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Development of Water Electrolysis System for Oxygen Production Aimed at Energy Saving and High Safety

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The Japan Aerospace Exploration Agency (JAXA) has been studying and developing Environmental Control and Life Support System (ECLSS) technologies, in particular an air regeneration system to support long-duration manned space missions beyond Earth orbit. Our goal is to develop an air regeneration system that is lightweight, compact and energy efficient. The air regeneration system comprises a water electrolysis subsystem for O_2 generation, a CO_2 removal subsystem and a CO_2 reduction subsystem. In this paper, we report on improvements to the water electrolysis subsystem. The water electrolysis cell uses a solid polymer electrolyte (SPE) developed by JAXA and a water/gas separator to separate generated H_2 from circulated water using a membrane. A previous design of the water electrolysis system had a number of issues. One was an increasing concentration of H_2 in the generated O_2 gas due to the low temperature of the circulated water. To address this issue, we improved the catalyst of the membrane electrode assembly (MEA) and as a result, low hydrogen concentrations were maintained at all temperatures. A further issue was a large pressure drop through the water/gas separator. By creating a stack of four separators and improving the internal flow path, the pressure drop was reduced to approximately one third of that of the previous design, and it became possible to circulate water at a high flow rate.

Nomenclature

CO_2 = Carbon dioxide
CH_4 = Methane
ECLSS = Environmental Control and Life Support System
H_2 = Hydrogen
H_2O = Water
ISS = International space station
JAXA = Japan Aerospace Exploration Agency
LEO = Low earth orbit
MEA = Membrane Electrode Assemblies
SPE = Solid Polymer Electrolyte
O_2 = Oxygen

I. Introduction

Currently, the supply of crew O_2 on the International Space Station (ISS) is produced mainly by electrolyzing water [1-5)]. Producing O_2 by water electrolysis has much lower cost than supplying O_2 from the ground, so water electrolysis for O_2 generation has been a very important topic of study, in particular by the European Space Agency (ESA)[6, 7)]. It is desirable to further reduce the supply of water required for O_2 generation to enable longer periods of human habitation in low Earth orbit and missions beyond. This could be achieved by a recirculating system as shown in Figure 1. A water electrolysis system produces O_2 and H_2 from water. The crew consumes the O_2 and exhales CO_2, which is concentrated in an absorbent by a CO_2 removal system using a pressure swing. The concentrated CO_2 is then reduced by a CO_2 reduction system using the Sabatier reaction ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$), producing H_2O and CH_4. The water is then electrolyzed and consumed by the crew again. This proposed air

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regeneration system can thus significantly reduce the volume of water supply needed and its only waste material is CH_4.

The theory of the air regeneration system has been well studied up untill now, but systems that operate well enough to be of practical use have not yet been developed. Although early realization of a closed-cycle air regeneration system for space applications is desirable, there are many technical problems to be overcome. One of the main problems is the significant limit on the amount of energy available. The maximum power generating capacity of the ISS is about 120 kW, and the available power on manned missions beyond Earth orbit will typically be more constrained. At least 0.75 kW is theoretically required to generate sufficient O_2 for ten crewmembers by water electrolysis, most of which is required for controlling systems and consumed by various energy losses. Another problem is that gas-liquid separation is required in many parts of the air regeneration system, but it is difficult to design a system that operates well in microgravity. This problem is particularly acute in the water electrolysis system, because the water required for electrolysis and the generated gas are constantly in contact, and incomplete gas-liquid separation not only has adverse effects on downstream sub-systems but also leads to the waste gas having a high H_2O content.

We have prioritized low energy consumption and safety of the O_2 generation water electrolysis system by concentrating on improving the electrolysis cell and the water/gas separator. Previously, water electrolysis at a very low cell voltage was achieved by an electrolysis cell using a solid polymer membrane developed by JAXA. Furthermore, energy efficient water/gas separation was achieved by a gas-liquid separator using a centrifugal membrane separation system with no moving parts, and the separator was demonstrated to operate at any gravity direction. As follow-on steps, we have been addressing issues which were recognized at the previous development stage, namely a concentration of H_2 in the generated O_2 gas, and a high pressure drop across the water/gas separator. In this paper, we report on developments to resolve to these issues.

