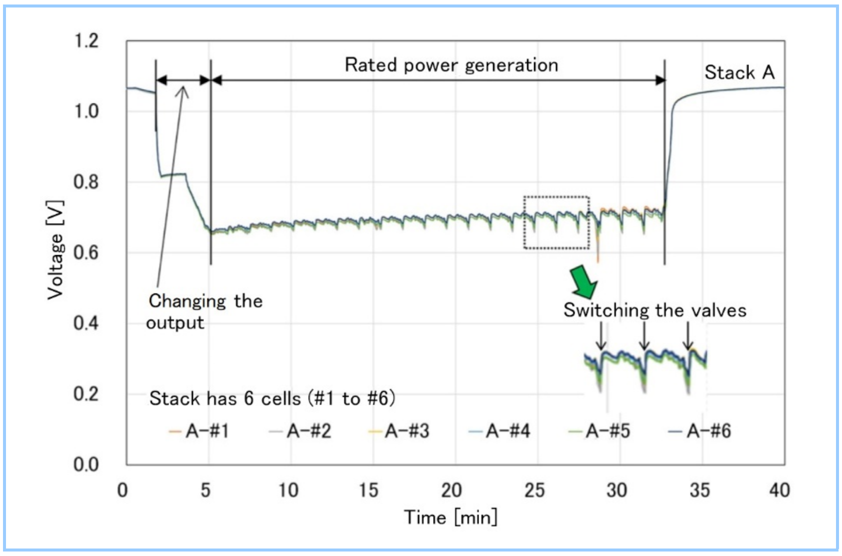


Figure 4 Result of power generation of prototyped fuel cell device

2.2 Examination of prototype water electrolysis device

The water electrolysis device that consists of the completely isolated scalable fuel cell system is based on the water electrolysis stack technology[2] that we have been developing and uses an equalizing/increasing pressure method that performs pressurization to increase the pressure with hydrogen and oxygen generated by electrolysis, while equalizing the pressure of the hydrogen and oxygen electrodes. The maximum operating pressure of this water electrolysis device was designed to be 29.9 MPa. In a general water electrolysis device, water for electrolysis is circulated only in the oxygen line, but in this device, water for electrolysis is also circulated in the hydrogen line in order to handle high-pressure hydrogen and oxygen safely. In addition, the amount of water supply for electrolysis is increased compared to the amount of water used for electrolysis, so that the generated hydrogen and oxygen are transported along with water. The water electrolysis stack is installed in the stack accommodating container to have a piping structure that makes the pressure in the hydrogen line and the pressure in the stack accommodating container the same. Furthermore, by controlling the pressures of the hydrogen line and the oxygen line to be the same, mixing of hydrogen and oxygen due to damage to the sealing material and gas leakage from the stack are prevented. Hydrogen and oxygen transported along with water are separated from the water for electrolysis in each gas-liquid separator and stored in the gas storage tanks. **Figure 5** is the appearance of the water electrolysis device. In this prototype, the water electrolysis device was mounted on the octagonal frame for the first time. This made it possible to accommodate the device in a bale-type pressure-resistant container used underwater. **Figure 6** depicts the water electrolysis stack accommodating container mounted on this water electrolysis device. **Figure 7** presents the water electrolysis stack installed inside this accommodating container.

