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Conceptual design of key components for a single-shot dilution refrigerator (DR) with small helium-3 Inventory assisted by adiabatic demagnetization refrigerator (ADR)

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Abstract. This study presents the design and single-cycle experimental results of an integrated cryogenic system aimed at achieving 0.1 K operation while minimizing helium-3 usage. The system integrates a commercial Gifford-McMahon (GM) cryocooler, a custom-built sorption cooler, and an adiabatic demagnetization refrigerator (ADR), and is intended to be combined with a single-shot dilution refrigerator (DR). This experiment was conducted to establish a baseline configuration for comparison with all subsequent improvements, focusing solely on evaluating the precooling performance of the ADR system with the added DR components. The ADR cycle experiments showed that the DR components were cooled to approximately 3.6 K, but quickly reheated due to significant heat ingress. Additionally, the experiments revealed critical technical limitations: the insufficient cooling power of the GM cryocooler, lack of a radiation shield at 4 K, eddy current heating (ECH), and degradation of the tin-based heat switch after repeated thermal cycling. If these challenges can be resolved, the ADR-based approach is expected to enable stable sub-Kelvin operation down to 0.7 K in compact DR systems for a future cold-cycle.

1. Introduction

Sub-Kelvin temperatures below 0.1 K are essential for superconducting devices, quantum computing, and low-temperature physics research. To achieve these temperatures, DRs are commonly used. However, the precooling stage of commercial DRs requires complex heat exchangers, which are difficult to design and fabricate, bulky, and expensive. In addition, the high cost and scarcity of helium-3 make it essential to develop cooling approaches that can still achieve 0.1 K operation while minimizing helium-3 usage. Furthermore, achieving the necessary precooling condition down to around 0.7 K often encounters significant structural and thermodynamic bottlenecks [1].

To overcome these limitations, this study proposes the use of an ADR as the precooling stage for a cold cycle DR. The ADR, which uses solid paramagnetic refrigerants, is free of moving fluids and offers a simple and compact design well-suited for high-precision environments [2]. In this paper, we present the design of an integrated system that combines a commercially available GM

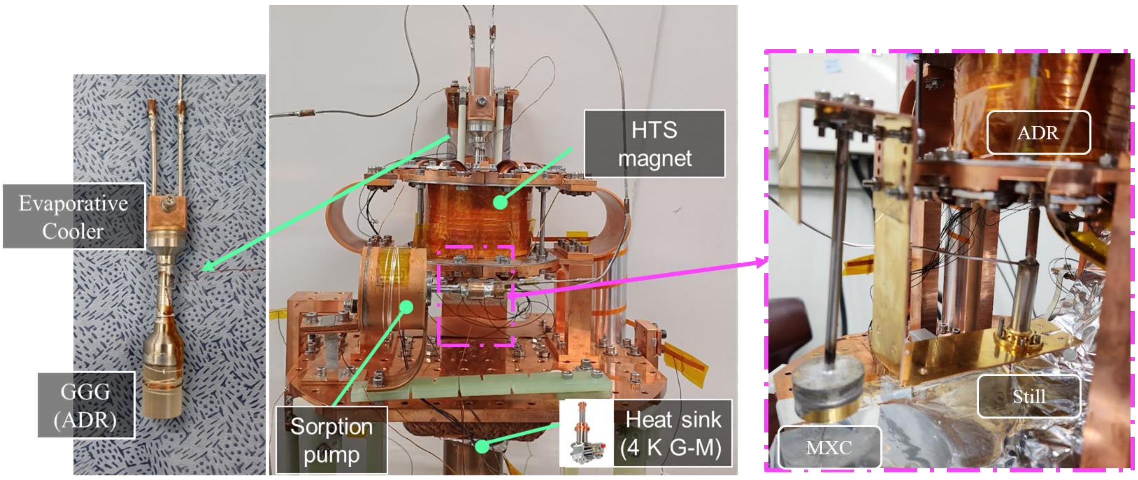

Figure 1. Images of the ADR system and DR components with labels

cryocooler with a custom-designed sorption cooler, ADR, and DR components, as well as the results of single-cycle experiments. We experimentally demonstrate the feasibility of using the ADR both alone and as the precooling stage for cold cycle DR operation, aiming to achieve reliable sub-Kelvin performance in compact configurations.

