On-orbit demonstration of Advanced Thermal Control Devices using JAXA Rapid Innovative payload demonstration SatellitE-2 (RAISE-2)

Hiroki Nagai[1], Hiroto Tanaka[2]
Tohoku University, Sendai, 980-8577, Japan

Satoshi Kajiyama[3], Takuji Mizutani[3] and Hosei Nagano[5]
Nagoya University, Sendai, 980-8577, Japan

Kenichiro Sawada[6]
Japan Aerospace Exploration Agency, Tsukuba, 305-8505, Japan

Kan Matsumoto[7], Yuya Shimoda[8]
WEL Reseaech Co. Ltd., Ichihara, 299-0102, Japan

In recent years, advances in thermal control technology have become essential for deep space exploration to achieve exploration goals. For missions that explore an outer planet, the limited power resources available from solar panels must be used to maintain the temperature of the spacecraft. Therefore, there is an urgent need to develop lightweight thermal control technology that does not use power resources. We have conducted research and development of original thermal control devices such as flexible deployable radiators, thermal straps, self-excited oscillating heat pipes, and heat storage devices. Their effectiveness has been confirmed in ground tests. However, there has been no opportunity for on-orbit technical demonstrations, and there has been no path to practical application. However, we were selected in 2018 to participate in the Innovative Satellite Technology Demonstration Program proposed by JAXA. We have the opportunity to conduct on-orbit experiments with the RApid Innovative payload demonstration SatellitE-2 (RAISE-2) around January 2022. In the orbit demonstration, we will demonstrate the Advanced Thermal Control Device (ATCD), a combination of three devices: a flexible-deployable radiator, a high thermal conductivity thermal strap, and a fluid-type thermal strap. This paper describes an overview of the ATCD.

I. Introduction

As satellites become more sophisticated (multifunctional, highly accurate, and energy-saving), innovative thermal control technology improvements are strongly desired. In particular, as satellites become smaller and smaller, there is an urgent need to develop lightweight thermal control technology that does not use power resources. We have been conducting research and developing unique thermal control devices such as flexible-deployable radiators, thermal straps, self-excited Oscillating Heat Pipes, and thermal storage devices[1-4] and confirmed their effectiveness at ground level. However, we have not yet had an opportunity to demonstrate these thermal control devices in orbit, and there is no way to put them to practical use.

Since 2015, JAXA has been implementing the Innovative Satellite Technology Demonstration Program[5], which provides opportunities for private companies and universities to acquire and accumulate new knowledge, create future

---

[1] Professor, Institute of Fluid Science, 2-1-1, Katahira, Aoba-ku, Sendai, Miyagi 9808579
[2] Graduate student, Department of Aerospace Engineering, 2-1-1, Katahira, Aoba-ku, Sendai, Miyagi 9808579
[3] Graduate student, Department of Mechanical System Engineering, Furo-cho, Chikusa-ku, Nagoya, Aichi 4648603 Japan
[4] Graduate student, Department of Mechanical System Engineering, Furo-cho, Chikusa-ku, Nagoya, Aichi 4648603 Japan
[5] Professor, Department of Mechanical System Engineering, Furo-cho, Chikusa-ku, Nagoya, Aichi 4648603 Japan
[6] Associate Senior Researcher, Research Unit II, Research and Development Directorate, 2-1-1 Sengen, Tsukuba, Ibaraki 3058505, Japan.
[7] Engineer, Space Development Engineering Division, 2-12-11 Aoyagi, Ichihara-Shi, Chiba 299-0102, Japan
[8] Engineer, Space Development Engineering Division, 2-12-11 Aoyagi, Ichihara-Shi, Chiba 299-0102, Japan

missions and projects, and conduct on-orbit demonstrations of key components and new elemental technologies for space systems by utilizing nano-satellites. The purpose of the program is to demonstrate technologies and ideas that will lead to the creation of missions that open up new applications and systems/subsystems that are competitive in the industry while addressing industry challenges and anticipating the future. In particular, priority is given to "innovative" technologies that are expected to achieve high results in the development of Japan's space technology and ensure the international competitiveness of the space industry, although the risks are high. The first small demonstration satellite (RAPIS-1: RAPid Innovative payload demonstration Satellite 1) was launched in January 2019 under this innovation program, and an on-orbit demonstration test was conducted. Currently, the second small demonstration satellite (RAISE-2: RApid Innovative payload demonstration SatellitE-2) is under development and is scheduled to be launched around January 2022.