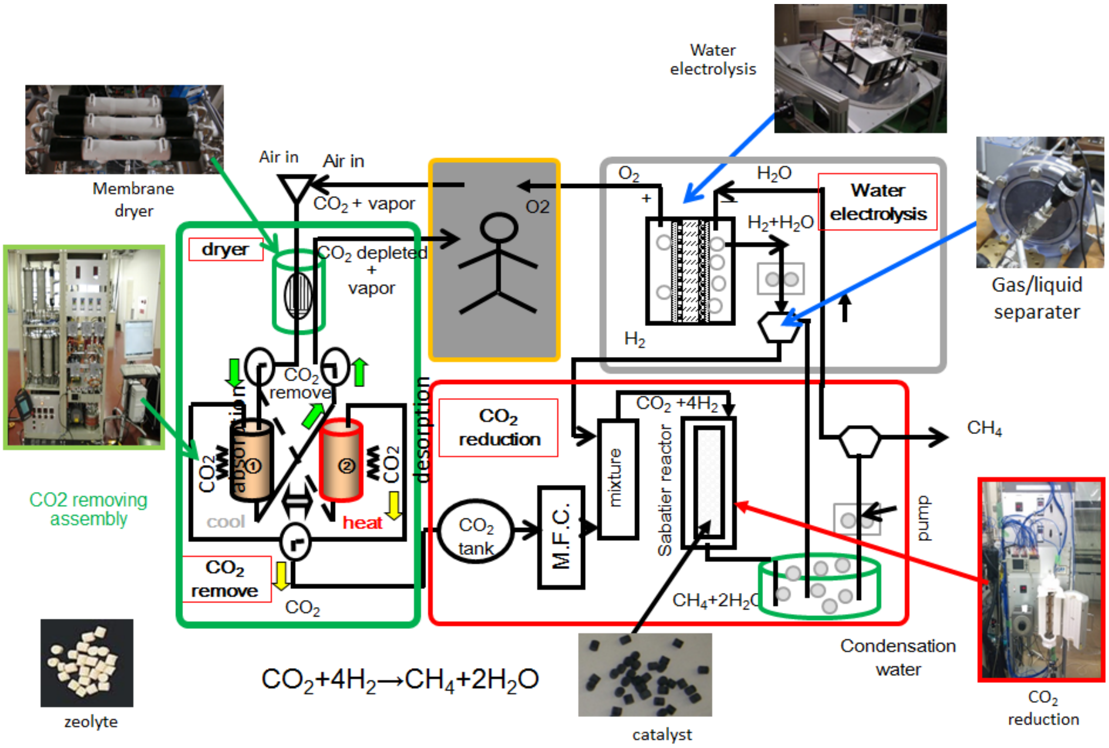


Figure 1 Concept of air revitalization system using CO_2 reduction

II. Experiments

In a conventional water electrolysis cell with a proton-conducting membrane (figure 4), water is fed to both the cathode and anode sides of the membrane to avoid insufficiency of water supply which can damage the membrane. It is possible to simplify the system by feeding water from only the anode side. This brings advantages such as lower weight, but has a problem in that the generated gases are rich in water vapor, and it will be necessary to dry the O_2 to make it suitable for breathing by humans in space. On the other hand, the cathode water feed method (figures 2 and

3) also gives a simple system but with relatively dry O_2. In this method, water migrates to the anode side of the cell from the cathode side through the membrane. Although the generated H_2 contains much water vapor, it is possible to obtain dry O_2. However, insufficient migration of water through the membrane to the anode can easily occur, resulting in a higher cell voltage.

This problem was addressed in our previous electrolysis cell design by using a solid polymer electrolyte developed by JAXA. The cell demonstrated a very low electrolysis voltage compared to a conventional type cell. The next step was to further reduce the cell voltage and to increase safety by lowering the concentration of H_2 in the generated O_2 gas.