Figure 1 shows an image of the ADR system and the DR components with labels. The commercial GM cryocooler serves as the heat sink, while the sorption pump is used for evaporative cooling [3]. A high-temperature superconducting magnet enables ADR operation, and below the GGG (gadolinium gallium garnet, Gd3Ga5O12), DR components such as the mixing chamber (MXC) and still are attached. We have previously demonstrated that the ADR alone can reach 0.3 ~ 0.5 K [4].

A single-shot dilution refrigerator (SDR) operates by using the phase separation of a helium-3/helium-4 mixture at temperatures below 0.85 K. In this system, helium-3 atoms move from the MXC to the still, absorbing heat and enabling cooling in the MXC. The Still is connected to the MXC via capillaries and distills helium-3 vapor, providing the driving force for the intended movement of helium-3 in the SDR. This process traditionally relies on large-scale helium-3 circulation systems, but integrating it with ADR-based precooling enables a more compact configuration.

2. System design

2.1 Conceptual System Design

The ultimate goal of this study is to implement a compact, integrated cryogenic system capable of reaching 0.1 K while minimizing helium-3 consumption. To this end, a commercially available GM (RDK 415D Sumitomo) cryocooler was used as the heat sink, and a developed sorption cooler and an ADR were integrated into a single system, which was intended to be combined with a single-shot DR to achieve sub-Kelvin operation. The ADR repeatedly undergoes cycles of magnetization, evaporative cooling, and demagnetization, aiming to precool the DR components to approximately the DR operating temperature of 0.7 K or below. This design aims to achieve stable sub-Kelvin operation with minimal helium-3 inventory, even in a simplified configuration. The cooling cycle is as shown in Figure 2, and the description is provided below.

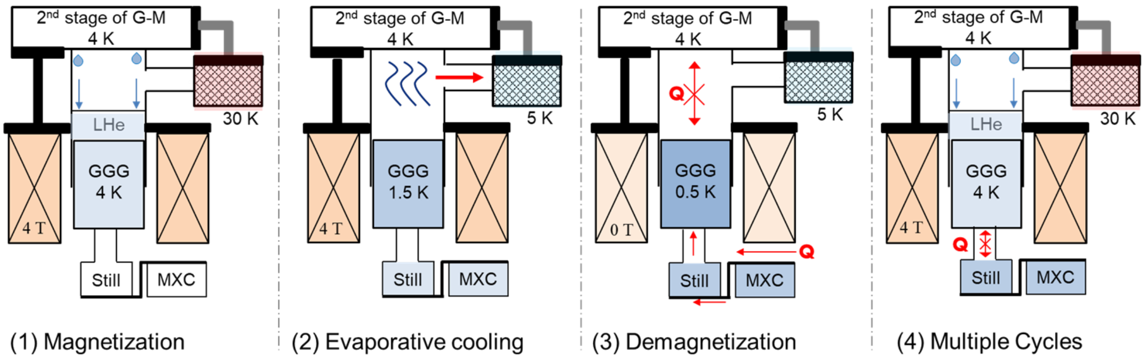

Figure 2. Process of ADR precooling cycle for DR components

2.2 Cooling cycle

- Step 1: The temperature of the sorption pump is set to 30 K, and helium is liquefied at the heat sink, bringing the entire system down to 4 K. At this stage, the superconducting magnet is magnetized to 4 T.
- Step 2: Using a passive heat switch, the temperature of the sorption pump is lowered to 5 K. This triggers adsorption, causing the liquid helium above the GGG to evaporate and cool the GGG.
- Step 3: Once the liquid helium has sufficiently evaporated, the superconducting magnet is demagnetized to provide additional cooling. Previous experiments have demonstrated that the ADR alone can cool the GGG down to 0.5 K. The GGG cooled to 0.5 K performs heat pumping for the DR components.
- Step 4: These steps are repeated from step 1 until the DR components reach the target temperature. In this process, thermosiphon acting as a heat switch is applied to enable heat pumping through multiple cycles.