We applied for this program and were successfully selected in 2018, which gave us the opportunity to demonstrate the thermal control device in orbit. In RAISE-2, we will demonstrate the Advanced Thermal Control Device (ATCD), which is a combination of three devices: a flexible-deployable radiator, a high thermal conductivity thermal strap, and a fluid-type thermal strap, all of which have relatively high Technology Readiness Level (TRL) among the thermal control technologies we have been developing.

This paper presents an overview of the Innovative Satellite Technology Demonstration Program and the three thermal control devices and their combination, the Advanced Thermal Control Device (ATCD).

II. Overview of RIASE-2

The small demonstration satellite-2 (RAISE-2) is a satellite developed by JAXA to carry the demonstration themes selected as "components" and "parts" and to demonstrate them in orbit as the second demonstration opportunity in the Innovative Satellite Technology Demonstration Program, which aims to maintain the industrial base, enhance international competitiveness, and create new innovations through space demonstrations of key satellite technologies. The external view of RAISE-2 is shown in Figure 1.

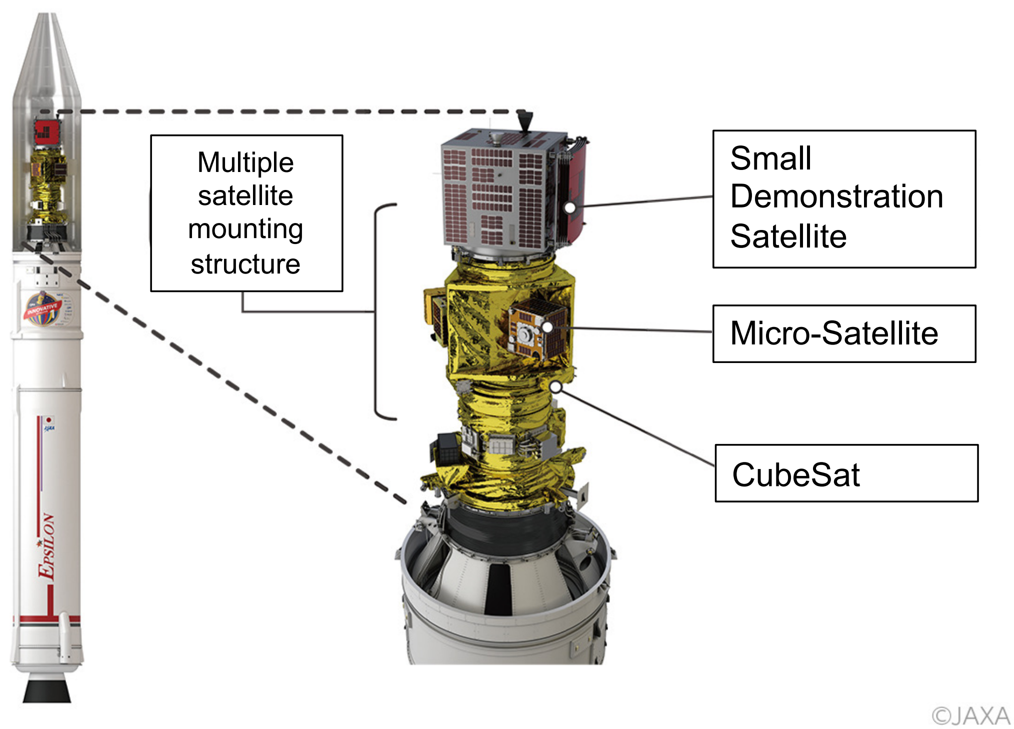


Figure 1. Schematics of RAISE-2[5]

Table 1.　RAISE-2 Main specifications[5]