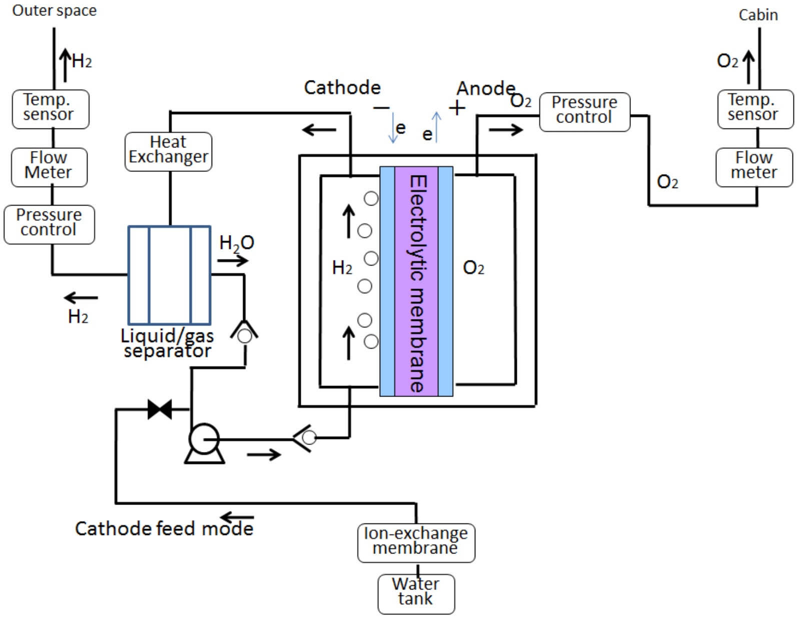


Figure 2 Flow diagram of cathode feed SPE water electrolysis

Our new water electrolysis cell has an improved Membrane Electrode Assembly (MEA) that uses a new membrane and catalyst developed by JAXA. The cell is a cathode feed single cell with a catalyst surface area of 64 cm^2. Under atmospheric pressure conditions, the nominal electrolysis current can reach a maximum of 64.0 A (1.0 A/cm^2) and the nominal operational temperature range is 30–80℃ measured at the inlet of the cell.

We investigated how varying the water feed rate (10–680 ml/min) affected the cell voltage and concentration of H_2 in the generated O_2 gas. In a water electrolysis system, reducing the water feed rate lowers the power consumption of the water pump and pressure drops at each part of the system, resulting in reduced energy consumption. However, there is danger that H_2 retention on the cathode surface will result in increasing leaks from the H_2-generating side to the O_2-generating side. We therefore examined the cell voltage and the concentration of H_2 in the generated O_2 gas as an indicator of system safety for a number of conditions.

The water electrolysis system designed by JAXA uses a membrane type water/gas separator[8,9] (figure 5). Because there are no moving parts in this type of separator, low energy consumption and long-term operational stability can be expected. Our previous design demonstrated good separation performance, but its pressure drop rapidly became large with increasing water feed rates. We resolved this pressure drop problem in our new separator by using a quadruple separator stack and improving the flow path of the fluid through the separator. Pressure drops were measured between the water-gas mixture inlet and the water outlet of the separator.

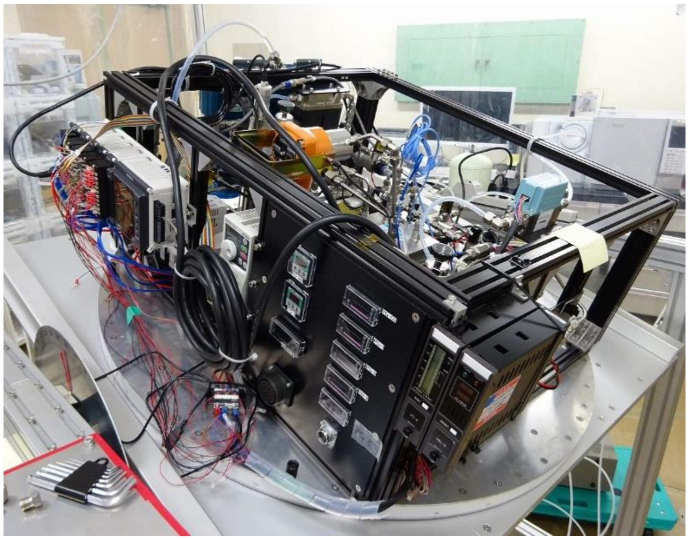


Figure 3 JAXA’s water electrolysis system for ground demonstration, containing all components in figure 2. This can test the flow of figure 2 at various gravity directions.