2.3 Baseline Configuration for DR Precooling

However, in this experiment, the DR components were added to the previously developed ADR system solely to establish a baseline for comparison. The DR components were not operated in this experiment; only the precooling temperature was evaluated. Although the need for radiation shielding and ECH shielding is evident, they were intentionally omitted to verify the baseline configuration. This approach aims to establish a baseline for comparison with all subsequent improvements, including the radiation shield, ECH shielding, and other enhancements.

3. Experiment

3.1 Measurement Locations of Each Sensor

Figure 3 shows the measurement locations and labels of each sensor, with the colors corresponding to those used in the plots presented later. T_{MXC} and T_{Still} represent the temperatures of the DR components, which are the target of the cooling. $T_{condenser}$ indicates the temperature at the actual liquefaction point above the GGG. T_{GM2nd} allows for estimating the cooling power provided by the commercial GM cryocooler. T_{SP} is the temperature of the sorption pump used for evaporative cooling. It is connected to the GM 2nd stage and a passive heat switch made of tin (Sn).

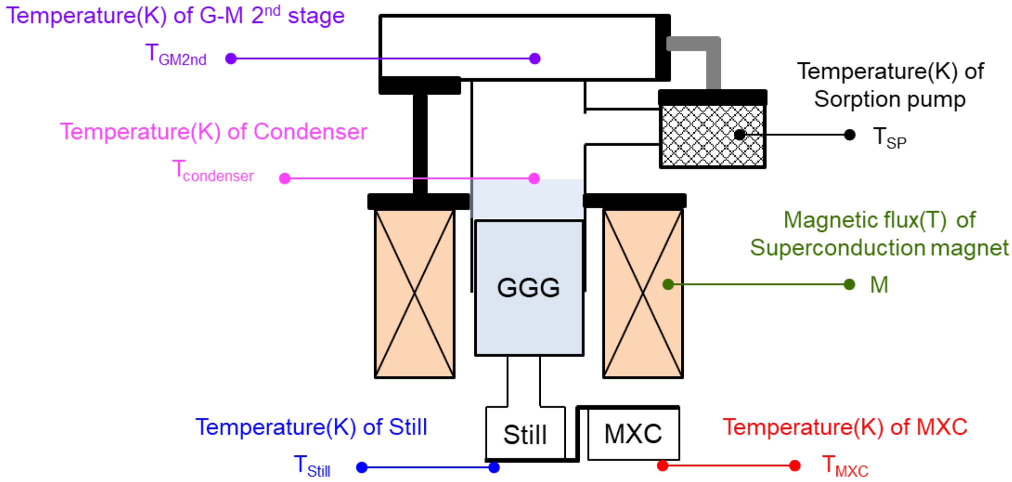

Figure 3. Schematic of the system and sensor locations with labels. The colors and abbreviations of the labels correspond to those used in Figure 4.

When the heater is turned off after maintaining 30 K or 13 K, it drops to 5 K, causing the liquid helium to evaporate and cool the GGG. Finally, the HTS magnetic flux density of the superconducting magnet is monitored, which is magnetized up to 4 T and then demagnetized to cool the GGG. The pressure at each location was monitored only via display and no data were collected.

3.2 Experiments

This section aims to verify whether the ADR cycle operates normally when the DR components are added. Specifically, it examines the applicability of the existing ADR cycle, the accumulation of liquid helium on the GGG and still bottom, the impact of demagnetization time on ECH, and the identification of experimental limitations. To this end, five experiments were conducted under the following conditions:

- (Case 1) T_{SP} was cooled from 13 K to 5 K, followed by dt 3s demagnetization
- (Case 2) T_{SP} was cooled from 13 K to 5 K, followed by dt 400s demagnetization
- (Case 3) T_{SP} was cooled from 30 K to 5 K, followed by dt 3s demagnetization
- (Case 4) T_{SP} was cooled from 30 K to 5 K, followed by dt 400s demagnetization
- (Case 5) T_{SP} was cooled from 30 K to 5 K, followed by dt 200s demagnetization

In cases 1 and 2, the T_{SP} started from 13 K instead of 30 K due to the condenser temperature. While the condenser temperature in the previous ADR system was 4.3 K, it exceeded 5.2 K(4He critical temperature : 5.19 K) when the DR components were added under the same conditions. To reduce heat ingress into the heat sink, the temperature of the sorption pump was lowered, and only when T_{SP} was reduced to 13 K did the condenser temperature converge to around 5.1 K, enabling liquefaction.

