Experimental study of a single-stage adiabatic demagnetization refrigerator after vibration reduction

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Abstract. The adiabatic demagnetization refrigerator (ADR), based on the principle of magnetocaloric effect, is a solid-state cooling device. One of its key advantages is the ability to operate under microgravity conditions while offering high thermodynamic efficiency and modular design. Moreover, it stands out as one of the few coolers capable of achieving sub-Kelvin temperatures. As a result, it is gaining significant attention in space applications requiring extremely low temperatures. This study presents the design and experimental performance of a single-stage adiabatic demagnetization refrigerator. The ADR incorporates a superfluid helium bath, providing a precooling temperature of approximately 1.2 K. The magnetocaloric material chosen for this setup is a paramagnetic salt (CPA). A superconducting magnet supplies a magnetic field of 2 T. Experimental measurements show that, under adiabatic conditions, this single-stage ADR can obtain a minimum temperature of 73.58 mK upon completely removing the magnetic field.

Keywords: ADR; sub-kelvin; vibration reduction; superfluid helium bath

1. Introduction

The adiabatic demagnetization refrigerator is a device used to achieve extremely low temperatures, widely applied in low-temperature physics research and scientific experiments requiring ultra-low temperature environments. Its working principle is based on the magnetocaloric effect, where the temperature of a paramagnetic material changes under adiabatic conditions when it is magnetized and demagnetized. Before the advent of the dilution refrigerator in the 1960s[1], achieving extremely low temperatures primarily relied on adiabatic demagnetization refrigerators (ADRs). After the introduction of dilution refrigerators, they gradually replaced ADRs for ground-based applications. However, since adiabatic demagnetization cooling is a form of solid-state refrigeration and is not affected by microgravity in space, ADRs remain the mainstream method for achieving extremely low temperatures in space. To date, several astronomical observation satellites equipped with adiabatic demagnetization refrigerators (ADRs) have been successfully launched internationally. Notable examples include Suzaku, launched in 2005[2], Astro-H, launched in 2016[3], and XRISM, launched in 2023[4]

In this paper, we describe the design of an adiabatic demagnetization refrigeration experimental system capable of cooling from room temperature to sub-Kelvin temperatures and present the latest experimental progress.

2. Cryogenic system design

The schematic diagram of the cryogenic system is in Figure 1. The two-stage GM cryocooler provides a 4 K environment for the system. This configuration ensures that the low-temperature superconducting (LTS) magnet in the ADR remains in normal operating condition. The precooling stage of the ADR is provided by a superfluid helium bath, which can reach a minimum temperature of 1.1K. Compared to the previous version of the experimental system, a corrugated pipe is now used to connect the GM refrigerator and the 300K cold plate, the first and the second stage cold heads of the GM refrigerator are connected to the 40K and 4K cold plates using copper braided thermal straps. The advantage of this approach is that it can reduce the impact of vibrations on the experimental results.

