Development of continuous ADR system for weak gravity missions

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Abstract. Adiabatic Demagnetization Refrigeration (ADR) does not use working fluids contrary to conventional refrigerators that make use of the fluid density difference, which leads to superiority of the ADR under the weak gravity condition. In this study, we developed a continuous ADR system to provide constant cooling temperatures ~ 0.1 K. The system consists of four stages of magnetic materials and magnets cascaded with heat switches. The magnetic materials CPA and GdLiF₄ are used for 3 stages between 0.1K and 1.4 K, and single stage between 1.4 K and 4 K, respectively. Passive heat switches are used for the stages > 0.3 K and a superconducting heat switch is used for the continuous stage at ~ 0.1 K. A G-M cycle cooler with a 100 V compressor unit is used to cool the ADR and cryostat shieldings. Total mass of flight model is less than 60 kg. Cooling tests with Transition Edge Sensor on the ground showed that the ADR provided continuous cooling temperatures between 105 mK and 120 mK and it successfully operated the TES. Airborne flight experiments confirmed the ability of the cooling system under the mili-gravity condition. The experimental results showed that the ADR could provide stable temperature under the weak gravity, however, strong vibrations coming from turbulence or takeoff affected to the stability of ADR cycle.

1. Introduction

Low temperature environments are essential for advanced space science missions such as X-ray astronomy or microgravity physics. One of most difficult issues in low temperature space experiment is to use of cryogen, typically solid neon and liquid helium. Since these cryogens cannot be reproduced in the space, the mission’s term often depends on the total amounts of cryogens. Recent progress in mechanical cryocoolers or helium sorption refrigerators will be able to offer more convenient cooling system in space, however, very low temperatures below 0.1 K are still very hard to produce by the both methods.

Adiabatic demagnetization refrigeration (ADR) is a typical cooling method used to provide temperatures below 1 K. In particular, ADR system has a dominant advantage in space applications because they do not need working fluids such as ⁴He or ³He and it can operate in zero gravity. In general, ADR will be able to cover the temperatures from 0.01 K to 4 K or higher, therefore, we may construct more efficient and conventional cooling system in space. For such ADR system, a Carnot cycle must be operated over a wide temperature span; thus a cascaded multi-stage ADR consisting of four units has been considered in NASA/Goddared Space Flight Center [1-3].
In Japan, we have launched an ADR project for weak gravity missions in late 2005. This paper will describe the details of the ADR system and experimental results on the ground and under the weak gravity.

2. Continuous ADR system for weak gravity mission

Figure 1 shows the concept of continuous ADR [1]. Two ADR units operate the Carnot cycle with shifting half period each other. When the unit M1 (continuous stage) exhausts the heat during magnetization process, the unit M2 operates the demagnetization process and it absorbs the both heats from M1 and cold stage (heat load). Note M2 must provide at least twice larger cooling capacity than that of M1. Typical experimental results showed that M1 kept a constant temperature of 0.09 K with the duration of 9 μK, while the temperature of M2 periodically changes.

Our ADR system is characterized by large cooling power, fast cycle and helium free system with a mechanical cryocooler as shown in Table 1. The whole ADR system consists of four ADR units operating the Carnot cycle with the specific temperature region as shown in Fig. 2. The heat from stage 1 (continuous stage) is transferred through the higher stages and finally exhausted to a mechanical cryocooler operating at 4.2 K or lower. The magnetic materials CPA (=CrK(SO₄)•12H₂O) and GLF (=GdLiF₄) are used for the stages 1 - 3 and the stage 4, respectively. Polycrystal GLF has been successfully developed to increase the cooling capacity for 1 K ~ 4.5 K [4].

Figure 3 shows the schematic of engineering model. Passive type gas-gap heat switches are used for the stage 2 ~ 4 and a superconducting one is used for the continuous stage. Figure 4 shows the whole cryogenic system including the ADR, a sample stage and a mechanical cryocooler. For the airborne experiment, total weight of the ADR cryostat was decreased down to 60 Kg by using many aluminum parts. A 4K G-M cycle cooler with a 100 mW cooling capacity (Sumitomo SRDK-101D) was chosen here because of the limit of power supply (125V, 20A).

3. Experimental Results

3.1. On the ground

We first tested the continuous mode of the ADR in our laboratory. Figure 5 shows typical experimental results on temperatures of four units with magnetic field changes. Each unit operates the Carnot cycle and the continuous stage provides constant temperatures of 120 mK and 105 mK. It is noticeable that the cycle period is very short (~30 minutes) compared with typical single shot ADRs (2 ~ 24 hours). This is because we need higher cooling power of 0.1 mW at 0.1 K for a solid helium experiment planned later, however, in this case, temperature stability gets worse because of simpler PID control. Actually observed temperature stability was ±200 ~ 600 μK for cooling temperature of 105 ~ 120 mK, but these values agreed with the simulation results. We also tested the TES (Transition
Figure 5. Continuous operation for 120 mK and 105 mK.

Edge Sensor), which is used to detect the X-ray with very high resolution of 10 eV order. The sensor was set on the continuous stage with SQUID amplifier and it could be operated with the continuous cooling mode for longer than 24 hours. The resolution was ~ 30 eV at 105 mK and it was consistent with the temperature stability.

3.2. Under the weak gravity

The airborne experiment can provide the weak gravity condition of $10^{-3}$ G for ~ 20 seconds by the parabolic flight, however, we experienced large G vibration noises up to 2 G in the cabin. Main G shock occurred at taxing and take-off time as shown in Fig. 6. Such large G shock made the thermal short of thermal switch in the ADR between the stage 2 and the stage 4. In this case, we had to re-start the continuous cycle and it takes more than 2 hours to reach the stable condition. Since the limitation of the flight time, we could not attain the continuous mode.
In order to avoid the G-noise, we constructed a vibration-free system consisting of coil springs and rubber dampers setting at the bottom of the cryostat. This system greatly reduced the noise for lower frequency of ~ 15 Hz produced by turbulence, but there still remained the higher frequency noise of ~1 kHz coming from jet engines. The thermal short in the gas-gap heat switches were more sensitive on the lower frequency noise, but we observed that the higher frequency noise generated some amounts of heat at the 2nd stage. The lowest temperature of 144 mK was obtainable at the 2nd stage, where the generated heat was 10 mW, so the cooling capacity is close to this value. Note that the 2nd stage temperature is usually lower than that of the 1st stage during demagnetization process.

It is very interesting to observe the ADR cycle during the weak gravity condition. Figure 7 shows the temperature change of the 2nd stage during the heat switch off condition. The shaded area show the mili-G process and we observed no heat generation in this region. The other stages also showed similar tendencies, so it can be concluded that the ADR works without any difficulty, or even better under the weak gravity condition.

![Figure 6. Thermal short during taxiing.](image)

![Figure 7. 2nd stage temperature during parabolic flight.](image)

4. Conclusion
We constructed the continuous ADR which could operate very fast cycle of ~35 min. to provide the cooling power of ~ 0.1mW at 100 mK. Continuous cooling was confirmed with TES X-ray microcalorimeter. The cryostat with optical windows was already made for the solid helium experiment and it is under testing. The thermal shorts were experienced during taxiing and take-off time, but this occurs typically for the airborne experiment and the ADR will not have any serious problem for space missions such as ISS/JEM ‘Kibo’.

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