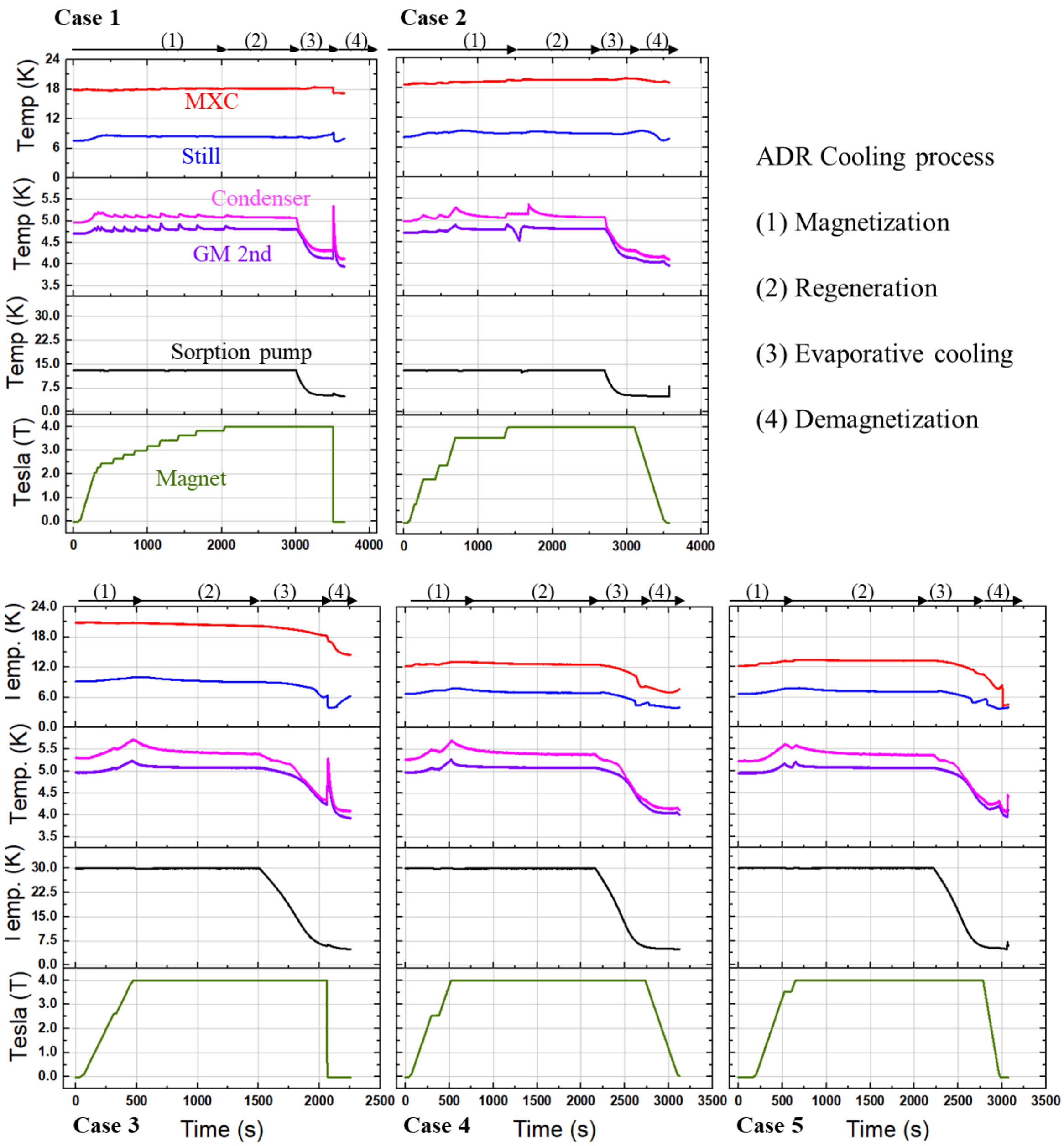

Figure 4. Experimental plots of Cases 1–5 in the ADR cooling cycle with DR components added