Figure 4 JAXA’s improved single water electrolysis cell.

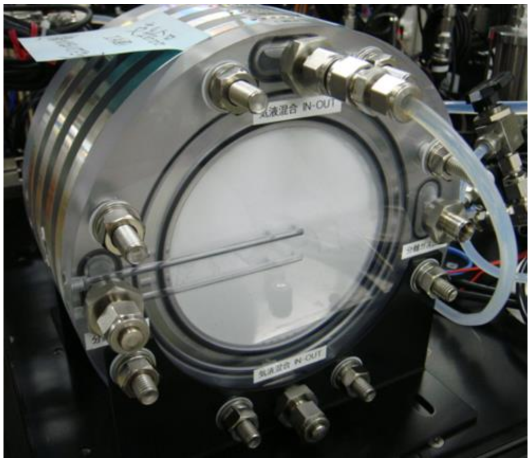


Figure 5 JAXA’s improved quadruple stack membrane-type water/gas separator.

III. Results and Discussions

Figure 6 compares the polarization curve of JAXA’s new water electrolysis cell with a conventionally designed water electrolysis cell using a Nafion 117 membrane. As temperature increases, the cell voltage of the improved cell becomes progressively lower than that of the conventional cell for a given current density. The new cell also has a higher current density at a given voltage than the conventional cell. Furthermore, the new cell achieves the lowest voltage performance in the world for a cathode-feed electrolysis cells for space applications.

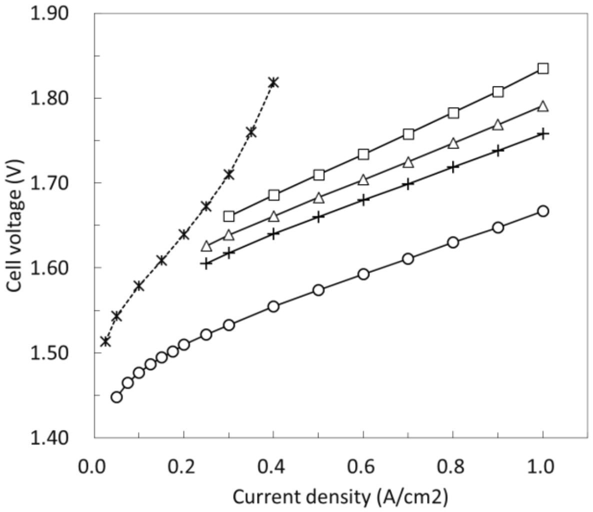
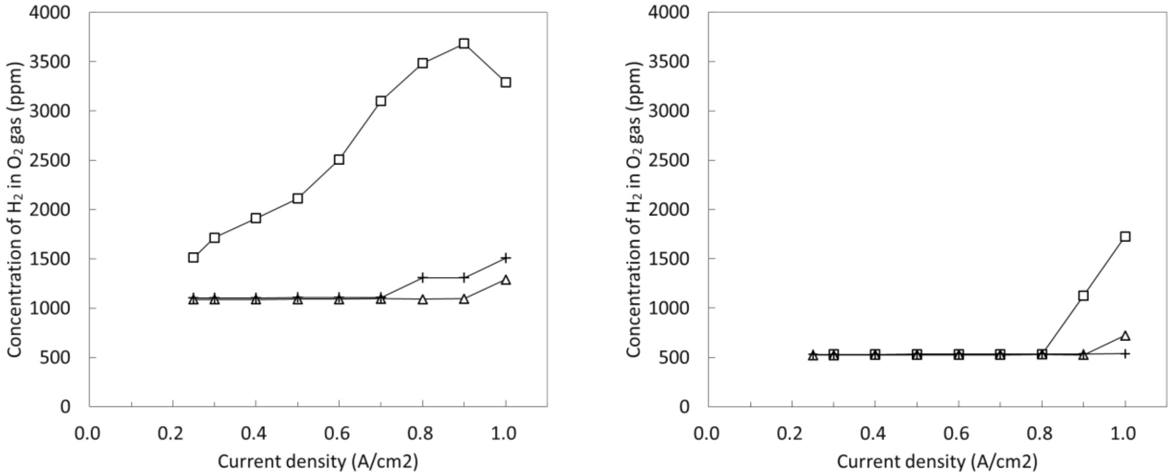