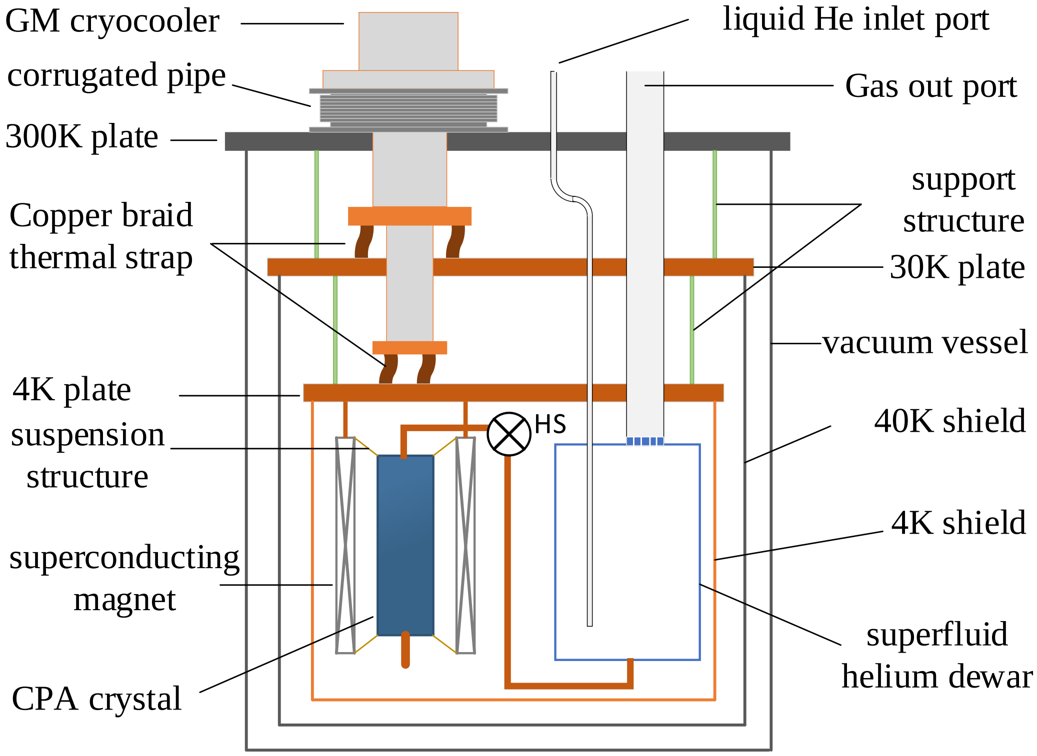

Figure 1. Schematic diagram of the cryogenic system.

2.1Precooling stage

This system uses a 1.1K superfluid helium bath to precool the ADR. At 2.17K, He-4 undergoes a phase transition from its normal state to a superfluid state. In its superfluid state, He-4 can form a thin film on surfaces and climb against gravity, a phenomenon known as the superfluid helium film creep effect. If this effect is not suppressed, the cooling performance achieved by reduced-pressure evaporation will significantly decline. An orifice plate structure or a knife-edge structure is typically used to suppress the superfluid helium film creep effect. Figures 2(a) and (b) show the actual designs of the orifice plate structure and the knife-edge structure, respectively. Through experiments, we found that among the two structures we designed, the orifice plate structure demonstrated better suppression of the superfluid helium film creep effect. With the orifice plate structure, the liquid pool can easily maintain a temperature as low as 1.1K, with the climbing film heat leak controlled within 3mW. Therefore, the designed superfluid helium liquid pool ultimately adopted the perforated plate structure to suppress the climbing film effect.

(a) (b)

Figure 2. Design options to prevent film creep effect. (a)Orifice plate structure (b)Knife-edge structure

In addition to the superfluid helium precooling method, we are also exploring the use of throttling refrigerators and adsorption refrigerators to precool the ADR. Using our lab's 4He JT cryocooler[5], the ADR can be precooled to around 4K. Employing the 3He JT cryocooler[6] and 4He sorption cooler[7], the ADR can be precooled to approximately 1K. Experiments using different precooling methods will be conducted in the future.

Compared to the previous system, the most significant improvement in this system is the vibration optimization. The GM refrigerator is connected to the vacuum cover by a corrugated pipe with a wall thickness of only 0.12 mm, providing good vibration-damping performance. The cold head and the cold plate are connected by copper braid thermal straps that we welded ourselves. These copper braids have a diameter of 4 mm, with each thermal strap consisting of two copper braids and both ends soldered to copper lugs. Twelve thermal straps are used between the 40K cold head and the cold plate, and six thermal straps are used between the 4K cold head and the cold plate. However, in the system before vibration optimization, the connections between the refrigerator and the various cold plates were rigid.

2.2 ADR stage

The ADR mainly consists of salt pills, superconducting magnets, magnetic shielding, heat switches, and suspension structures. Figure 3 shows the 3D model of the designed ADR. The salt pill is composed of a paramagnetic material and a thermal bus. This ADR uses CPA as the paramagnetic material, which has a magnetic ordering temperature as low as 9 mK[8] and is one of the most commonly used paramagnetic materials. The thermal bus consists of hundreds of oxygen-free copper wires that pass parallel through two perforated titanium alloy plates, with the number of holes matching the number of copper wires. The wires are then welded to two oxygen-free copper connectors. Its function is to enhance the heat exchange of the CPA. The superconducting magnet is wound from NbTi wire, and the magnetic shielding is made of pure iron. The suspension structure is made of high-strength, low-thermal-conductivity Kevlar wires.

