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Technology Demonstration of New Water Recovery System onboard ISS

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This paper describes the next-generation water reclamation system being researched and developed by Japanese Aerospace Exploration Agency (JAXA), which was demonstrated in orbit using the International Space Station (ISS). During the on-orbit demonstration, there were some defects, but they were resolved through repairs and a series of water regeneration processes were implemented. As a result of performing performance evaluations in orbit, we were able to demonstrate the principle of the system by demonstrating performance comparable to that on the ground. In addition, by acquiring data while changing experimental parameters, we confirmed the microgravity effect on water electrolysis and found a threshold at which electrolysis becomes impossible in a region where the flow rate is small.

Nomenclature

Bo = Bond number
d_B = bubble diameter
ECLSS = Environmental Control and Life Support Systems
g = gravitational acceleration
G = unit of gravitational acceleration (=9.80665 m/s^2)
ISS = International Space Station
JAXA = Japanese Space Exploration Agency
L = characteristic length
MSPR = Multi-purpose Small Payload Rack
NASA = National Aeronautics and Space Administration
SD = Standard Deviation
SSP = Space Station Program
SWEGs = Spacecraft Water Exposure Guidelines
TOC = Total Organic Carbon
u = velocity
We = Weber number
σ = surface tension

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I. Introduction

Human activities should become an essential part of future space exploration. Furthermore, spaceflight by private companies is not far off in the present day. In a closed, habitable cabin in space, active environmental control and life support systems (ECLSS) are necessary for the removal of trace contaminant gases and carbon dioxide, as well as the provision of adequate supplies of oxygen, water, and food. Each person needs 3.2 kg of water per day including potable water, food rehydration water and hygiene water.[1] Recycling techniques will be necessary beyond missions lasting several months to reduce the need for resupply from Earth. Currently, water recovery systems provided by National Aeronautics and Space Administration (NASA) and Russia are operational on the International Space Station (ISS).[2-5] Japanese Aerospace Exploration Agency (JAXA) is actively engaged in the research and development of ECLSS for future space missions, including the Lunar Orbital Platform-Gateway and Moon exploration within the Artemis program.[6-10] In the realm of ECLSS for space applications, it is imperative to meticulously assess gravity dependence and factor its effects into equipment design. Failing to do so significantly raises the risk of the system not performing as expected in space. Given that the orbiting platform operates within a microgravity environment, experiencing a partial gravity environment of 1/6 G on the Moon and 1/3 G on Mars, we emphasize the importance of designing systems that minimize gravity dependence. This approach is crucial because the performance validated on the ground should seamlessly translate to space conditions.

This paper addresses the foundational technologies of water recovery systems. We are actively engaged in the research and development of water purification technology aimed at maximizing water recovery once it is transported into space, purifying it to meet potable water standards for crew members. Our water recovery system employs electrolysis as a key component of the treatment process. Organic carbon is oxidized and removed from the water as carbon dioxide gas during electrolysis. During the electrolysis process, bubbles form around the electrodes. To facilitate efficient oxidative decomposition treatment, it is imperative to promptly remove these bubbles from the electrode surface. In terrestrial conditions, buoyancy might aid in detaching bubbles from the electrode surface due to gravitational effects. However, in microgravity environments, such buoyancy effects are absent. In our system, we aim to achieve bubble detachment through water flow. However, the quality of treated water varies depending on the balance between treatment speed and water flow velocity.

A technology demonstration was conducted onboard the ISS to validate the function and performance of our novel water recovery system as a proof of concept. And we also confirmed that the effect of gravity on the electrolysis process by changing governing parameters such as flow rate and electrolysis currents. This paper introduces the results of the technology demonstration of our water recovery system in space.

II. Water Recovery System Overview

A. Water Purification Process

Wastewater, including urine, crew latent humidity condensate, and hygiene water, should be recycled into potable water. In our development of a water recovery system for space activities, we opted to initially focus on the regeneration of urine into potable water. Urine presents unique challenges, such as a high concentration of organic carbon, elevated levels of calcium and magnesium compared to condensate, and a demanding water purification load. Our concept prioritizes high efficiency, compactness, and minimal consumables.

Urine comprises various components, and in a microgravity environment, there is an increased release of cations, such as calcium and magnesium ions, compared to terrestrial conditions. This phenomenon can lead to equipment failure due to precipitation in the urine regeneration system. To address this, we integrated four processes for water purification to meet International Space Station system specifications (SSP41000) and/or potable water quality requirements outlined in the Spacecraft Water Exposure Guidelines (SWEG, JSC 63414).[11,12] Additionally, an ion exchange resin activation process was incorporated to eliminate consumables. The four processes include (1) ion exchange, (2) electrolysis, (3) electrodialysis, and (4) regeneration of ion exchange resin, as illustrated in Fig. 1.