Item	Contents
Operation period	1 year (regular operation period after the initial operation (about 1 month))
Launch trajectory	Orbit type: Solar concurrent track Orbital altitude: 560km ±10 ㎞ Orbital inclination angle: 97.6deg ±0.2deg Descending intersection point through the local solar time: 9:30 a.m. -0 minutes/+10 minutes
Launch	January 2022 Enhanced Epsilon rocket
Size	About 0.75m×1m×1m
Mass	110 kg or less (demonstration theme equipment + satellite bus system)
Power system	Power generated: 215 W or more (average during BOL daylight) Power that can be supplied to the demonstration theme equipment: 112Wh or more per lap (BOL)　 #BOL: Beginning Of Life
Communication system	HK Operation: S-band（Uplink：4kbps、Downlink:64kbps） Mission DL: X-band（Downlink:16Mbps）
Attitude control system	Earth pointing (Nominal during experiments, except for some experiments) Earth station pointing (during X-band communication)
Structural system	Panel system using aluminum plates and honeycomb panels (Carbon Fiber Reinforced Plastics (CFRP), skin and aluminum core)

III. Advanced Thermal Control Device, ATCD

The significance and purpose of the mission are to develop and demonstrate a unique, lightweight, power-saving thermal control technology that has never been developed before and to deploy it domestically and internationally to contribute to the improvement of the market competitiveness of satellite systems from small to large satellites.
The overview of the ATCD with each thermal control device combined is shown in Figure 2, and the external view of RAISE-2 are shown in Figure 3. The ATCD is mounted exposed on the satellite structure to perform the deployment radiator test. The flexible-deployable radiator is placed in the +Z plane, and each thermal strap is attached to the structure in the ±Y plane of ATCD and thermally coupled to the deployment radiator.

The purpose of the demonstration test is to verify that the thermal control device performs as well in orbit as in the ground test. For the flexible-deployable radiator, verify that the heat-generating component must be within the desired temperature range, and the radiator must be fully deployed and fully stowed. For the high thermal conductivity thermal strap and the fluid-type strap, verify that thermal conductance values obtained in ground tests are achieved in orbit. The success criteria of the demonstration test are shown in Table 2.

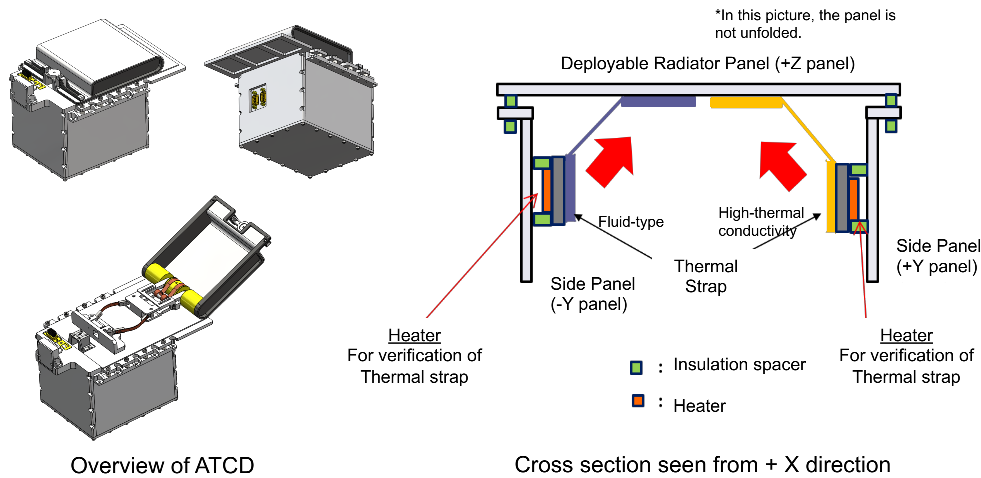


Figure 2. Overview of ATCD with each thermal control device combined

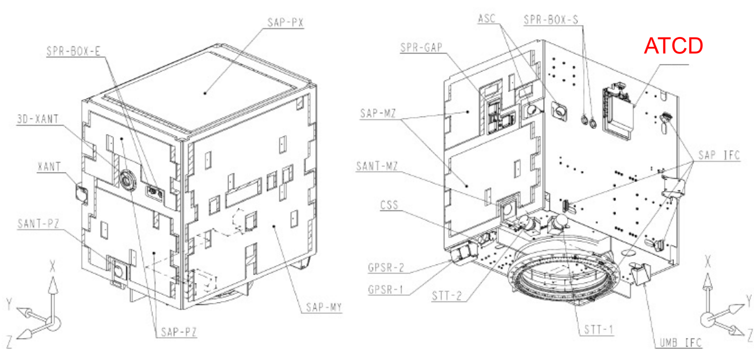


Figure 3. RAISE-2 external view (in orbit, + X is the direction of travel, + Z is the direction toward the earth

