Experimental Research on Water Restoration Within a Spacecraft Using CMED Technology

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The upcoming long-term space missions to the Moon and Mars require an effective solution to the problem of organizing a closed-cycle water supply for the spacecraft. Accordingly, the development of systems and technologies to ensure the highest possible degree of water recovery from wastewater is an extremely urgent task today. As part of the research work, experimental studies were carried out on water recovery during the processing of all types of wastewater generated on the spacecraft: urine, flush water, humidity condensate, and hygienic water. The total amount of wastewater processed during the experiment is equal to the daily volume of wastewater generated as a result of the vital activity of a 4-person crew. Natural human urine, pre-treated with an appropriate preservative agent, was used as urine. Artificial test solutions were used as humidity condensate and hygienic water. The proposed technology is based on the principle of processing all types of wastewater in one apparatus, which provides significant advantages in terms of simplicity and reliability of the equipment. The Centrifugal Multi-Effect Distiller (CMED) was used as such a device. As a result of laboratory tests, it was shown that the proposed technology provides a Recovery rate of 98%. Specific energy consumption to obtain 1 liter of clean water is less than 300 Wh. The distillate obtained as a result of the experiment meets the basic requirements.

Nomenclature

AF	=	air filter
BR	=	brine reservoir
CMED	=	centrifugal multi effect distiller
CWEx	=	cool water exchanger
DR	=	distillate reservoir
HWEx	=	hot water exchanger
HWP	=	hot water pump
HWT	=	hot water tank
ISS	=	International Space Station
NASA	=	National Aeronautics and Space Administration
SPC	=	specific power consumption
SSR	=	source solution reservoir

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SSV	=	source solution valve
TDS	=	total dissolved solids
THP	=	thermoelectric heat pump
VCD	=	vapor compression distiller
VP	=	vacuum pump
VR	=	vacuum receiver

I. Introduction

The International Space Station (ISS), which has a continuous crew presence, is currently actively used to study outer space and solve various problems, including problems associated with future long-term space flights beyond the Earth's orbit. One of the most important tasks is to ensure the vital functions of the spacecraft crew during a long flight, in particular, to provide its members with clean water. Obviously, ensuring the delivery of cargo, including containers with clean water, to a ship located outside of low Earth orbit will be problematic. Supplying the spacecraft with a supply of water to support the entire flight will lead to a significant increase in the launch mass of the spacecraft, which is also unacceptable. The only solution to this problem is to equip the spacecraft with a system capable of obtaining clean water from the water resources available onboard, which consist of wastewater from the life support system. Of course, it will most likely not be possible to create a closed water supply cycle for a spacecraft due to the inevitability of water losses, but achieving water recovery at a level of more than 90% (up to 98%) is already quite possible today. Such a water recovery system must meet a number of specific requirements: small size and weight, high reliability, low energy consumption, sufficient performance, etc. However, the quite important parameter that directly affects the launch mass of the spacecraft is water recovery.

Researchers from different countries are proposing solutions for recovering water from wastewater in spacecraft conditions [1-4]. Despite this, to date no equipment has yet been developed that fully satisfies NASA's requirements. The most promising development is the system [5-8], proposed by National Aeronautics and Space Administration (NASA) specialists and undergoing testing on board the ISS for more than 10 years. It is based on the use of several technologies, in particular Vapor Compression Distiller (VCD) technology. However, this system also has a number of critical shortcomings [9], which cannot yet be resolved by its creators. In this regard, the issue of water recycling during long-term space flights remains open.

An alternative technology that can be used for the above purposes is the use of Centrifugal Multi Effect Distiller (CMED) [10-19]. This report will discuss the new results of experiments on the desalination of test solutions that simulate a mixture of spacecraft wastewater.

II. Pilot Plant Description

The schematic diagram of the pilot plant, as well as the symbols of its components, are shown in Fig. 1. The main equipment of the installation are:

- centrifugal distiller CMED
- the various tanks for various types of water named: SSR-1, SSR-2, BR, DR, HWT
- vacuum pump (VP) with vacuum receiver (VR). The VR is an intermediate tank and serves to protect the VP from unfavorable operating conditions
- heat exchangers of the hot circuit (HWEx) and cold circuit (CWEx)
- source solution valve (SSV) for supplying the initial solution to the distiller

The main working part of the system, which ensures the separation of the processed liquid into clean water and waste (distillate and concentrate, respectively), is the CMED distiller. The principle of its operation is based on the evaporation of liquid on rotating surfaces (disks) in a vacuum environment.

Wastewater from the crew's life support system is supposed to be collected and treated separately. Urine and flush water are collected in tank SSR-1, humidity condensate and hygienic water are collected in tank SSR-2. Reservoirs BR and DR are used to collect concentrate and distillate, respectively. For the convenience of measuring the amount of individual types of liquids, all tanks are placed on scales.