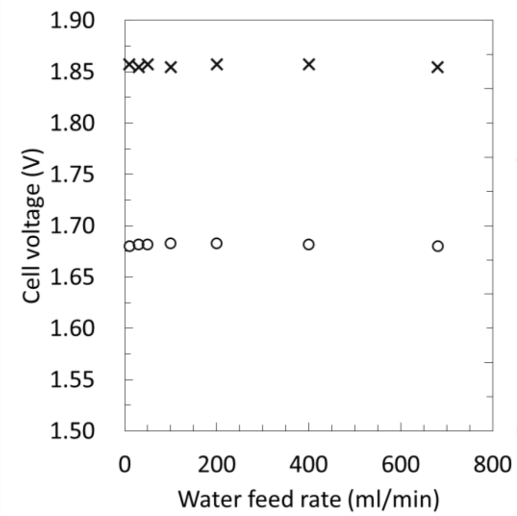
Figure 6 Polarization curves of new cathode-feed water electrolysis cell and conventional reference cell. Water temperatures are 30℃ (□), 40℃ (△), 50℃ (+) and 80℃ (○) at the new cell's inlet. The (∗) curve is of a conventionally designed water electrolysis cell using a Nafion 117 membrane at 30℃.



A: Previous electrolysis cell (unmodified catalyst) **B: New electrolysis cell (modified catalyst)**

Figure 7 Relationship between electrolysis current density and concentration of H_2 in generated O_2 gas. Water temperatures are 30℃ (□), 40℃ (△) and 50℃ (+).

Figure 7 compares the concentration of H_2 in the generated O_2 gas of the previous electrolysis cell with the new cell featuring the modified catalyst. In the previous cell, the H_2 concentrations at 30℃ in figure 7-A rise rapidly with increasing current density. Since low-temperature operation of O_2 generation is desirable in space applications, this problem should be resolved. The new cell shown in figure 7-B, on the other hand, shows clearly improved performance, with H_2 concentrations of around 500 ppm except at the highest current densities. The new cell thus achieves safer operation while maintaining a high cell current density.



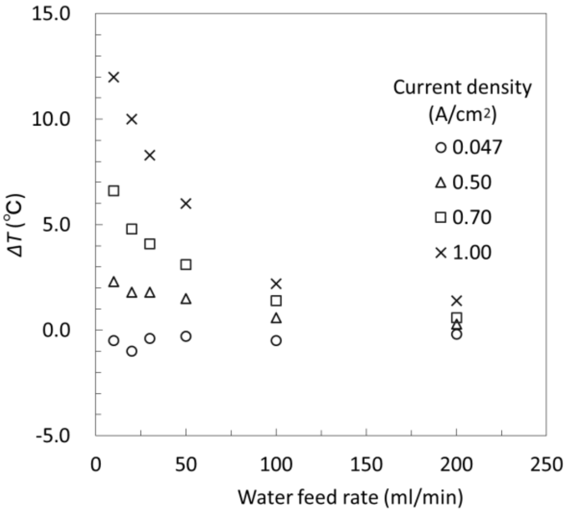


Figure 8 Relationship between water feed rate and cell voltage (○: left axis) and H_2 concentrations in generated O_2 gas (×: right axis) at a current density of 0.4A/cm^2 and a water temperature of 35℃.

Figure 9 Temperature changes between inlet and outlet of electrolysis cell for each water feed condition.

Figure 8 shows that there is no correlation between water feed rate and either cell voltage or concentration of H_2 in the generated O_2 gas, implying that sufficient water was supplied for electrolyzing the SPE. This suggests a potential for operating at very low water flow rates.

Figure 9 shows the temperature difference between the inlet and the outlet of the cell at each condition in figure 8. The temperature differences become larger as the feed rate is reduced. This is because the amount of heat carried away from the cell per unit time becomes smaller as flow rates decrease. Although dangerous temperature differences were not found at very low water feed rates, further investigation is required to ensure that no hotspots develop on the MEA and elsewhere.

