Development status of active thermal control system for future crew module

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This paper introduces the active thermal control system of a crew module for future manned space missions, such as NASA's Deep Space Gateway and the post-International Space Station program. Total heat generation of 8 kW or more is transported by single-phase mechanical pump loops to radiators mounted on the outer surface of the module. Both the double loop system and the single loop system are studied because the single loop system is more efficient for minimizing the radiator area under the same amount of heat dissipation. Several coolant candidates are investigated for the single loop system. The waste energy generated in the module is dissipated from the body-mounted radiators into deep space. The sides of the cylindrical module are covered with radiator panels. Air conditioners or desiccant coolers are used to regulate air temperature and humidity. These features make it possible to eliminate the inner loop below the dew point of the cabin air, thereby allowing the radiator area to be minimized. High-performance pumps have been developed for both the single loop system and the double loop system.

Nomenclature

ATCS	=	Active Thermal Control System
CO2	=	Carbon-Dioxide
DSG	=	Deep Space Gateway
EVA	=	Extra-Vehicular Activity
HAB	=	Habitation Module
ISS	=	International Space Station
IVA	=	Intra-Vehicular Activity
JEM	=	Japanese Experiment Module
JAXA	=	Japanese Aerospace Exploration Agency
TRL	=	Technical Readiness Level
THC	=	Temperature and Humidity Control
TCCS	=	Trace Contaminant Control System

I. Introduction

FUTURE manned space modules require more lightweight and compact systems in order to go beyond low Earth orbit.. Therefore, weight reduction is also important for development of the active thermal control system (ATCS). The Japan Aerospace Exploration Agency (JAXA) has conducted a study on the ATCS, targeting the Deep Space Gateway (DSG). The DSG concept is emerging as the consensus next step that meets multiple exploration paths including the Moon, Mars, and beyond.[1] Deep space exploration will be developed in phases, and the DSG

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will be built in Phase 1 to demonstrate the exploration systems in cislunar space. Twenty-eight objectives that include demonstrating habitation elements to support missions with at least four crew members for a minimum of 30 days are defined in Phase 1.[2] Figure 1 shows an imaginary image of the DSG. The DSG would have a power bus, a small habitation module (HAB), and a logistics module. Other elements such as an airlock would be installed later.[3]

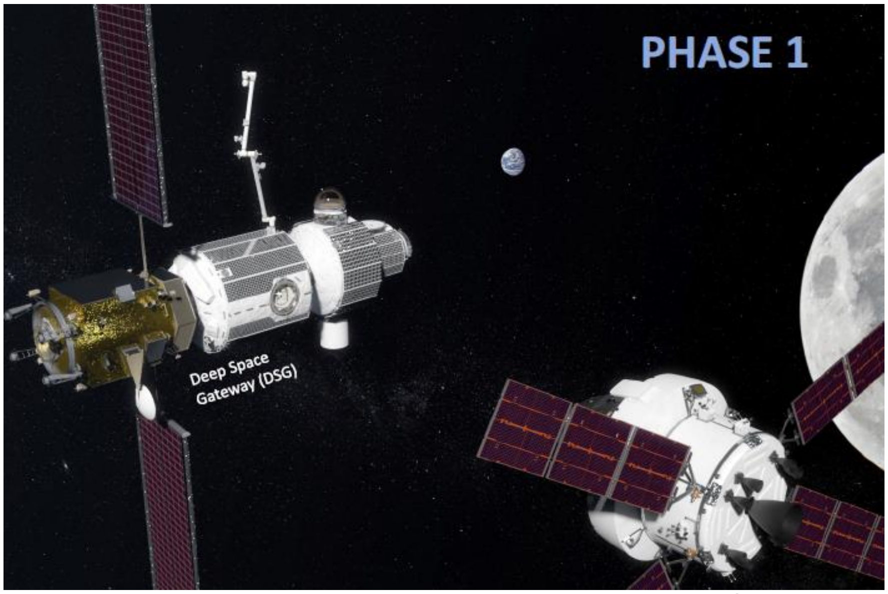


Figure 1. Imaginary image of the Deep Space Gateway[3]

In the DSG, the HAB is assumed to be diameter 4.2 m × length 5 m in size and will house four crew members. The sides of the cylindrical module are covered with radiator panels. The heat generated in the module is dissipated from the body-mounted radiators into deep space. The total heat generation of 8 kW should be transported by mechanically pumped fluid in closed-loop circuits to the radiators. This paper compares the single loop system and the double loop system, as well as certain challenges regarding the development status, such as the mechanical pumps and the Temperature and Humidity Control (THC) system.