Table 2. Success criteria

Minimum Success	**Flexible deployment radiator** Radiator fins to expand **Fluid-type thermal straps** Fluid-type thermal straps to be activated by the heater in orbit.
Full Success	**Flexible-deployable radiator** Autonomous deployment and retraction of radiator fins To confirm the autonomous control function by the change of the external environment (solar incidence). **High thermal conductivity thermal strap** To be able to measure the temperature and demonstrate the comparison of thermal conductance with the ground. **Fluid-type thermal strap** Conduct temperature measurement and compare the thermal conductance with that on the ground.
Extra Success	Confirm the operation for more than one year.

Next, we will introduce each device of ATCD.

(a) Flexible-deployable radiator

In recent years, nano-satellites have become increasingly powerful, and 3U satellites such as PowerCube[6] are considered for 100W-class missions. The larger the size of the solar cells, the larger the heat dissipation (Radiator) area required. However, the heat dissipation area is insufficient for 3U satellites, so developing a deployable radiator is urgently needed. Therefore, our research group has been developing a flexible-deployable radiator[1] for nano-satellites in Figure 4.

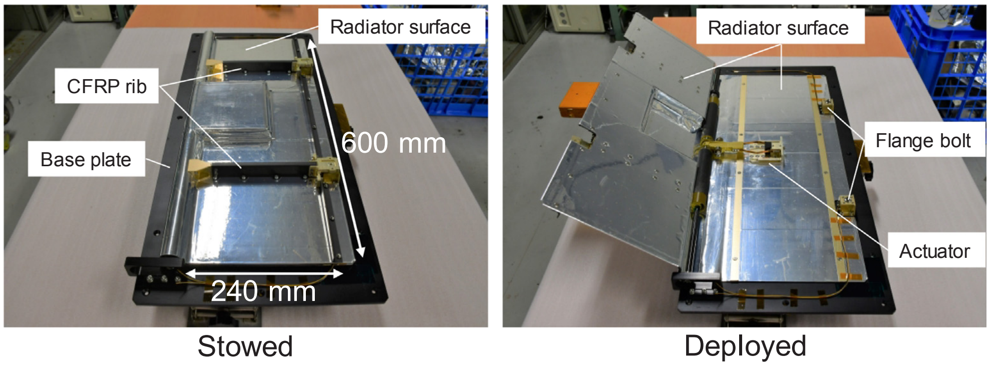
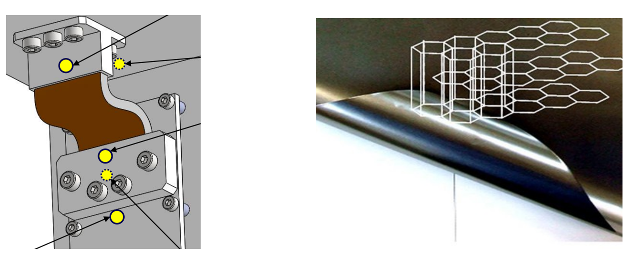


Figure 4. Flexible-deployable radiator[1]

This radiator uses highly thermally conductive graphite sheets for heat conduction enhancement and shape memory alloy for the deployment mechanism and can dissipate 1U~50kg class nano-satellites (5~50W) and the heat of small satellites (~100W). Overseas, a deployment radiator combined with a fluid loop has been developed, but its use has been limited to large satellites because of its heavyweight (several tens of kilograms). However, the proposed radiator is a deployment radiator that utilizes the flexibility and high thermal conductivity of flexible graphite sheets. Its heat dissipation per unit weight is about 100W/kg, much lighter than that of general deployment radiators (less than 50W/kg). Therefore, it has an overwhelming advantage as a deployment radiator for nano-satellites. Also, by using a reversible actuator, it is possible to autonomously (self-detecting and self-adapting) dissipate heat at high temperatures, retain heat at low temperatures, and absorb heat from sunlight. Therefore, it applies to a wide range of missions, from earth orbit satellites to deep space exploration. Details of this radiator can be found in reference 1.