3.2.1 Case 1

Figure 4 shows the experimental data. The initial magnetization process took a long time due to large AC losses. The experimental cycle consisted of (1)magnetization, (2)regeneration, (3)evaporative cooling, and (4)demagnetization. It was originally expected that the GM cryocooler alone would be sufficient to liquefy helium at the still bottom, but this was not achievable because the condenser temperature was too high, and the still bottom temperature did not converge to the liquefaction point during the regeneration time. In addition, attempts at evaporative cooling with the sorption pump only lowered the temperatures of the GM and the condenser, while the demagnetization step caused ECH, resulting in an almost negligible temperature change. The

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lowest temperature reached was 5.32 K, which was insufficient to liquefy helium in the DR components.

3.2.2 Case 2

The same basic method was used, but to reduce ECH, the dt(demagnetization time) parameter for demagnetization $(dB/dt)^2$ was increased to 400 seconds. However, this approach resulted in virtually no cooling or heating, and no meaningful temperature change was observed. While the temperatures of the GM 2nd stage and condenser indicated that the influence of ECH was greatly reduced, the actual cooling effect from demagnetization was also negligible. This suggests that the absence of cooling was not due to the lack of demagnetization cooling itself, but rather because in a system with large heat ingress, a longer dt causes the temperature to return to the thermal equilibrium point faster than it can be cooled. This highlights the necessity of radiation shielding to reduce heat ingress.

3.2.3 Case 3

The approaches in Cases 1 and 2, which attempted to remove latent heat of liquefaction through the heat sink, were effectively unsuccessful. As a result, we adopted a cooling approach by lowering the temperature of the sorption pump from 30 K to 5 K. Although minimal, a slight decrease in the still temperature was observed as the sorption pump temperature was reduced. During the subsequent demagnetization process, cooling of the still and MXC was observed, but the still temperature quickly returned to its original thermal equilibrium point. Additionally, under the dt=3 s condition, heating due to ECH was also evident.

3.2.4 Case 4

One notable aspect is that this experiment was performed after Case 3, meaning that the thermal equilibrium temperatures of the MXC and Still had already decreased slightly compared to the initial conditions. While Cases 1 and 2 had no meaningful cooling effect and thus were effectively independent, Case 3 produced some degree of cooling in the DR components, allowing Case 4 to start from a slightly lower initial temperature. The experiment followed the same approach as in Case 3 but increased the dt to 400 seconds. As a result, the influence of ECH was significantly reduced; however, due to the long demagnetization time in a system with large heat ingress, the cooling capacity was still not enough.

3.2.5 Case 5

In this case, dt was reduced to 200 seconds in an attempt to minimize heating by heat ingress even if some influence by ECH remained. Case 5 started from the initial conditions that were similar to those in Case 4. Due to the shorter dt, some heating of the GM 2nd stage and condenser was observed by ECH. Nevertheless, both the still and the MXC were cooled, resulting in the best cooling performance among the five cases. However, subsequent repeated cycles under the same conditions did not achieve lower temperatures, and during the hold period, the still temperature returned to approximately 7 K while the MXC temperature returned to around 13 K. This indicates that, despite the cooling capability of the ADR, the system ultimately converged to certain thermal equilibrium temperatures due to heat ingress.

3.3 Key findings from ADR precooling experiments

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Table 1 shows a summary of the experimental results. In these experiments, starting with a low TSP to overcome the latent heat of liquefaction resulted in insufficient sorption cooling and negligible net cooling effects. Although increasing the demagnetization time (dt) successfully reduced ECH, it ultimately allowed more heat ingress, suggesting that an optimal dt rather than an indefinitely long one is essential. Through repeated cooling cycles and improvements in operational know-how, the temperatures of TSTill and TMXC gradually decreased; however, they ultimately converged to a certain temperature around case 5, and further cycles did not achieve lower temperatures. These results indicate that to successfully integrate DR components with the ADR system, additional measures are needed to overcome these limitations. Therefore, in this experimental setup, additional measures such as radiation shield, ECH shield, and optimization of dt are essential.