II. Fluid pumped loop

Two types of ATCS loop configuration are proposed: single loop and double loop as shown in Figure 2 and 3, respectively. Compared with the double loop configuration, the single loop configuration requires less radiator area under the same condition of heat dissipation and the temperatures of components that generate waste energy. In the double loop, a temperature difference between the inner loop and the exposed loop occurs in the heat exchanger. However, there is no such temperature loss caused by the temperature drop at the interface heat exchanger in the single loop, so that the radiator temperature can be kept higher. The single loop also has an advantage in that such fluid components as the mechanical pumps can be installed inside the module. This achieves not only high maintainability and reliability, but also a significant reduction of crew time for Extra-Vehicular Activity (EVA). The total mass of the ATCS can also be drastically reduced. In addition to the effect of simply reducing the number of fluid components, in view of the experience acquired on the Japanese Experiment Module (JEM) with an inner loop and an exposed loop, the mass of the inner pump package is less than that of the exposed one. Table 1 shows the results of comparing the single loop and double loop systems in terms of radiator area, and the estimated total mass. The mass of loops includes mainly the mass of pump, accumulator, valves, sensors, pipes, and coolant. The pipes are assumed to be made of SUS, which length is calculated assuming the routing shown in Figure 4. The mass of other components is estimated based on the JEM's achievements. The estimated total ATCS mass is about 300 kg less in the single loop system than in the double loop system.