(b) High thermal conductivity thermal strap

The thermal strap is used as a heat transfer path to meet both low stiffness and high thermal conductivity requirements. The thermal strap is a valuable means of heat path for onboard satellite equipment and nano-satellite systems, and its use is expected to increase in the future. In Japan, the thermal strap, which has already been commercialized overseas, has been installed on the X-ray astronomy satellite ASTRO-H "Hitomi "[7]. To be widely used for nano-satellites in the future, it must be lighter and has higher thermal conductance. Conventional thermal straps are made of laminated aluminum foil or braided copper fiber rope. However, there is a need for a lighter and more thermally conductive material. Therefore, in Japan, Kaneka Corporation and Nagoya University have been conducting research and developing a thermal strap laminated with a highly thermally conductive graphite sheet in Figure 5.



Multi-layer graphite sheet thermal strap

Graphite sheet[8]

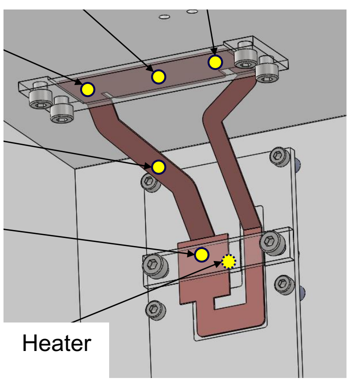
Figure 5. Thermal strap laminated with a highly thermally conductive graphite sheet

High thermal conductivity thermal strap is a thermal strap manufactured by layering graphite sheets with high thermal conductivity. Because it is made of graphite sheets, it is very lightweight and has high flexibility. The local thermal coupling from the heat source to the heat-dissipating part can be easily performed.

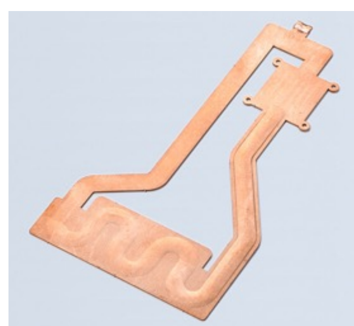
The graphite sheet developed by Kaneka Corporation[8] has a high potential as a heat transfer enhancement material for nano-satellites because its thermal conductivity is about four times higher than that of pure copper. At the same time, its density is only one-tenth that of pure copper. In recent years, straps made of pyrolytic graphite and carbon fiber have been developed overseas, but they have many problems, such as lack of flexibility and low thermal conductivity. Also, they are costly and take a long time to be delivered, which hinders their application to satellites—manufacturing thermal straps domestically and making them more efficient (higher thermal conductance, lower cost) than those made overseas will lead to higher performance, lower cost, and shorter delivery times for satellite development in Japan. Furthermore, advanced domestic thermal element technology can be deployed in overseas markets.

(c) Fluid-type thermal strap

The fluid-type thermal strap is a smaller and thinner version of the loop heat pipe. An overview is shown in Figure 6. It is about 0.2 mm thick, made of copper, has flexibility, and is much lighter than conventional copper thermal straps. It has a high thermal conductance because the heat is transported not only by the heat conduction of the material as in conventional thermal straps but also by the latent heat of evaporation and condensation of the working fluid sealed inside. Water is used as the working fluid. For use in space, it is desirable to use ammonia, which does not freeze even in a low-temperature environment. However, when ammonia is used, high pressure is generated inside. This fluid-type thermal strap cannot be used because it is made of a thin copper foil-like material and the pressure resistance is not sufficient. One of the concerns with using water is freezing. We have confirmed that the LHP starts up and shows its original performance after the water inside is frozen and thawed by the heater in the ground test. One of our objectives is to confirm whether the LHP will actually start up in space in the same way. We have also conducted experiments on the ground to confirm that there are no problems with thermal strap damage or liquid leakage due to expansion caused by freezing. Even if water leaked, it would not be a problem because the amount of water contained in the straps was very small.