(1) Ion exchange process

It is known that in a microgravity environment, scale problems are more likely to occur than on the Earth.[2] In order to prevent scale from occurring within the system, the causative calcium and magnesium ions in urine are removed using a cation exchange resin at the first stage of the system which is "Ion exchange" process in Fig. 1. This resin is repeatedly regenerated by acid and alkali produced as a by-product in the electrodialysis unit described below, so it does not become a consumable item.

(2) Electrolysis process

Human urine contains approximately 6000 mg/L of organic carbon.[1] To produce drinking water, the organic carbon must be reduced to less than 3 mg/L.[11] Electrolysis is employed for this purpose. High pressure (5 MPa) and high temperature (250 °C) promote oxidation in a near subcritical state, efficiently decomposing persistent organic carbon. The gases generated during the electrolysis process, namely carbon dioxide and hydrogen, are separated in a gas-liquid separator installed downstream of the electrolyzer.

(3) Electrodialysis process

Residual ions such as sodium ions and chloride ions contained in electrolyzed water are electrically removed by passing the treated water through a desalination chamber separated by an ion exchange membrane in an electrodialysis unit. In addition to a cation exchange membrane and an anion exchange membrane, the ion exchange membrane uses a bipolar membrane that has a structure in which a cation exchange membrane and an anion exchange membrane are bonded together. In bipolar membranes, water electrolysis occurs within the membrane when electricity is applied, and hydrogen ions are released on the cation exchange membrane surface and hydroxide ions are released on the anion exchange membrane surface.

(4) Ion exchange resin regeneration process

The removed ions are then treated with highly concentrated acids and alkalis water. It can be recovered as these acids and alkalis are used to regenerate the above-mentioned cation exchange resin.

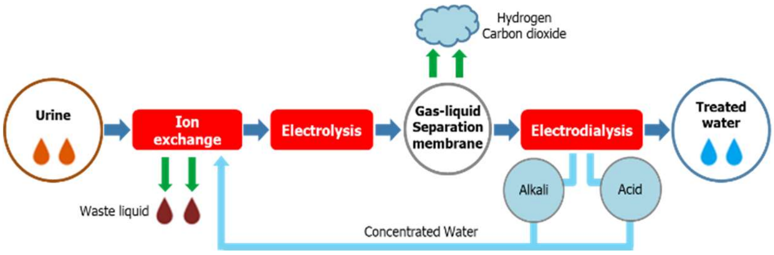


Figure 1 Concept of water treatment process.

B. Technology demonstration in microgravity

This technology demonstration was a very important mission as it demonstrated the principle of our unique water recovery system, and identified issues with on-orbit operation.

In the electrolysis process, bubbles are generated through the electrolysis of water and the oxidative decomposition of organic matter. The size of bubbles formed on electrodes typically ranges from tens of micrometers to several millimeters.[13,14] In a gravity environment, buoyancy forces might facilitate bubble detachment from the surface more easily than in microgravity. This phenomenon may impede electrolysis as prolonged bubble residence reduces the effective area of the electrodes used for electrolysis. Although the electrolysis cell should be designed to minimize gravity dependence, the processes of bubble formation, detachment, and oxidative decomposition by electrolysis are extremely complex. Therefore, it is necessary to demonstrate water purification technology under microgravity conditions to improve system reliability and validate the design.

Prior to the development of future water recovery systems, we conducted a demonstration experiment in space using a sub-scale system to confirm each function in a microgravity environment that cannot be replicated on the ground. We investigate how gas bubbles retained in the liquid affect the water treatment process and utilize the knowledge accumulated through ground and microgravity experiments in the development of future practical water recovery systems. The urine is regenerated and purified to achieve a recovery rate of 85% or higher. The demonstration of water recovery system in microgravity was performed the ISS Kibo module. The experimental facility was designed as a sub-scale system, with a target urine throughput of more 0.3 liters per day. The dimensions of the processor unit were 535 mm × 600 mm × 480 mm, and the control unit measures 120 mm × 580 mm × 475 mm. The maximum power consumption is less than 350 watts. The objectives of the demonstration are to assess whether the treated crew urine meets the drinking water quality standards specified in SSP41000 and to verify the effect of microbubble behavior on water recovery performance under microgravity conditions.

