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Experimental investigation of compact 2 K GM cryocoolers

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Abstract

On the basis of a conventional 4 K Gifford-McMahon (GM) cryocooler, we developed a new 2 K GM crycooler, which can provide considerable cooling capacity and yet being highly compact in physical size. A series of experiments were conducted to confirm and show the cooling characteristic and cooling capability of this new cryocooler. Under no-load condition, the lowest temperature reached about 2.1 K on the second stage and the temperature oscillation displacement was less than ±20 mK. Even under a thermal-load of 1 W / 20 mW, temperature reached 44.4 K on the first stage and 2.23 K on the second stage. Detailed cooling load-map and cool-down curve will also be introduced in this paper.

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Keywords: Temperature oscillation; Gifford-McMahon cryocooler; cryocooler; cryogenics

1. Introduction

Cryocoolers have been widely used for superconductor cooling in various applications and research projects including MRI (magnetic resonance imaging), superconducting electric power transmission, and superconducting electric motor, space infrared telescope, etc. (Hasse et al. (2014), Green et al. (2008)). While high power, high efficiency cryocoolers still remain of a great importance in large-scale applications, compact designed cryocoolers increasingly gain attention due to the rapid growth of research and development of superconducting electronic devices (Olson et al. (2014)).

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1.1. Background

Superconductors have several unique properties compared to normal conductors under the superconducting phase transition temperature, for instance, zero electrical DC resistance, Meissner effect and London moment effect. Since those properties are crucial to superconducting electronic devices, cryocoolers with high reliability and adequate bottom temperature (below 2.3 K) are needed. A good example of superconducting electronic devices is Superconducting Single Photon Detector (SSPD) project which is now under development at National Institute of Information and Communications Technology, Japan. (Miki et al. (2012)).

On the other hand, compact, high-reliability cryocoolers with low bottom-temperature are in short supply in spite of existence of several outstanding products such as the RDK-101D GM cryocooler provided by Sumitomo Heavy Industries, Ltd. (SHI). To provide a cooling solution which can meet the new demand by such applications, we developed a new 2 K GM cryocooler system which can reach the temperature of 2.10 K under no-load condition and yet being highly compact in physical size.

1.2. Design target

We chose the RDK-101D as our development base since it has been the smallest 4K GM cryocooler in the world. Thus, this cryocooler would be a good starting point for further improvement. The basic specification of RDK-101D and design target for the new 2 K GM cryocooler is shown in Table 1 below.

Table 1. Design target of current development.

Item	RDK-101D	Development Object
First stage cooling capacity at 60 K	3 W	1 W
Second stage cooling capacity at 2.3 K	Unreachable	20 mW
No-load second stage temperature	Over 3 K	2.2 K
Total height of expander	442 mm	67% of RDK-101D
Temperature oscillation displacement	Over ±30 mK	±20 mK

Considering the targeted cooling application, we set the design temperature targets of the first and the second stages under 1 W and 20 mW of thermal load to be 60 and 2.3 K, respectively. The most challenging objective is to reduce the total height of the expander to 67% compared to the existing RDK-101D GM cryocooler. The details on the approaches for reduction of the total height of the expander will be reported in another paper at this conference by Xu et al. (2014). The temperature oscillation displacement is designed to be under ±20 mK. The latter is, in fact, a natural side-effect of low bottom temperature and will be discussed in the result section of this paper. While the development is still in progress, the prototype unit was used to show the cooling capacity in our recent development. Fig.1 shows the cylinder of a prototype unit compared with that of the RDK-101D GM cryocooler.

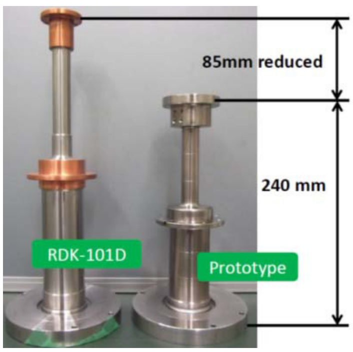

Fig. 1. Cylinders comparison of the prototype unit and a RDK-101D GM cryocooler.

2. Experiment setup

The GM cryocooler system which has been studied in this paper is similar to a normal GM cryocooler and thus consists of a compressor and an expander. As described in the previous section, all the experiments in present study were conducted based on the prototype unit which is still under development and which is shown in Fig.1. As for the compressor, an SHI CNA-11B air-cooled helium compressor was used for the test. The system, including the compressor and the expander, was filled by helium gas up to 2.06 MPa at 293K. Power supply for the compressor is 100V/50Hz AC and the cold-head operating frequency is 1 Hz.

2.1. Experiment apparatus

As shown in Fig. 2, the whole cylinder was set in a vacuum vessel in order to reduce the heat penetration from the environment. In addition, the second stage was covered by a radiation shield in order to reduce the heat radiation.