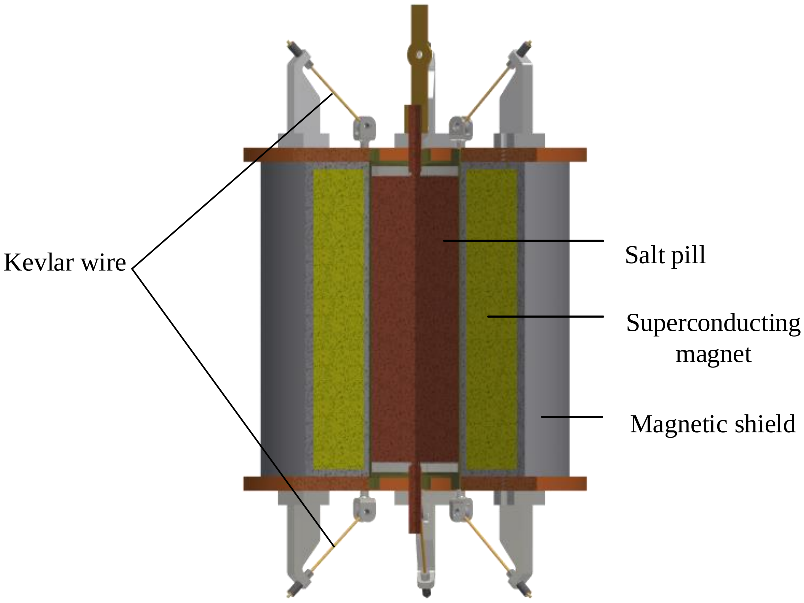

Figure 3. 3D model of the ADR.

3. Experiments

3.1 Operating Procedure

After the experimental system is set up, a mechanical pump and a molecular pump are first used to evacuate the system. When the system vacuum is less than 10^-3 Pa, the GM cryocooler is turned on. After a period of cooling, the first and second stages of the GM cryocooler will reach temperatures of approximately 40K and 4K, respectively. Then, liquid helium will be introduced into the superfluid helium bath, and an Agilent TS-600 dry pump will be used to reduce the pressure of the bath. The superfluid helium bath can ultimately reach 1.1K. During this process, the heat switch remains closed, so the temperature of the CPA crystal decreases along with the bath temperature. Due to some conductive heat leakage between the bath and the crystal, the final precooling temperature of the crystal stabilizes at 1.15K. Next, a power supply is used to energize the superconducting coil to provide a magnetic field for the CPA crystal. During the application of the magnetic field, the crystal will generate magnetization heat, which the superfluid helium bath will carry away. The temperature of the CPA crystal will rise slightly during this process. After the target magnetic field is reached, the CPA crystal gradually cools back down to 1.15K. Finally, the heat switch is disconnected and uniformly reduce the magnetic field to 0T, causing the temperature of the CPA crystal to decrease from 1.15K gradually.

3.2 Results

In this experiment, all temperature measurement points use diodes and ruthenium oxide thermometers from Lakeshore. Temperatures are collected using Lakeshore models 218, 336, and 372 temperature controllers. The maximum magnetic field applied in the experiment is 2T, and the initial temperature during demagnetization is 1.15K. Figure 4 shows the temperature changes of the CPA during magnetization and demagnetization. After demagnetization, the CPA crystal can be cooled to a minimum of 73.58mK. The lowest temperature has significantly decreased from the previous 318.5mK[9].