The composition of real urine varies depending on individual differences and the time of collection. Therefore, we considered it important for the ingredients to be stable in order to evaluate performance, and thus used artificial urine as the raw water for treatment. When synthesizing artificial urine, the components were determined and compounded with reference to Ewert et al. 2022.[1] The composition and properties of synthetic urine is listed in Table 1 with the potable water quality requirements determined by SSP41000.

The on-orbit demonstration hardware and test samples, including synthetic urine, were launched by Cygnus NG-12 in November 2019. The experimental apparatus was installed in the Multipurpose Small Payload Rack (MSPR) in Kibo by ISS crew (Fig. 2). After the hardware setup, the system operated remotely from the Tsukuba Space Center.

Table 1 Composition and properties of synthetic urine.

Constituent	Synthetic urine	Potable water quality requirements by SSP41000
Sodium	3,150 mg/L	-
Potassium	2,428 mg/L	340 mg/L
Ammonium	572 mg/L	0.5 mg/L
Magnesium	133 mg/L	50 mg/L
Calcium	291 mg/L	30 mg/L
Chlorine	5,645 mg/L	4 mg/L
Hydrogen carbonate	403 mg/L	-
Carbon trioxide	203 mg/L	-
Nitrate	586 mg/L	10 mg/L
Sulfate	2,076 mg/L	250 mg/L
Phosphate	124 mg/L	-
Organic constituent		
Total Organic Carbon (TOC)	5,989 mg/L	3 mg/L
Physical parameter		
pH	6.5	4.5-8.5

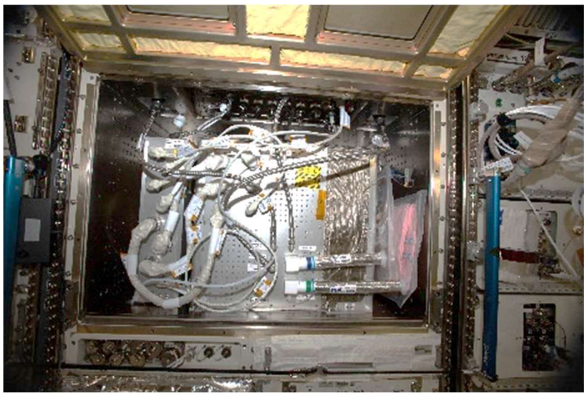


Figure 2 Technological demonstrator apparatus of JAXA water recovery system installed in Multipurpose Small Payload Rack in the ISS. ((c) JAXA)

Table 2 shows the standard experimental conditions. Under standard experimental conditions, basic characteristics of the system were obtained. Based on these conditions, the flow rate of the electrolytic process which the standard condition was 1.0 mL/min was varied in the range of 0.1 to 2.5 mL/min to confirm the microgravity effect. Furthermore, the electrolytic current of cell B was in the range of 0.5 to 7.1 A compared to the standard condition of 5A. Changing the current leads to changing the amount of electrolytic bubbles generated.

The treated water was sampled using a syringe on-orbit and returned to the ground in a frozen state to prevent the growth of microorganisms. A detailed component analysis was conducted on the treated water to evaluate the performance processing in microgravity.

Table 2 Standard experimental conditions

Process stage	Parameter	Value	Unit
Ion exchange	Flow rate	4.6	mL/min
Electrolysis	Flow rate	1.0	mL/min
	Current at cell A	6.5	A
	Current at cell B	5.5	A
	Temperature	250	°C
	Pressure	5.0	MPa
Electrodialysis	Flow rate	2.0	mL/min
	Voltage at cell A	16	V
	Voltage at cell B	12	V
Regeneration of resin	Flow rate of treated water	0.7	mL/min
	Flow rate of acid solution	15.0	mL/min
	Flow rate of alkali solution	4.8	mL/min

III. Results and discussion

Several malfunctions occurred during on-orbit operation, and astronauts performed troubleshooting each time. Most of the problems that occurred during these on-orbit technology demonstrations did not arise during ground verification, and they provided numerous suggestions for practical system design. The major issues included poor liquid delivery by the pump and chemical cracks in the degassing membrane module. The main causes of pump failure were sediment in the urine clogging the pump and air being sucked into the pump, preventing it from pumping liquid. To prevent precipitates from entering the pump, a filter was installed immediately after raw water was added. The problem of air suction was resolved by increasing the pump's primary pressure. The chemical cracks in the degassing membrane are thought to have been caused by trace amounts of ammonia from the cushioning material used during launch. Therefore, the module's casing material was changed, and cracks were prevented from occurring.

Performance was evaluated based on water regeneration rate, treatment speed, and treated water quality. The regeneration rate was calculated as the ratio of the amount entering the treatment equipment to the resulting treated water. Processing speed was calculated based on the time required to perform a series of processes. The quality of the treated water was evaluated by collecting samples of the treated water on the ground and analyzing their components. Results are summarized in Table 3. The processed water quality is shown in Table 4.