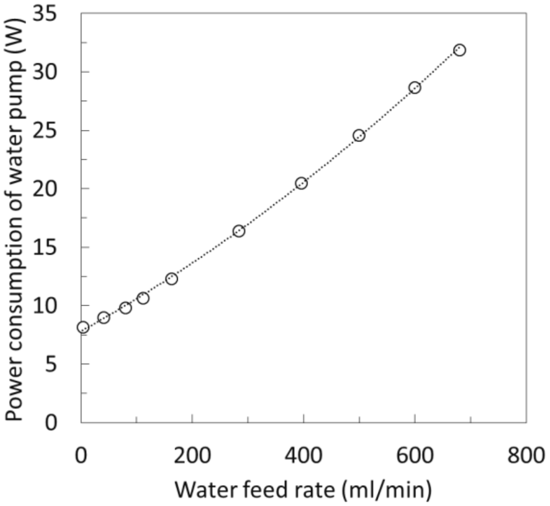


Figure 10 Relationship between water feed rate and water pump power consumption.

Regarding energy consumption, we measured the power consumption of the water pump at different flow rates (figure 10). The water feed rate at 32 W is about 680 ml/min, which we define as a sufficiently safe flow rate. The minimum value measured in the experiments was at 10 ml/min at 8.1 W. There is an energy consumption difference of about 400% between these points. If it is possible to operate the system at a very low water feed rate, it will bring greater energy saving for the O_2 generation system.

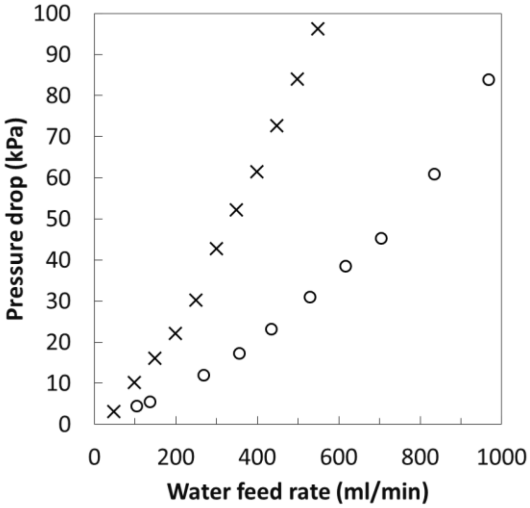


Figure 11 Relationships between water feed rate and pressure drop of the previous water/gas separator (×) and the improved version (○).

Figure 11 compares the pressure drops of the previous water/gas single separator design and the improved quad stack separator with a modified internal flow path. The pressure drop of the improved water/gas separator is clearly lower than that of the previous one, becoming about one third in value. In other words, a higher water flow rate is possible at a given pump power. A system with the improved separator can therefore generate large amounts of O_2 and has sufficient flow capacity for path cleaning or emergency purge inside the separator. These factors will be considered in creating water/gas separator design guidelines.

IV. Conclusion

This paper reports on the progress of JAXA's development of a water electrolysis subsystem for O_2 generation as part of an air revitalization system for long-duration manned space missions. We have improved the water electrolysis cell and the water/gas separator to increase the energy efficiency and safety of the water electrolysis system.

The improved water electrolysis cell gives lower cell voltages than conventional cells at all conditions while at the same time yielding lower concentrations of H_2 in the generated O_2 gas, which was a problem of the previous water electrolysis cell design. We confirmed that there was no correlation between the water feed rate and the cell voltage, showing the possibility of electrolysis at very low water feed rates. This latest development therefore improves the energy efficiency and safety of the water electrolysis system. Moreover, we succeeded in reducing the pressure drop of the water/gas separator. By using a stack of four separators and improving the internal flow path, the pressure drop across the separator was reduced to one third that of the previous design. This improvement can reduce the energy consumption of the water electrolysis system and guide the design of the water/gas separator for the system.

JAXA's short-term goal is to demonstrate a closed-cycle air regeneration system including water electrolysis, CO_2 removal and CO_2 reduction assemblies. Demonstrations of a ground prototype of the system will start early in the 2015 fiscal year. These demonstrations will apply the water electrolysis technologies described in this paper. Problems may appear when the water electrolysis subsystem is integrated into the air regeneration system. We will investigate these as they arise, and aim to further develop water electrolysis for O_2 generation and acquire more advanced air regeneration system technology.

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