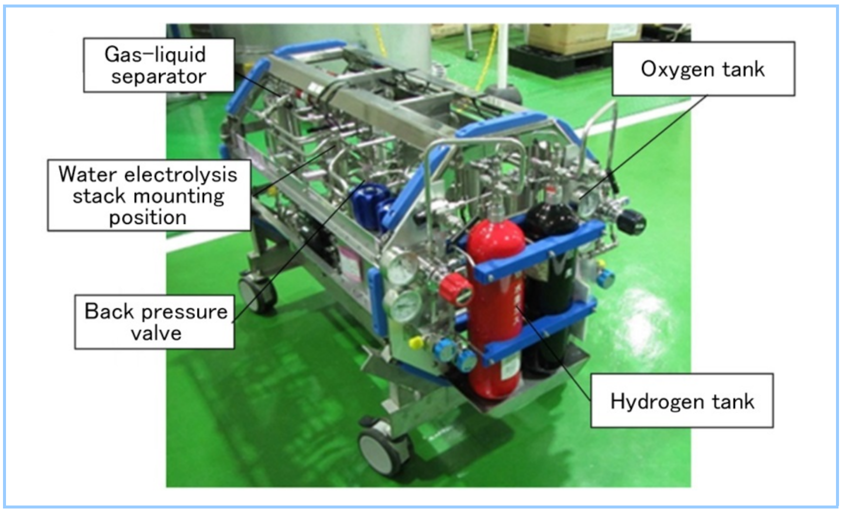


Figure 5 Prototyped water electrolysis device

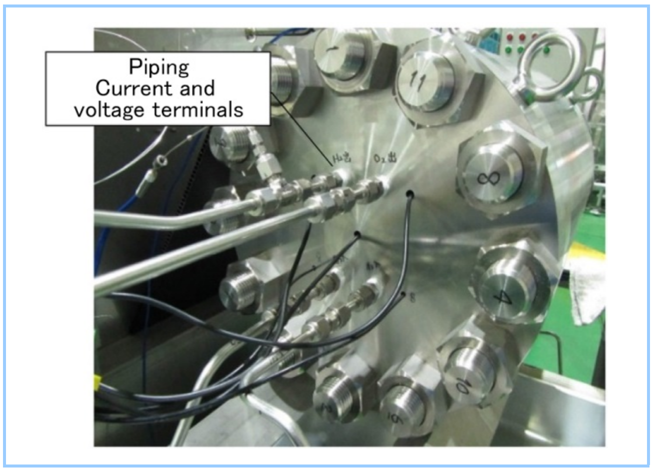


Figure 6 Water electrolysis stack accommodating container

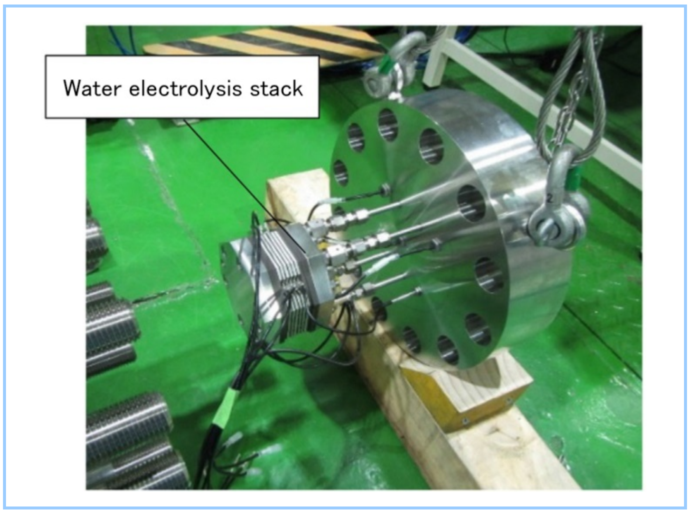


Figure 7 Water electrolysis stack

Figure 8 presents the results of acquiring the IV characteristics of the water electrolysis stack. The electrolytic voltage of the stack prototyped this time tended to be higher than that of the element verification cell. Furthermore, when the electrolytic state was maintained at 20A, the phenomenon where the electrolytic voltage increased with time was observed (① in the figure).