2.2. Temperature monitoring

To show the cooling capacity of this prototype cryocooler, temperature on the heat flanges of the first and the second stages were measured by a PtCO senor (Chino) and a Cernox (cx-1050) temperature sensor (Lakeshore) respectively. As we will describe in the next section, temperature oscillation on the second stage heat flange was also measured by the Cernox sensor.

3. Experiment results and discussion

All the experiments performed in present study were operated in a similar way:

- 1. Start operation from room temperature;
- 2. Leave the cryocooler untouched until temperature on heat flange stabilized;
- 3. Apply thermal load to heat flange by resistor heater.

We repeated step 2 and 3 and achieved detailed load-map for the present prototype system.

3.1. Cool-down process

Fig. 3 shows the cool-down process of the first stage and the second stage heat flanges from room temperature. Under no-load condition, the cool-down process took about 3 hours. In that time, the temperature of the first and the second stages reached 39.5 and 2.10 K respectively. At the inlet of the rotary valve, the high and low pressure at steady state was about 2.45 and 0.8 MPa, respectively.

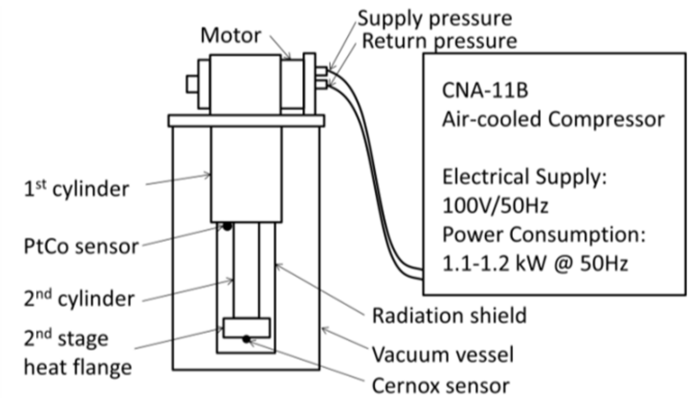

Fig. 2. Schematic drawings of the experiment apparatus.

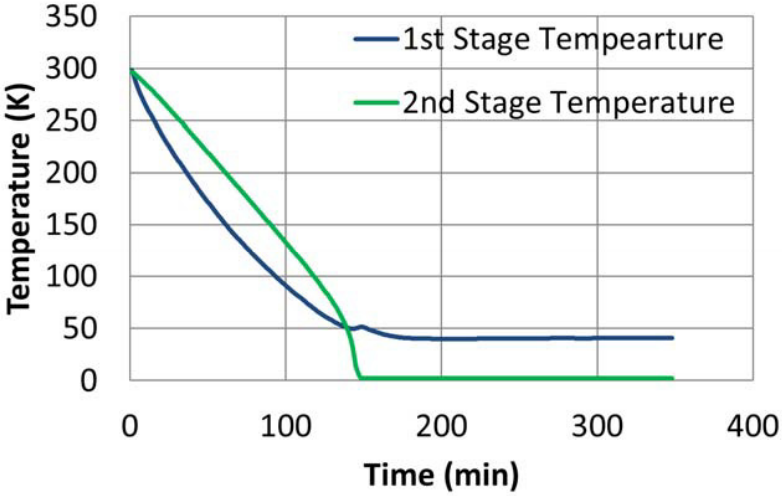

Fig. 3. Cool-down curves of the first and the second stage.

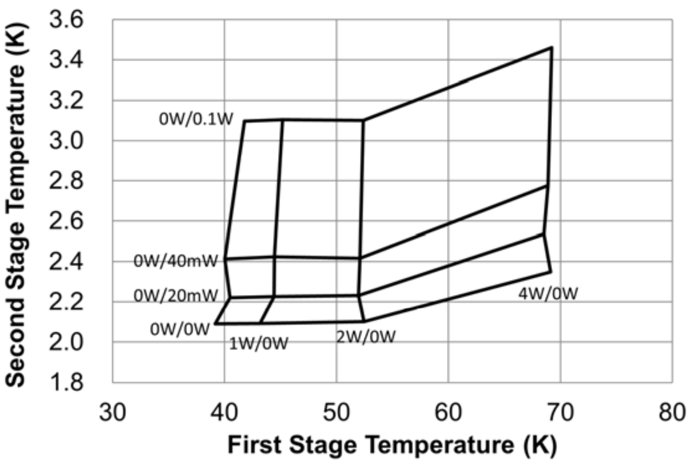

Fig. 4. Load-map of a prototype unit of the 2K GM cryocooler.

3.2. Load-map

To show the cooling capability of the current prototype cryocooler, we applied a variable thermal load. The load was varied from 0 W (no-load) to 0.1 W for the second stage and from 0 W to 4 W for the first stage. The temperature of each stage was measured for each applied load. Fig. 4 shows a typical load map of a prototype unit. Under no-load condition, temperature reached 2.09 K on the second stage and below 40 K on the first stage. And also, it is noticed that in most conditions, the temperature on the second stage flange could be kept below 3 K. Thus, we believe that the current prototype cryocooler has sufficient cooling capability and can meet a wide range of superconducting electronic devices cooling requirements.