The process rate met the target. On the other hand, the water recovery rate was 83.9 %. The rate did not meet the target, but we believe this is due to the fact that several operational runs could not be performed due to malfunctions. The rate is defined as the ratio of the amount of raw water the amount that came out as treated water. There are several temporary water storage tanks in the system, and the recovery rate varies depending on the amount of water remaining in the tanks. The entire process was evaluated with only one run of water treatment. The average of the five runs in Proto Flight Test (PFT) was 85.5%, which varied between 83.2% and 87.8%. It is considered that the performance on orbit was equivalent to that on the ground.

Regarding the water quality shown in Table 4, other components satisfied the standards except for ammonia and total organic carbon concentration, which unfortunately did not meet the standards. The unsatisfied components are thought to be due to a problem in which untreated water was sent to the primary water storage tank during the previous run. In addition, chloride ions are removed by electrodialysis, but the probable cause is an increase in electric resistance due to the effects of the electrodialysis cell being stopped for a long time and air being mixed in the microgravity environment. This suggests the necessity of regular water circulation during long-term outages.

Table 3 Evaluation of performance

Item	Target	Value
Processed water quality	SSP41000 requirement	Refer to Table 4
Process rate	> 0.3 L/day	0.39 L/day
Water recovery rate	> 85 %	83.9 %

Table 4 Chemical component analysis results of processed water

No.	Chemical	Requirement in SSP	Synthetic urine	Processed water	Judgement
1	Ammonium	1	572	3.3 mg/L	NG* 99.4% removal
2	Calcium	30	291	<1 mg/L	OK*
3	Chlorine	4	5600	116 mg/L	NG 97.9% removal
4	Magnesium	50	133	<1 mg/L	OK
5	Nitrate(N03-N)	10	586	0.8 mg/L	OK
6	Potassium	340	2100	52.5 mg/L	OK
7	Sulfate	250	1600	59 mg/L	OK
8	Benzene	0.07	No data	<0.001 mg/L	OK
9	Chloroform	6.5	No data	<0.006 mg/L	OK
10	Dichloromethane	15	No data	<0.002 mg/L	OK
11	TOC	3	5989	27.1 mg/L	NG 99.5% removal
12	pH	4.5-8.5	5.0	7.8	OK

* NG stands for "no good" which means the concentration of component in processed water satisfied the requirement in SSP41000. OK means satisfied.

Regarding electrolysis under microgravity, the state of bubbles inside the electrolytic cell was estimated from the applied current and voltage behavior. On the ground, the buoyant force that acts on air bubbles due to gravity promotes bubble separation from the electrode surface, but in a microgravity environment where buoyancy does not act, bubbles are thought to have difficulty in separating. There are several studies that have demonstrated the effect of gravity on the bubble behaviors.[13-15] In the electrolytic cell, water electrolysis is performed under forced flow, and air bubbles are pushed by the water flowing from the electrolytic cell side, which has the effect of suppressing dryout on the electrode surface. In a previous report, we confirmed the gravitational influence by hydrodynamic order evaluation. By introducing the bond number, Bo, the ratio of buoyancy to surface tension was calculated.

$$\mathrm{Bo} = \frac{\Delta\rho g \ {}_{B}{}^{2}}{\sigma} \tag{1}$$

where, $\Delta\rho$ is density difference between bulk fluid and bubble, g is gravitational acceleration, d_B is bubble diameter and σ is surface tension between liquid and bubble. Assuming that the bubble diameter is 100 µm, the Bond number is on the order of 10^{-3} under the gravity on the ground, and it is considered that the surface tension is dominated even on the ground.