The VP creates a reduced pressure in the system. This allows us to achieve the following benefits:

1) a decrease in the boiling point of the liquid in the distiller, and therefore a decrease in the specific energy consumption for the recovery of 1 liter of water;

2) the ability to move liquid through the system without the use of any pumps, which significantly simplifies the design and increases the reliability of the equipment.

The system also has auxiliary units:

- cooling system for the cold circuit of the distiller in the form of a CWEx heat exchanger;
- heating system for the hot circuit of the distiller in the form of an HWEx heat exchanger, an HWT tank with a heater and an HWP pump.

It should be noted that the abovementioned heating and cooling systems, if necessary, can be replaced by a thermoelectric heat pump (THP), the use of which simplifies the design of the system and allows further reduction of specific energy consumption. The results of experiments on the use of CMED using THP are described in [13].

The electrical conductivity of the resulting distillate is determined by the built-in TDS meter. Other distillate quality parameters are determined in the laboratory.

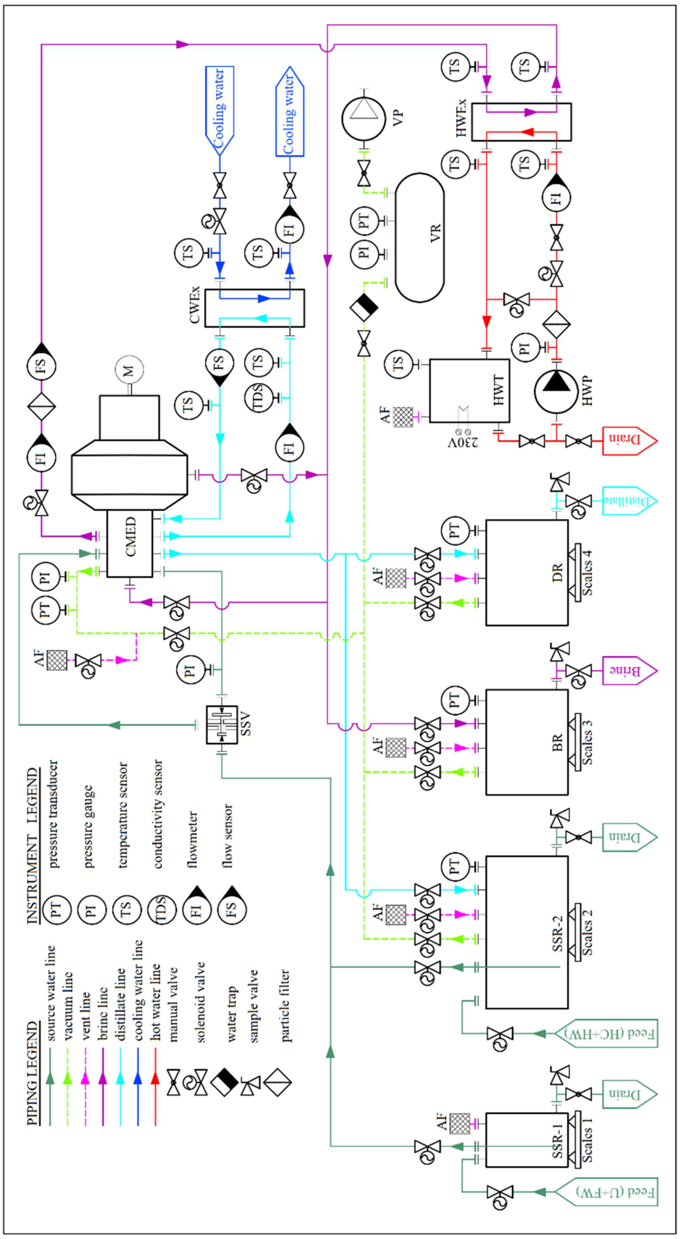

Figure 1. CMED system diagram

III. Results and Discussion

The solutions used for the experiment quantitatively and qualitatively simulate the wastewater generated as a result of the vital activity of a spacecraft crew consisting of 4 people. The quantitative composition of the spacecraft crew wastewater is given in Table 1.

Table 1: The quantitative composition of the spacecraft crew wastewater

Wastewater	**Value (kg/day)**	
	1 crew member	**4 crew members**
Urine	1.50	6.00
Flush water	0.30	1.20
Humidity condensate	1.95	7.80
Hygiene wastewater	7.24	28.96

The types of wastewater indicated in the table can be divided into 2 types. Type 1 wastewater contains contamination (toilet water). This type includes urine and flush water. The flush water itself is not contaminated, but after mixing with urine in the toilet, this wastewater must be treated together. Type 2 wastewater is conditionally clean and does not contain toilet contamination (gray water). This type of waste includes humidity condensate and hygienic water. Based on the fact that the pollution degree of these types of wastewater is different, many researchers use various methods for their purification. In our experiment, a different approach was used - the above mentioned types of wastewater were processed separately, but using only one apparatus. As a result, the distillation process of the entire volume of wastewater was technologically divided into 2 stages: 1) Type 1 wastewater distillation; 2) Distillation of type 2 wastewater and type 1 wastewater distillate. The main feature of the proposed technology is that the most contaminated waste liquid, namely urine, was subjected to double distillation during the experiment. Type 2 wastewater, that is, conditionally pure water, went through the distillation process only once. To process the wastewater mixture at stage 1, a source solution in a volume of 7.29 kg was prepared, consisting of urine (6.0 kg), flush water (1.2 kg), and preservative solution (0.09 kg).