The power consumption of the compressor was also measured simultaneously with the load-map measurement. At no-load condition the power consumption was 1.09 kW and at 1 W / 20 mW condition, the power consumption was almost the same. There was only slight increase with a thermal load of 4 W for first stage and the power consumption was 1.13 kW at 4 W / 0.1W.

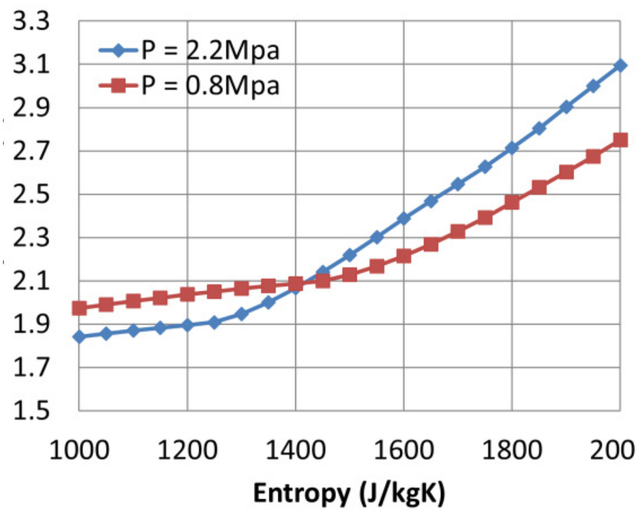

Fig. 5. Helium gas properties.

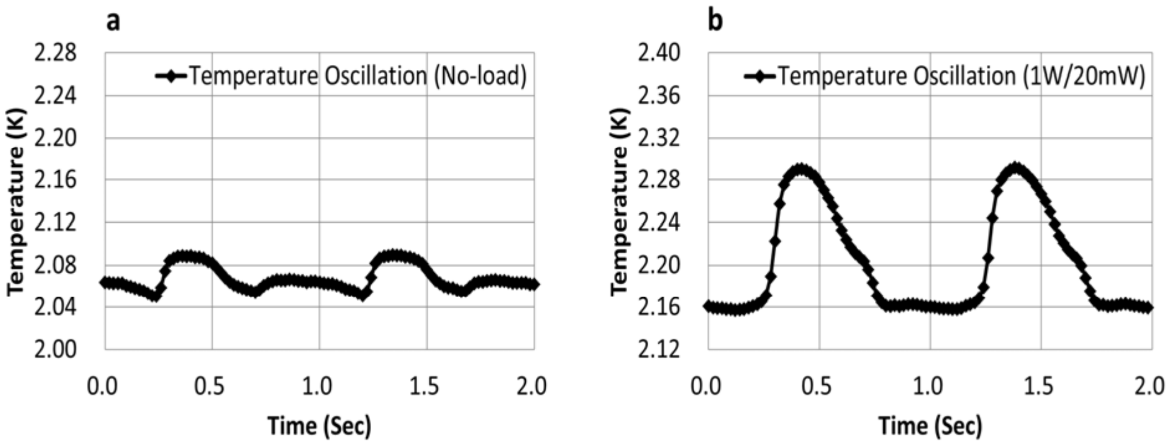

Fig. 6. Temperature oscillation on the second stage heat flange. (a) No-load; (b) 1 W / 20 mW.

3.3. Temperature oscillation

Due to the expansion and compression of helium gas inside the GM cryocooler cylinder, temperature of the second stage is actually oscillating continuously during the operation. Fig. 6 shows that temperature oscillation measured at a sampling rate of 50 Hz. By comparing the oscillation amplitude, it's obvious that oscillation became stronger under a relatively high thermal-load condition. The main reason for this phenomenon is rooted in the properties of helium gas and can be briefly described as follows:

The expansion process of helium gas inside the expansion volume can be referred to as an unsteady adiabatic expansion if the latter is assumed to be sufficiently fast. Furthermore, if the irreversibility is considered negligible, the gas properties inside the expansion volume should vary along the isentropic line, shown in Fig. 5. Since near the lambda point (about 2.05 K at 0.9 MPa, which is the estimated low pressure inside the second stage expansion space), expansion from high pressure to low pressure almost results in no temperature drop, thus the temperature oscillation is suppressed as a natural result of this fact. By using this method, temperature oscillation amplitude could be easily estimated. The measured results of temperature oscillation amplitude were compared with this theoretical analysis results and it's found that the results were consistent with each other. A detailed discussion could be found in a related paper by Xu et al. (1999).

4. Conclusion

A new, compact GM cryocooler has been developed for small-scale cooling application which needs rather low cryogenic temperature, for example, superconducting electronic devices. Under no-load condition, low second stage temperature of 2.1 K and temperature oscillation displacement of less than ±20 mK have been achieved.

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