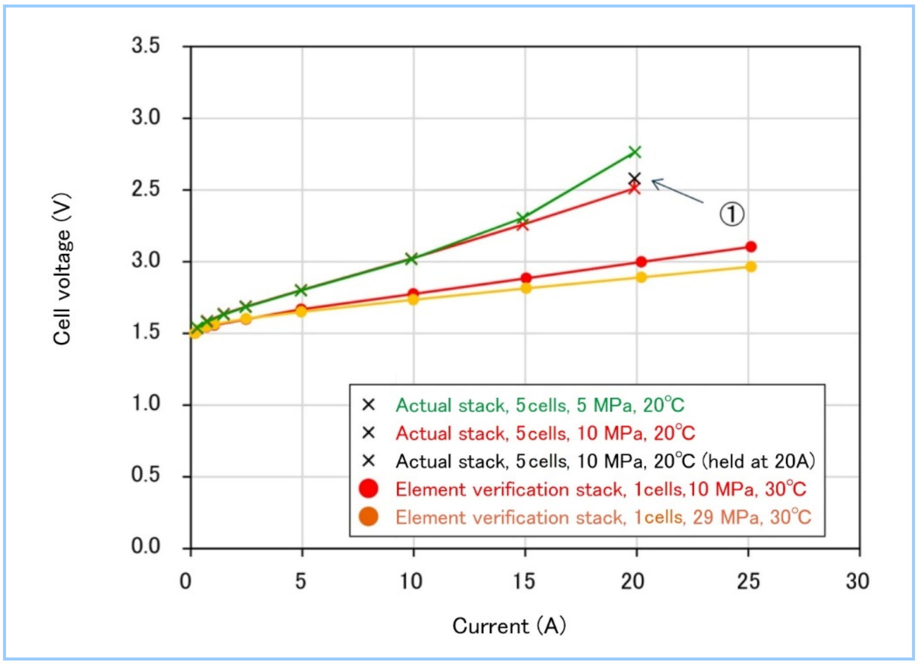


Figure 8 IV characteristic of water electrolysis stack

Factors that increase the electrolytic voltage include an increase in the resistance of the electrolytic membrane due to the adsorption of impurities derived from residues and supply water in the system, a decrease in catalytic activity and an increase in contact resistance due to a decrease in the contact between the electrolytic membrane and the feeder, so investigation of this matter is needed.

3. Examination of building completely isolated scalable fuel cell system

We built a completely isolated scalable fuel cell system by combining the prototyped fuel cell device and water electrolysis device. **Figure 9** is the appearance of the system. **Figure 10** illustrates the active material cycle in this system.

Hydrogen and oxygen generated by the water electrolysis device are stored in the gas storage tanks and supplied to the fuel cell device. The water generated by the fuel cell reaction is transferred by the drainage pump of the fuel cell device. This time, a high-pressure water supply pump is used to return the water to the water electrolysis device.

We conducted an operation test of this system by the following procedure: replacing both the hydrogen gas storage tank and the oxygen gas storage tank with high-purity hydrogen and high-purity oxygen; carrying out electrolysis in the water electrolysis device that held sufficient water for electrolysis and storing the hydrogen and oxygen produced from the electrolysis in the gas storage tanks; supplying hydrogen and oxygen from the gas storage tanks to the fuel cell device to generate electricity; and returning the generated water to the water electrolysis device with the high-pressure water pump after the power generation was finished. At this time, the valve operation necessary to supply hydrogen and oxygen was manually performed. Similarly, the pump operation necessary to move the generated water was performed manually.