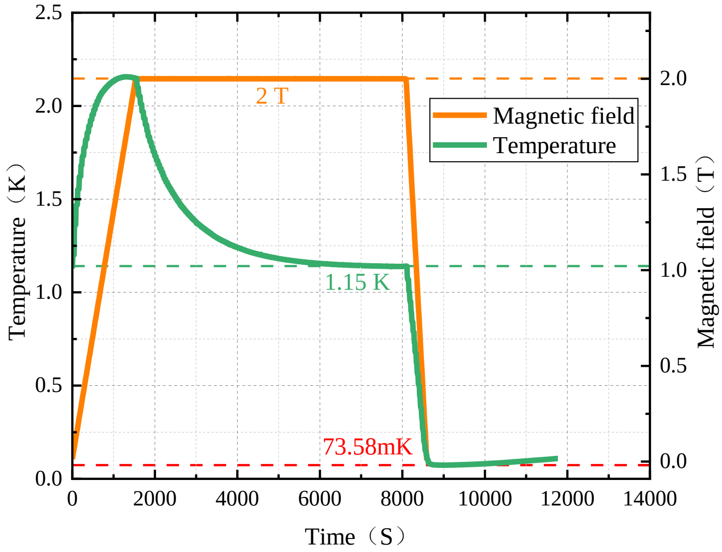

Figure 4. Temperature changes of the CPA during magnetization and demagnetization.

After complete demagnetization, the temperature retention of the CPA in an adiabatic state was observed and compared with previous experimental results. Figure 5 shows the temperature variation of the CPA crystal in an adiabatic state after complete demagnetization in this experiment, compared to the last experiment before vibration optimization. From the figure, it can be seen that after vibration optimization of the experimental system, the temperature rise rate of the CPA crystal significantly decreased. Within about 20000 seconds, the temperature reached 4.2 K before optimization, while after optimization, it was only 0.31 K. Estimates indicate that heat leakage due to vibrations has been reduced by at least 30 μW.

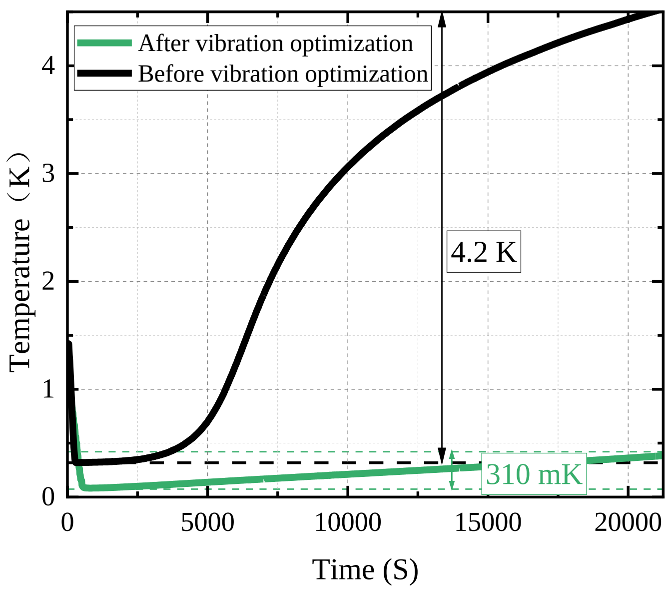

Figure 5. CPA temperature changes with time after the end of the demagnetization.

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4. Conclusion

This paper mainly introduces the design and construction of an experimental refrigeration system with a single-stage adiabatic demagnetization. In the precooling stage, two different structures for suppressing superfluid helium film creep were tested. Based on our previous experiments, the system was vibrationally optimized, including replacing the thermal connection between the cold head and the cold plate with a flexible connection and using a corrugated pipe to connect the cryocooler and the vacuum hood. After vibration optimization, under conditions of a 2 T initial magnetic field and 1.15 K initial temperature, the CPA can obtain a minimum temperature of 73.58 mK, a significant reduction compared to previous experimental results.

Additionally, the temperature rise rate in the adiabatic state after demagnetization also decreased significantly, which indicates a substantial reduction in the system's vibrational heat leakage and highlights the significant impact of vibration on this experiment. Current estimations suggest that the system's heat leakage is still above 10 μW. Further optimization of the system is planned, focusing on the heat switch and thermometer leads, in addition to addressing vibration, to further enhance the performance of this ADR.

5References

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