Natural human urine was used with ordinary distilled water being used as flush water. A solution of a preservative agent was added to the mixture at the rate of 15 g per 1 kg of urine. A solution of the following composition was used as a preservative solution: H_2SO_4 (36.5%), CrO_3 (9.0%), H_2O (54.5%). During the distillation process, the source solution was taken from tank SSR-1, and the resulting distillate was sent to tank SSR-2, that is, the tank containing type 2 wastewaters. The main 1st stage distillation process parameters of the experiment are given in Table 2.

Table 2: The main 1st stage distillation process parameters of the experiment are given

Parameter	**Units**	**Value**
Source solution amount	kg	7.29
Distillate amount	kg	6.74
Brine amount	kg	0.55
Capacity	kg/hour	3.0-3.5
Rotor speed	rpm	1225
Distillate conductivity	µS/cm	115-150
Specific power consumption	Wh/L	280
Process duration	hour	2.3
Recovery	%	92.4

The system parameters changed during the process. At the beginning of the process, the distillate capacity of the system was 3.5 L/h, and the conductivity of the resulting distillate was about 115 µS/cm. By the end of the processing cycle, productivity dropped to 3.0 L/h, and the quality of the resulting distillate dropped to 150 µS/cm. Obviously, these changes can be explained by increasing concentrations of impurities in the circulating brine solution. Specific power consumption (SPC) takes into account the energy consumption to heat the water in the HWT tank, as well as the operation of the electric motor that rotates the CMED rotor.

To process the wastewater mixture at stage 2, 43.5 kg of source solution was prepared, consisting of distillate obtained at the 1st stage of the experiment (6.74 kg), synthetic humidity condensate solution (7.8 kg), synthetic solution of hygienic water (28.96 kg).To prepare synthetic solutions of humidity condensate and hygienic water, the recipes given in [20] were used. During the distillation process, the source solution was taken from the SSR-2 tank, and the resulting distillate was sent to the DR tank. The main 2nd stage distillation process parameters of the experiment are given in Table 3. The general results of the experiment based on the results of both stages are shown in Table 4. The main parameters of the resulting distillate are given in Table 5.

Table 3: The main 2nd stage distillation process parameters of the experiment are given

Parameter	Units	Value
Source solution amount	kg	43.5
Distillate amount	kg	42.92
Brine amount	kg	0.58
Capacity	kg/hour	3.2-3.7
Rotor speed	rpm	1220
Distillate conductivity	µS/cm	38-57
Specific power consumption	Wh/L	280
Process duration	hour	12.8
Recovery	%	98.7

Table 4: The general results of the experiment based on the results of both stages

Parameter	Units	Value
Source solution amount	kg	44.05
Distillate amount	kg	42.92
Brine amount	kg	1.13
Process duration	hour	15.1
Recovery	%	97.4

Table 5: The main parameters of the resulting distillate

Parameter	Units	Value
Turbidity	NTU	0.34
pH	--	4.11
Total organic carbon	ppm	15.2
Nitrate	ppm	0.46
Total dissolved solids	ppm	23.0
Iron	ppm	0.056
Manganese	ppm	< 0.005
Ammonium	ppm	0.127

Since the 2nd stage stock solution has a lower concentration compared to the 1st stage stock solution, we obtained a much higher quality distillate. System capacity has also increased slightly. Most quality indicators meet the requirements for drinking water, but some of them (pH, total organic carbon) require additional adjustment. The daily volume of wastewater was processed in just over 15 hours. This fact shows that the system has sufficient capacity to handle increased amounts of wastewater, for example, from a crew of 6 people.

It is worth noting that in this experiment a distiller of a 3-stage design was used. The authors also have a 5-stage CMED at their disposal. The advantages of the 5-stage CMED are that it can increase plant productivity up to 8 L/h and reduction of specific power consumption to produce 1 liter of distillate to 100 Wh/L.

IV. Conclusion

The data obtained as a result of the experiment allow us to conclude that the technology under consideration is promising for its application in the field of water restoration by recycling waste from the crew life support system during long-term space flights. The system's performance is sufficient to process the entire daily volume of wastewater within 15 hours. The quality of the resulting distillate is at a high level, however, for use as drinking water, a post-purification unit should be provided, including disinfection, which will obviously be the subject of further research. It should also be noted that, despite the high performance achieved, CMED technology has the potential for further improvement (use of 5-stage distillers, use of heat pumps, etc.), which will allow for improved energy efficiency of the system.

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