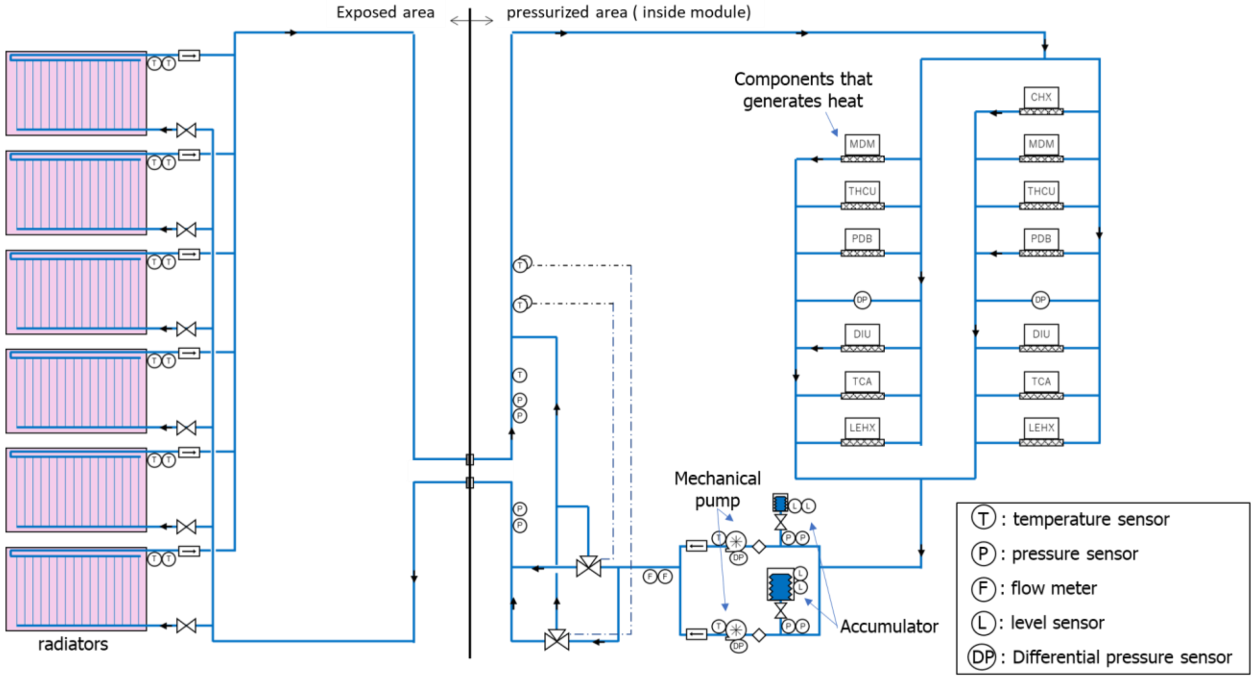


Figure 2. Schematic diagram of single loop system

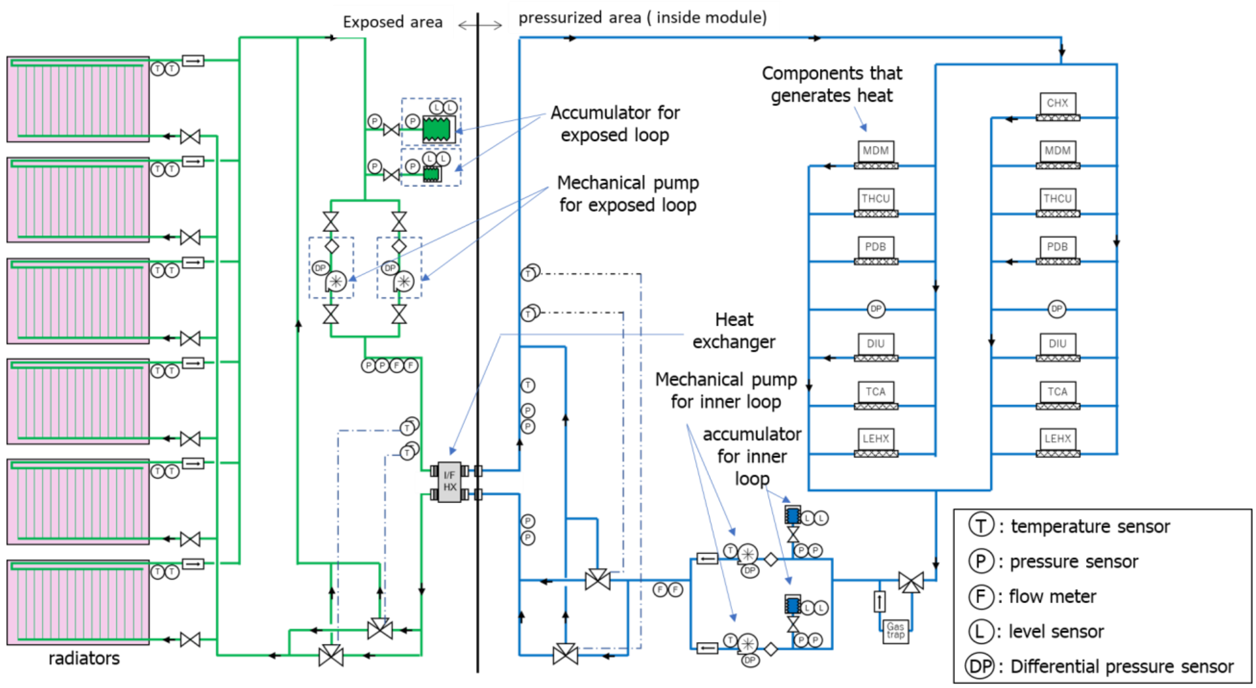
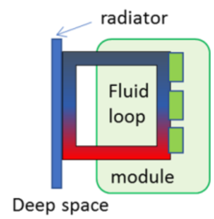
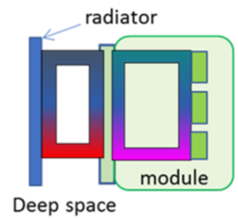


Figure 3. Schematic diagram of double loop system

Table 1. Estimated total ATCS mass

item	estimalted total ATCS Mass (kg)	
	single loop 	double loop 
radiators	343 (area: 35.0 m^2)	383 (area: 39.1 m^2)
Fluid loops for single loop (including coolant)	346	-
External loops (including coolant)	-	325
Internal loop (including coolant)	-	252
Heat exchangers	-	22
Cold plates	50	50
Thermal insulation for internal loop	0	0
MLI (multi-layer insulation)	29	29
Heaters, sensors	30	30
Heater control units	30	30
sum	828	1121