Fluid-type thermal strap



Ultra-thin Loop Heat Pipe[9]

Figure 6. Fluid-type thermal strap

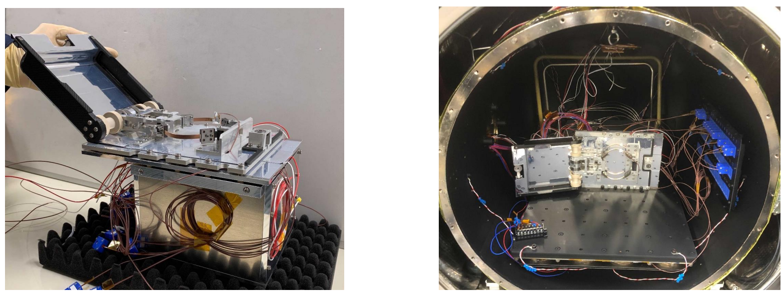
Originally, it has been developed as a heat-transport device for small consumer electronic devices. This on-orbit demonstration is an opportunity for the company to enter the space field. Shinko Electric Industry[9], the developer of this technology, already has the facilities to produce small, thin LHPs of stable quality. Also, we have established the technology to bend the strap without blocking the flow path, which is required for thermal straps. The new strap has achieved a thermal conductance of about 5W/K in a ground-based evaluation, which is much higher than that of conventional high thermal conductivity thermal straps (~1W/K). LoadPath has developed a thermal strap using self-excited Oscillatin Heat Pipes as a similar technology[10], but the thermal conductance is low (less than 1 W/K).

On the other hand, our proposed fluidic thermal strap has no similar development case and has overwhelming advantages in performance and uniqueness. Therefore, when the strap is put to practical use after its performance in orbit, it is expected to have a large market as an innovative Japanese original strap. Therefore, the major issues are whether the working fluid will not freeze on the orbit and whether it can be thawed and operated even if it freezes.

IV. Thermal Vacuum Test

Currently, we are conducting thermal vacuum testing of the Engineering Model (Figure 7). We will use the results of the thermal vacuum test to correlate the thermal conductance of each device in the ATCD enclosure.

Thermal Mathematical Model (TMM) consisting of 510 nodes has been constructed to predict the on-orbit temperature. The base plate and the enclosure are insulated and thermally coupled by spacers only, as shown in Figure 8. The fluid-type thermal strap (or Loop Heat Pipe, LHP) and the High-conductivity thermal strap (or Graphite thermal strap, GTS) are installed inside, and their thermal conductance is set based on the results of preliminary experiments. Figure 9 shows the example of the temperature prediction results for two Earth orbits calculated with corrected TMM, and it can be seen that the temperature of each onboard device increases as the flexible-deployable radiator (or Reversible Thermal Panel, RTP) heater starts heating.