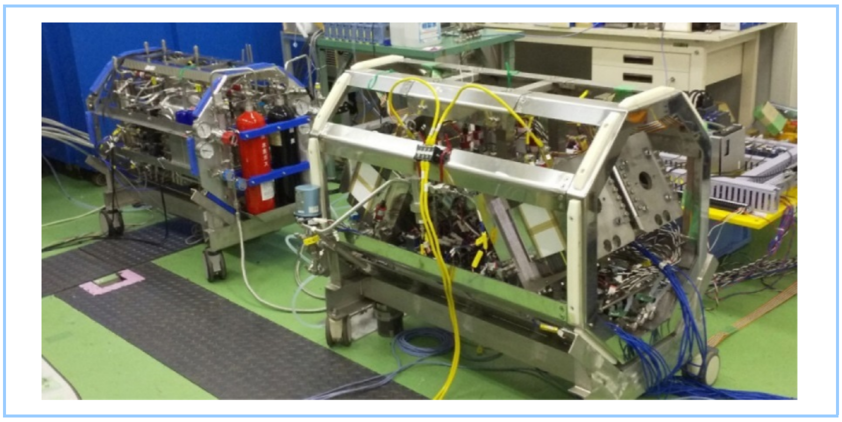


Figure 9　Completely isolated scalable fuel cell system

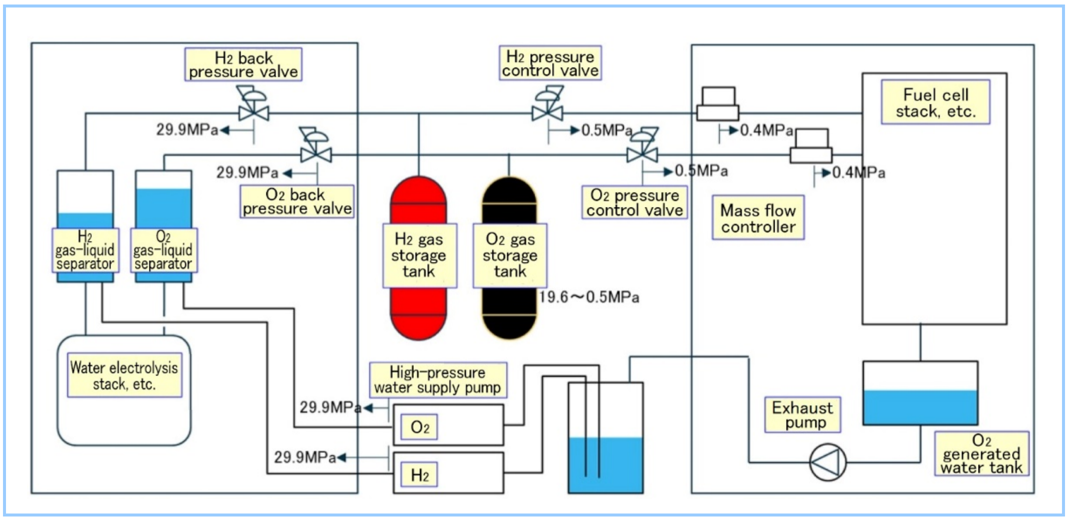


Figure 10　Active material cycle (gas supply and generated water recovery)

Figure 11 and **Figure 12** show the results of cycle operation. An operation in which electrolysis and power generation were repeated while being switched every 10 minutes was planned to simulate the actual operation. To understand the situation, the number of repetitions was set to six. At this time, the electrolytic pressure was set to be constant at 10 MPa.