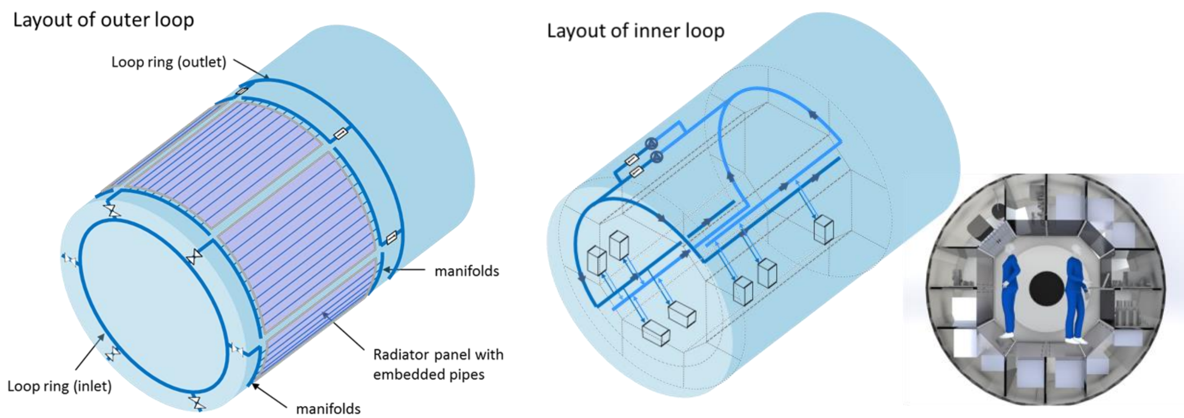


Figure 4. Layout of outer loop and inner loop (Common for single loop and double loop)

Regardless of the single loop or double loop system, two pumps and two accumulators are installed in one loop for redundancy. The pumps and accumulators in the pressurized module are installed in parallel as pairs. Even in case of pump and accumulator failure in another line, the loop can be maintained with the remaining pump and accumulator by having the crew change the connection of piping in Intra-Vehicular Activity (IVA). On the other hand, the pumps and accumulators of the exposed loop are installed in independent lines, thus making it possible to use the exposed loop as it is without having to disconnect and then reconnect the pipes, even if one pump and one accumulator should fail.

The branches flowing in the cold plates for the components are in parallel so that coolant in the lowest temperature condition can be supplied to each component. It is necessary to adjust the mass flow rate of each branch so that the differential pressure of each branch is approximately the same. The inlet temperature of the branches is kept constant by adjusting the degree of opening of the two three-way mixing valves downstream of the pumps installed inside the pressurized module.

The branches flowing to the radiators are parallel so as to dissipate heat at high temperature from each radiator efficiently. The flow paths in each radiator are also arranged in parallel for high efficiency heat dissipation and small pressure loss.

The temperature of the inner loop is proposed to be medium to high: even in case of the single loop or double loop system, the temperature of the loop flowing through the inside of the module is above the dew point of cabin air. This allows for less radiator area and less thermal insulation for the inner loop than for the loop having lower temperature. It also leads to easier piping maintenance because dew condensation does not occur around the piping.

Table 2 lists the physical properties of some coolant candidates for the mechanically pumped loop, along with those already used as coolants on the International Space Station (ISS). Two particularly important properties for single loop coolant are toxicity and freezing point. Having a freezing point of at least below -60°C to -70°C should not be harmful to the human body. Fluorinert FC-770 and Galden® are candidates for the single loop as both are relatively non-toxic and their freezing points are below -80°C, while their thermal properties are not as good as those of water and ammonia. Fluorinert decomposes when exposed to a high temperature of 200°C or higher and generates toxic gases such as hydrogen fluoride. It is necessary to avoid mixing Fluorinert into the devices of the trace contaminant control system (TCCS) and CO_2 removal system that take in cabin air and heat it. Typically, the highest temperatures of these devices exceed 200°C. JAXA has been developing a new TCCS and CO_2 removal system. Due to the successful development of a low-temperature oxidation catalyst, these devices could be operated at less than 200°C. The candidate coolants will be evaluated for other toxicities to check whether the candidates can be used as the single loop coolant. For the double loop system, HFE-7200 and a propylene-glycol/water mixture used as coolants in the ATCS of the Orion Multi-Purpose Crew Vehicle[4] are proposed for the exposed loop and inner loop, respectively.