Table 1. Summary of experimental results

Case	Independent variables		Dependent variables	
	T_{SP} (K)	dt (s)	Min T_{Still} (K)	Min T_{MXC} (K)
1	13	3	6.32	17.1
2	13	400	6.56	18.6
3	30	3	3.85	14.4
4	30	400	3.93	6.97
5	30	200	3.64	4.20

4. Discussion

The lowest temperature we achieved in the experiments was approximately 3.6 K for the still and 4.2 K for the MXC. The previously developed integrated ADR system continued to operate stably over multiple cycles. However, several issues that need to be addressed were identified in these experiments.

- **Insufficient cooling power of the GM cryocooler :** When the DR components were added under the same conditions, the cooling power of the GM cryocooler became insufficient, causing the condenser temperature to exceed 5.2 K. This indicates that not only were additional components added, but also the overall heat ingress increased. The difference in heat ingress, known from the specifications of the commercial GM cryocooler, between the previous ADR system[4] and the current system with DR components is approximately 0.5 W. However, increasing the cooling power of a commercial GM cryocooler is challenging, so alternative solutions must be needed.
- **Need for additional radiation shielding :** In the current system, the radiation shield with MLI enclosing both the ADR and DR components is attached to the GM 1st stage (=45 K). In the previous system [4], this arrangement was sufficient because the GGG was located within the magnet. However, in the present experimental apparatus, the DR components were directly exposed to radiation from the 45 K radiation shield. Adding a radiation shield for the GM 2nd stage (=4 K) could promise better cooling performance.
- **Need to suppress ECH :** The main material of the DR components is copper, which is susceptible to ECH. Although adjusting the dt is an effective strategy, it is not sufficient. An ECH shield would allow for better cooling performance.

- **Reliability issues with the tin heat switch :** Tin-based passive heat switches often require frequent replacement or experience failures due to the tin pest phenomenon, which means tin degrades at low temperatures.

If these challenges can be addressed, it is expected that the developed ADR system alone will be capable of reaching the target temperature of 0.7 K required for operating the DR.

5. Conclusions

In this study, we proposed an integrated cryogenic system designed to reach 0.1 K while minimizing helium-3 usage. The system combines a sorption-integrated ADR and a single-shot DR. The ADR cycle—consisting of magnetization, evaporative cooling, and demagnetization—was successfully operated in repeated cycles.

While the ADR cycle operated stably, the system failed to reach the target temperature of 0.7 K due to the following three key limitations:

1. Insufficient cooling power of the GM cryocooler : The thermal capacity of the overall system exceeded the available cooling power, resulting in slow cooldown of the ADR and DR components.
2. Excessive heat ingress: Based on the temperature increase at the GM cryocooler 2nd stage, we inferred that the heat ingress increased by approximately 0.5 W, likely due to thermal radiation and ECH. Or, there may have been unexpected parasitic heat transfer, such as molecular conduction or heat leakage through piping.
3. Degradation of the tin-based heat switch : Although initially functional, the heat switch exhibited signs of performance degradation after repeated thermal cycling.

The proposed configuration demonstrated the functional feasibility of applying a CADR-based precooling approach to compact DR systems. However, the three limitations identified above remain critical barriers to achieving stable sub-Kelvin operation. Future work will focus on improving radiation shielding, implementing measures to suppress ECH, and enhancing the reliability of the heat switch. These improvements are expected to support further development toward a tandem or continuous cold-cycle dilution refrigerator architecture.

Acknowledgments

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References

[1] Kim, P. H., Hirschel, M., Suranyi, J., & Davis, J. P. (2025). A continuously-cooled 3He/4He phase separation refrigerator. arXiv preprint arXiv:2503.10754.
[2] Jahromi, A. E., & Shirron, P. J. (2023). Compact and efficient continuous adiabatic demagnetization refrigerator for line emission mapper. Journal of Astronomical Telescopes, Instruments, and Systems, 9(4), 041003-041003.
[3] Bae, J. H., Kim, K. J., & Jeong, S. (2019). The design of sorption compressor and heat exchanger for the 5 K cryogenic sorption JT refrigerator. In The 6th International Conference of Saving Energy in Refrigeration and Air-Conditioning. The Society of Air-Conditioning and Refrigeration Engineers of Korea.
[4] Kwon, D., Bae, J., & Jeong, S. (2024). Development of the sorption-integrated adiabatic demagnetization refrigerator (ADR) without active heat switches. Cryogenics, 137, 103777.