Engineering model of ATCD   Overview of Thermal vacuum test

Figure 7. Thermal vacuum testing of Engineering Model

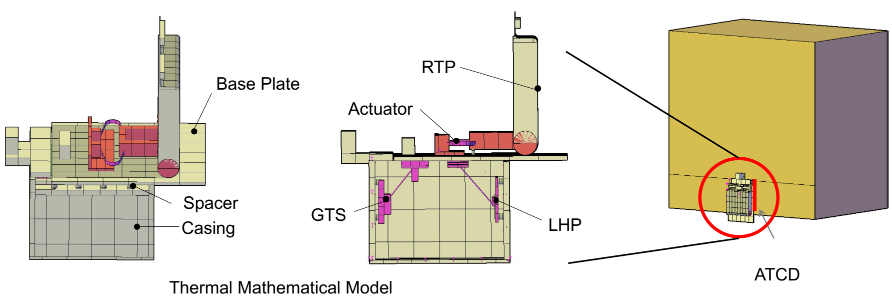


Figure 8. Thermal Mathematical Model (TMM) of ATCD

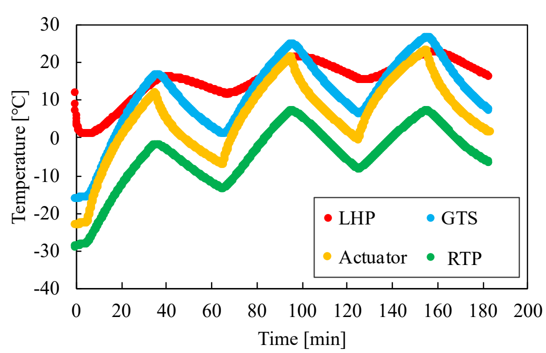


Figure 9. Temperature prediction results for two orbits.

V. Conclusion

In this paper, we have described the Advanced Thermal Control Device (ATCD) outline and the details of each device, which is scheduled to be installed in the Innovative Satellite Technology Demonstration Program 2. At present, we are preparing the Engineering Models (EM), conducting operation verification tests of various devices in consideration of the thermal environment in orbit, and assembling the ATCD to conduct operation verification tests. Some of the results will be reported during the conference.

Acknowledgments

The development of the high-performance thermal control device was supported by a strategic development research grant from the Engineering Committee of the Institute of Space and Astronautical Science, JAXA. Also, we are grateful to the members of the Innovative Satellite Technology Demonstration Group, Research and Development Directorate, JAXA, for their various advice and all-round support in considering the installation of the device on the Innovative Satellite Technology Demonstration Program No. 2. We would like to express our deepest gratitude to them.

We also would like to express our gratitude to Mr. Yasushi Nishikawa of KANEKACorporation and Mr. Yoshihiro Machida of Shinko Electric Industries for their great cooperation in developing and supplying devices.

References

[1] Akizuki Yuki, Nagano Hosei, et al., “Development and testing of the re-deployable radiator for deep space explorer,” Applied Thermal Engineering, Vol. 165, 25 January 2020, 114586.

[2] Xinyu Chang, Noriyuki Watanabe, Hosei Nagano, “Visualization study of a loop heat pipe with two evaporators and one condenser under gravity-assisted condition,” International Journal of Heat and Mass Transfer, Vol. 135, June 2019, Pages 378-391.

[3] Kouhei Yamada Hosei Nagano, and Tsuyoshi Totani, Development of Heat Storage Panel for Micro/Nano-satellite and Demonstration in-Orbit,” Applied Thermal Engineering, Vol. 91, 5 December 2015, 894-900.

[4] Takuro Daimaru, Hiroki Nagai, et al. “Comparison between numerical simulation and on-orbit experiment of oscillating heat pipes”, International Journal of Heat and Mass Transfer, 109(2017), 791-806.

[5] JAXA, Retrieved from https://www.kenkai.jaxa.jp/eng/research/innovative/innovative.html (18.3.2021).

[6] Jonathan Wrobel, Robert Hoyt, Jeff Slostad, Nathan Storrs, Jesse Cushings, Todd Moser, Jory St. Luise and Gregory Jimmerson, “PowerCube(TM) - Enhanced Power, Propulsion, and Pointing to Enable Agile, High-Performance CubeSat Missions,” AIAA SPACE 2012 Conference&Exposition, September 2012.

[7] Tadayuki Takahashi, Motohide Kokubun, Kazuhisa Mitsuda, et al., “Hitomi (ASTRO-H) X-ray Astronomy Satellite, JOURNAL OF ASTRONOMICAL TELESCOPES, INSTRUMENTS, AND SYSTEMS, Vol. 4, No. 2, April 2018.

[8] KANEKA Corporation, Retrieved from https://www.kaneka.co.jp/en/business/qualityoflife/eit_003.html (18.3.2021).

[9] SHINKO ELECTRIC INDUSTRIES CO., LTD., Retrieved from https://www.shinko.co.jp/english/product/under-development/m3hp/ (18.3.2021).

[10] Mike R. Wilson, Derek W. Hengeveld, Brent S. Taft, Advanced Manufacturing of Flexible Oscillating Heat Pipes for Next-Generation Thermal Straps,” 47th International Conference on Environmental Systems, ICES-2017-71, 2017.