Table 2. Candidate coolants for fluid pumped loop

	Candidates for single loop		**candidate for inner loop of double loop**	**candidate for exposed loop of double loop**	**coolant used for inner loop on the ISS**	**coolants used for exposed loop on the ISS**	
product name	**FC-770**	**Galden® HT-80**	**Propylene-glycol/water mixture**	**Novec™ 7200**	**Water**	**Ammonia**	**FC-72**
boiling point [°C]	95	80	182	76	100	-77.4	56
pour/freezing point [°C]	-127	< -110	-59.5	-138	0	-33.4	-90
flash point [°C]	-	-	109	-	-	132	-
density [kg/m^3]	1790	1690	1033	1430	998.2	624.6	1680
specific heat [J/kg/K]	1038	962	2510	1214	4185	4676	1100
thermal conductivity [W/m/K]	0.063	0.065	0.2~0.6	0.068	0.602	0.529	0.057
latent heat [kJ/kg]	86	71	-	126	2454	1226	88
vapor pressure [MPa]	0.0065	0.018	0.00001	0.016	0.0023	0.615	0.03
thermal decomposition temperature [°C]	200	290	-	200	-	-	200

III. Mechanical pumps

Two types of domestic mechanical pumps have been operating on the JEM: one type circulates water for the inner loop and the other type circulates FC-72 for the exposed loop. The new domestic pumps for both the inner loop and exposed loop on the JEM have been developed for the spares. It is considered that the new pump developed for the exposed FC-72 loop can be improved in terms of performance and also applied to the single loop of the DSG HAB module. The shaded area in Figure 5 shows the operation range of the JEM exposed pump. When the coolant is Galden® HT-80 and the total heat dissipation is 8.8 kW, the mass flow rate and total pressure loss of the single loop in the DSG HAB module are calculated to be more than 1800 kg/hr. and 330 kPa, respectively. Considering the margin, the specifications of the newly developed pump are a mass flow rate of 2500 kg/hr and discharge pressure of 400 kPa when using Fluorinert as a coolant. Figure 5 also shows the operation point of the pump for the single loop system. It is beyond the performance range of the JEM's exposed pump, but is assumed to be sufficiently feasible.

The newly developed pump is a centrifugal pump, and its size shown in Figure 6 is about 100 mm in diameter and 170 mm in length. It is smaller than the pumps on the JEM that have a length of 261 mm, a height of 92 mm, and a width of 99 mm. The weight is around 5.2 kg, which is lighter than the JEM pumps that weigh 6.6 kg. Due to the improved performance, however, the power consumption of the new pump is higher than that of the JEM pump. The power consumption of the JEM pump is approximately 400 W at maximum operation, while that of the new pump is more than 600 W.

A prototype model of the pump was built and performance tests are currently underway. The performance tests are conducted by flowing HFE-7200 until the end of March 2018.