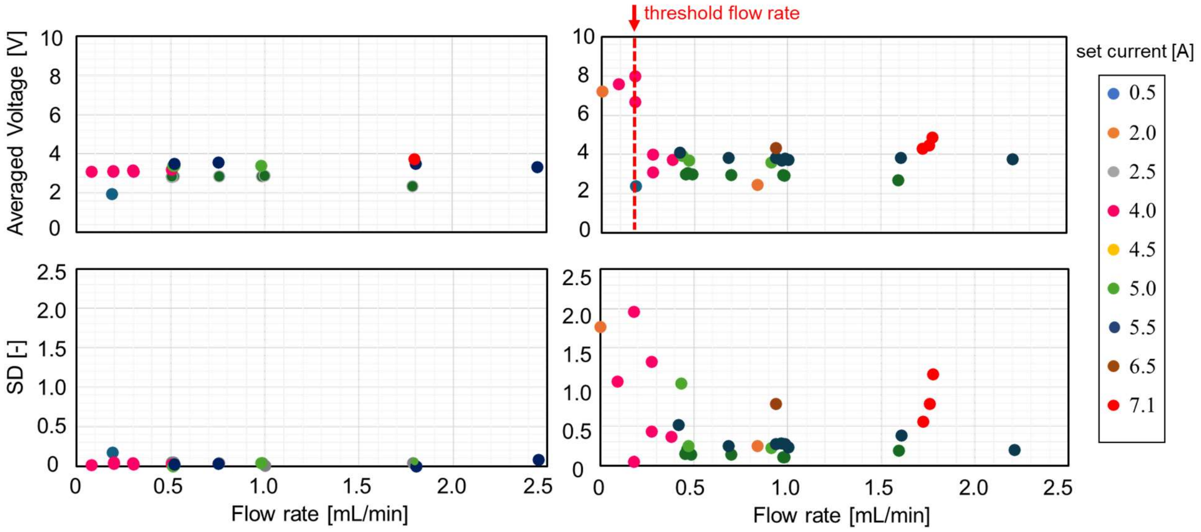
On the other hand, the ratio of flow inertia force to surface tension was evaluated using the Weber number, We.

$$\mathrm{We} = \frac{\rho L u^2}{\sigma} \tag{2}$$

where, ρ is the density of liquid, L is characteristic length, u is average velocity of liquid flowing between electrodes, σ is the surface tension.

The Weber number was very small, on the order of 10^{-5}. This means that the bubbles are difficult to deform due to flow. However, the elementary processes involved in bubble separation are extremely complex and difficult to predict. We found that by lowering the flow rate, the number of air bubbles increases between the electrodes of the electrolytic cell, that is, the void ratio becomes high, and the anode and cathode become insulated. It is hypothesized that there may be a threshold at which it becomes impossible. Therefore, data was acquired using the flow rate as a parameter. Figure 3 shows the relationship between flow rate and electrolysis voltage on the electrolysis cell B. It also displays the standard deviation of voltage fluctuations. Electrolytic cell B is connected in series with cell A. The electrolytic bubbles generated in cell A also flow into cell B, which is downstream, and further bubbles are generated in cell B, resulting in a high void fraction. Both results are compared between on-orbit test and the ground reference test. The operating conditions were same between the ground and on-orbit tests.

In the ground reference test, it can be seen that the average voltage is the same regardless of the flow rate, and the fluctuation in voltage is also smaller in the standard deviation graph. On the other hand, the on-orbit test showed almost the same average voltage as the ground test at flow rates above 0.2 mL/min. This is thought to result in almost the same electrolytic performance as on the ground. However, the voltage increases below 0.2 mL/min of flow rate. This is considered to be a result of the resistance between the electrodes increasing due to the small flow rate of bubbles between the electrodes. As a result, under the standard condition of 1.0 mL/min, performance is achieved without being affected by microgravity, but at extremely low flow rates, the void ratio increases, meaning that proper water electrolysis cannot be performed. The large standard deviation appears to higher current conditions of 7.1 A at flow rate of around 1.75 mL/min. In this situation, the bubble formation is much active than lower current conditions, so this is probably why the voltage fluctuations became large.



(1) Ground reference test (2) On-orbit test

Figure 3 Averaged voltage and standard deviation of voltage fluctuations during electrolysis in cell B as a function of flow rate. Upper graph is averaged voltage and lower is standard deviation (SD). The upper voltage limit is set to 8.0 V.

IV. Conclusion

We conducted an in-orbit demonstration of our unique water recovery system, which is being implemented as part of our ECLSS research and development. Although several problems occurred on-orbit, most of them provided important knowledge for designing practical system for future exploration. The system performance was almost equivalent to the ground test after subtracting performance degradation due to malfunctions, and we believe that the system was successful in confirming its validity and verifying its principles. Regarding the effects of microgravity, we have also found a threshold at which when the flow rate is lowered during the electrolysis process, the resistance between the electrodes increases and electrolysis cannot be performed properly. On the other hand, under standard operating conditions, water electrolysis was possible in a region unaffected by microgravity which was also confirmed by hydrodynamic order evaluation, confirming the validity of the design. When designing an actual system in the future, it will be necessary to scale up by increasing the amount of processing, but even in that case, this can be done by increasing the quantity without changing the configuration of the main components, because we were able to find a parameter range that is not affected by gravity. Additionally, modeling the phenomenon based on the data obtained from this on-orbit technology demonstration will lead to more reliable designs.

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