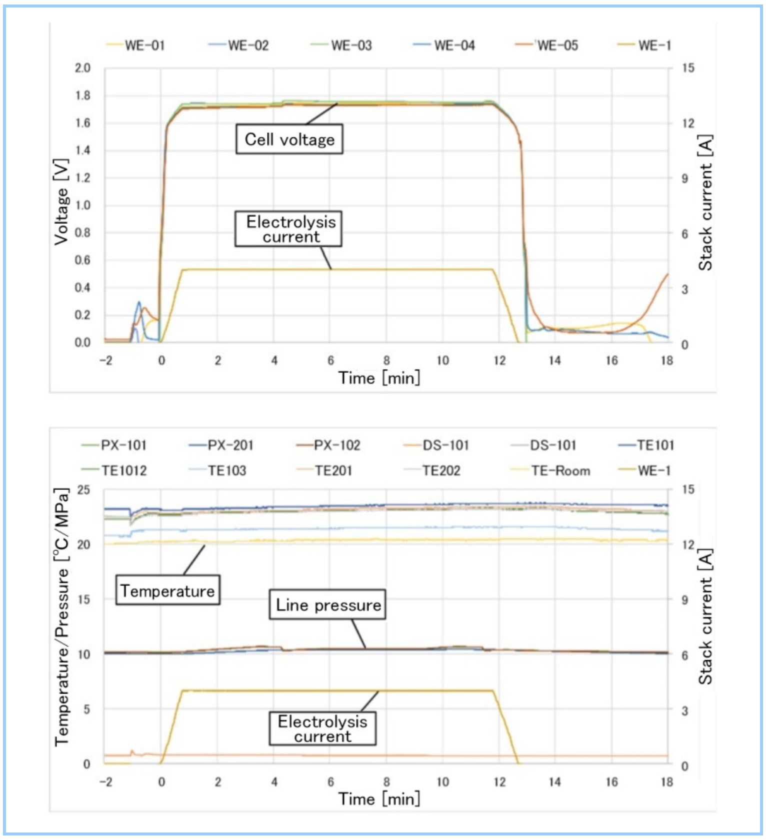


Figure 11 Electrolysis characteristic at sixth cycle

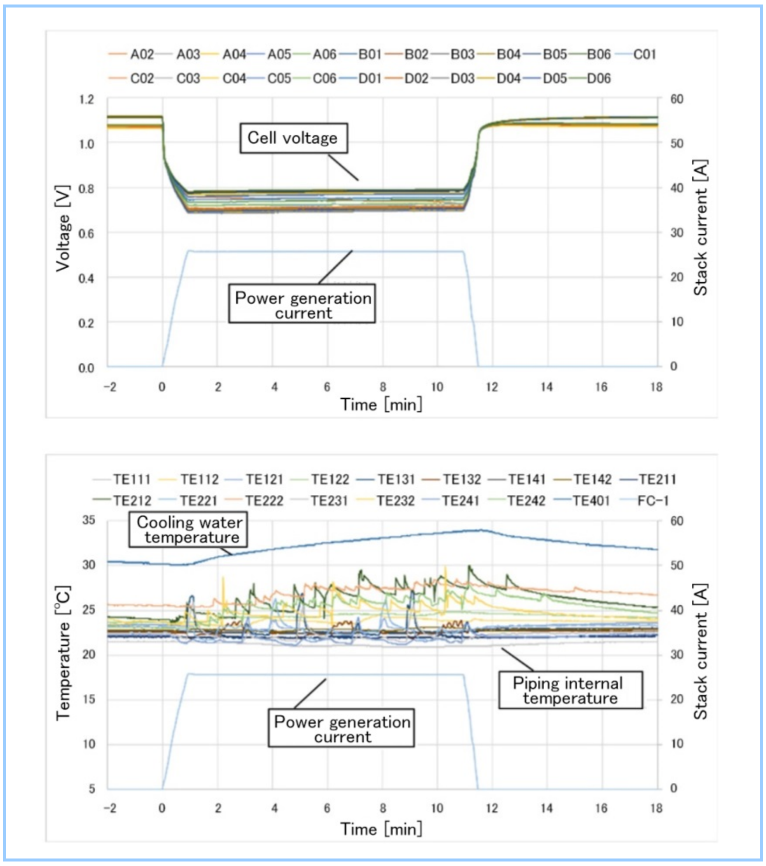


Figure 12 Power generation characteristic at sixth cycle

In the first electrolysis and power generation, the stack current was increased while observing the system behavior and cell voltage, so some time was required for settling to the predetermined current value. However, in the second time and later, the current could be increased smoothly and repeatedly to the predetermined value. The behavior of the water electrolysis device and the fuel cell device was almost the same every time and the operation for switching and the behavior at that time were also almost the same every time. By the sixth repetition, the behavior of the whole system could be observed.

4. Conclusion

We prototyped a fuel cell device and a water electrolysis device and combined them to build a completely isolated scalable fuel cell system and then conducted an operation test, in which electrolysis and power generation were repeated, to observe the characteristics at that time such as voltage behavior, temperature behavior, pressure behavior, etc. It was confirmed through this operation test of repeated electrolysis and power generation that this system attains the function and performance of a regenerative fuel cell operating in a completely isolated system. Although some manual operation was required, the production of hydrogen and oxygen with water electrolysis that reuses the generated water and power generation with the produced hydrogen and oxygen in a completely closed space could be realized, so it can be said that we are approaching the establishment technology of a completely isolated power supply fuel cell system. We believe that it will be possible to put the completely isolated scalable fuel cell system into practical use as an electric power source for marine use products by utilizing the experience and knowledge gained this time. In addition, due to its characteristics, we expect that this system can be applied as an electric power source in various extreme environments and can be developed as a power supply that can be widely used even in space, such as an overnight power source for lunar activity[3].

This research and development project was supported through the support program for starting up innovation hub promoted by the Japan Science and Technology Agency and carried out in collaboration with the Japan Aerospace Exploration Agency (JAXA) as a project selected from their fourth request for proposals (RFP) for the space exploration innovation hub.

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