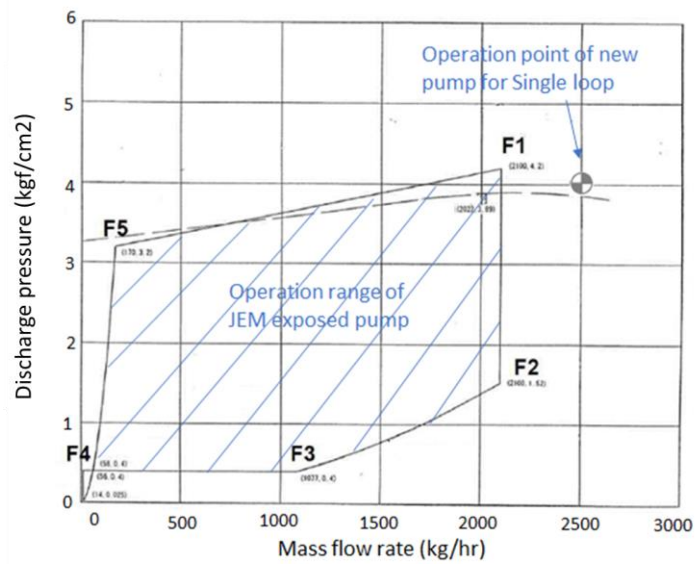


Figure 5. Operation range of the JEM exposed pump and the new pump

Figure 6. Newly developed pump

IV. Temperature and Humidity Control of Cabin Air

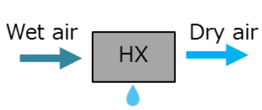
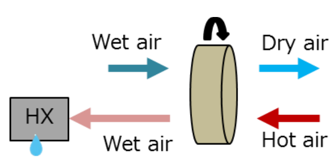
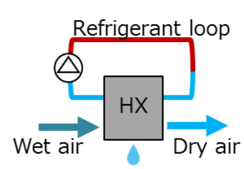
In the pressurized module of JEM, the cabin temperature is adjusted by cooling it using low-temperature cooling water of 4°C (i.e. temperature below the dew point). In this method, water vapor in the cabin is condensed in the process of cooling, and moisture discharged from the crew members is also dehumidified at the same time. However, in the case of medium to high temperature loops, dehumidification by this method is impossible because the loop temperature is above the dew point.

As a method of temperature and humidity control without using a low temperature loop, two types of air conditioners are proposed: an air conditioner with a compressor using the expansion and compression of coolant, and an air conditioner using a desiccant that adsorbs/desorbs water vapor in the cabin, with temperature being controlled subserviently or independently. Table 4 shows the comparison results of each method. The Technical Readiness Level (TRL) of the desiccant dehumidifier technology is "3" because it has been commercially developed, though never developed for space use, while the TRL of the current JEM system and air conditioner with a compressor is "9" because the system is already used in the ISS. The weight and size of the desiccant air conditioner may be smaller than those of the air conditioner with a compressor due to the compressor and coolant, which need a sealed case to avoid leakage. However, more power consumption is required than for the current system and air conditioner with a compressor due to the latent heat of water. Therefore, the new THC system shown in Figure 7 has been investigated in reference to the commercial desiccant dehumidifiers.[5] A prototype system targeting space use has also been developed.

After cabin air is introduced to the desiccant rotor, which has a honeycomb geometry and absorbs moisture in the air, the dried air return to the cabin, being cooled by the ATCS internal loop so that cabin temperature is kept constant. The desiccant rotor rotates and is regenerated by the closed loop at the bottom as shown in Figure 7. Regenerated air is heated and adsorbed water is desorbed by this loop in passing through the rotor. Humid, high-temperature air from the rotor is cooled by the ATSC internal loop and condensed water is collected by a water separator.

The targeted amount of condensed water is 7.2 L/day, which corresponds to the moisture discharged by four people in a day, and the control range of cabin air temperature is from 21°C to 27°C. The water separator used in the JEM can also be used in this system because it can treat 7.2 L of water per day. However, since it is not confirmed whether temperature can be controlled with dehumidification at the same time, the protorype function is limited to the area enclosed by the dotted line in Figure 7. It is necessary to prepare the temperature control unit separately from the humidity control unit and operate both independently in case temperature control cannot be performed subserviently. The increase in the mass and volume of the system is assumed to be slight as only an extra blower fan is required as a component. Assuming independent and separate control of temperature and humidity, the size of the heat exchanger is estimated to be the same as that of the current heat exchanger installed in the JEM. Therefore, the air conditioner with a desiccant may not become as heavy and large as in the current JEM system. Power consumption will be also confirmed using the prototype.

Table 3. Temperature and humidity control method

Method	**Current system (the JEM THC)**	**Air conditioner with desiccant**	**Air conditioner with compressor (THC in ISS service module)**
Overview **(Figure is on dehumidification function)**	Temperature is controlled by low temperature cooling water. Humidity cannot be not controlled, but moisture is condensed at the same time as temperature control. 	Humidity is controlled using a desiccant, which adsorbs/desorbs moisture. Temperature is controlled to be medium to high in the temperature loop. 	Temperature is controlled by using the compression and expansion of the refrigerant. Humidity cannot be not controlled, but moisture is condensed at the same time as temperature control. 
Loop temp.	4.5°C	> dew point	> dew point
Water condensation capability	5 L/day	7.2 L/day	11 L/day<
Heat removal capability	2410 W	1000 W	700 W<
Weight	138 kg	40 kg	24 kg for compressor
Power	445 W	350 W	270 W for compressor
TRL	9	3	9

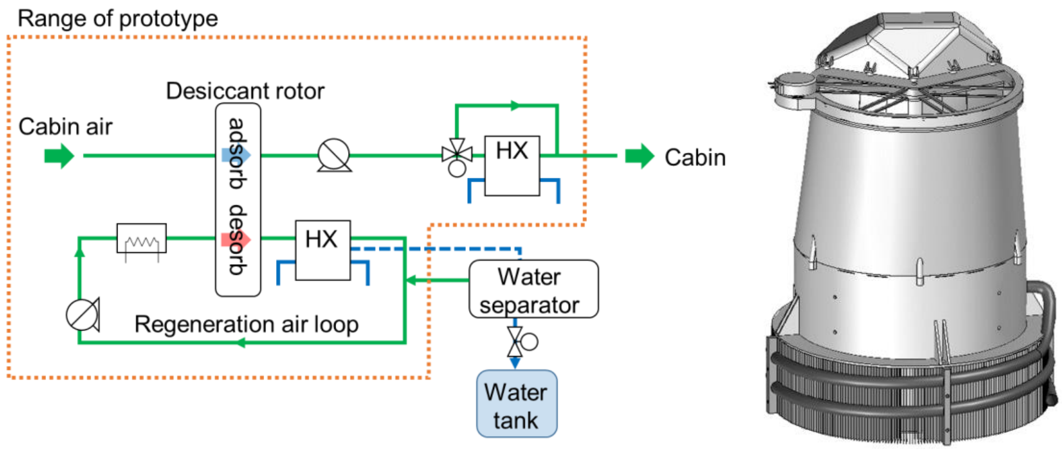


Figure 7. Diagram of temperature and humidity control system (left) and appearance image of prototype (right)

As an option, we are also studying humidity control using a desiccant bed installed in the CO_2 removal system being developed by JAXA,[6] in which condensed water is available in the latter stage of the regenerating desiccant. As almost all water vapor including that in the cabin air is adsorbed and desorbed, assuming that cabin air at 23°C/RH 50% is cooled down to 20°C with a medium-temperature loop, the water for four people can be recovered when the desiccant regeneration time is less than 0.46 times longer than the adsorption time. Regarding humidity control, the cycle design depends on the condition of cabin air and the flow rate of inlet air. The feasibility of this combined system of CO_2 removal and THC will be investigated on an ongoing basis.

V. Summary

JAXA has studied the architecture of the ATCS of the DSG HAB, especially the single loop method, and developed a mechanical pump and a new THC method to confirm feasibility. In case of the single loop system, the estimated total ATCS mass is about 300 kg less than that of the double loop system. Regardless of the single loop or double loop system, high maintainability is achived by installing mechanical pumps inside the module and setting the temperature of the inner loop above the dew point of the cabin air. Single loop system would be better choice if the following points are confirmed because of the advantages of mass and maintainability; 1) development of a new pump having enough performance for single loop system, 2) establishment of a new THC system which can increase loop temperature, 3) solving the problem of toxicity of the coolant or its degradation products. The new pump developed for the exposed FC-72 loop in JEM is likely to be improved in terms of performance and applied to the single loop system of the DSG HAB. Performance tests of the pump's prototype model are being conducted by flowing HFE-7200 until the end of March 2018. An air conditioner with a desiccant achieves medium to high inner loop temperature and whether temperature control is possible at the same time as humidity control will be confirmed by the end of March 2018. Humidity control using the desiccant function in the CO_2 removal system was also investigated. The prospects are getting better thanks to our desk study, and we will establish necessary technology through prototyping and testing in the future.

Acknowledgment

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