Recent development status of compact 2 K GM cryocoolers

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Abstract. To meet the growing demand for a compact cooling solution for superconducting electronic devices, we developed a two-stage 2 K GM cryocooler and a cryostat system, which can reach 46.3 K / 2.2 K on the first and second stages under no-load conditions. Nevertheless, with several innovative technologies applied, the total length of the expander cylinder is reduced to under 70% of the smallest conventional 4 K GM cryocooler. In this paper we will present the design method, including material selection and structure design with detailed explanation, which has been confirmed by both simulation and experiment.

1. Introduction

1.1. Background

As a reliable cooling solution providing cryogenic temperatures under 80 K, Gifford-McMahon(GM) cryocoolers have been widely used for the past 30 years in various applications. During the early stages of its development, the most notable application of GM cryocoolers was cooling charcoal adsorbers to about 15 K for cryopumps, which in turn provided an ultra-clean environment for semiconductor fabrication equipment. In the 1990s, rare earth material with high heat capacity in the 4 K region was developed and introduced to the regenerator of GM cryocoolers, which in turn made it possible for GM cryocoolers to achieve temperatures around 4 K [1]. The market for GM cryocoolers in MRI cooling applications was opened by this significant advancement and still remains one of its most active applications today.

Recently, the rapid development of superconducting electronic devices indicates a new, large, substantial market for cryocoolers because most of them need to be cooled down to cryogenic temperatures. Since, in most cases, noise level decreases with temperature, temperatures even lower than 4 K are desired for these devices or sensors [2]. Also, in contrast to large scale applications such as MRI’s or superconducting motors, a more compact size is desired to eventually achieve a reasonably-sized measurement system. In the hopes of filling this spot in the current market, we launched this development project in 2012. Among the various types of cryocoolers, multiple choices including GM, pulse tube, Joule-Thomson and Stirling-type cryocoolers were theoretically possible as a starting point of development. However, considering the cooling capacity and temperature requirement, Joule-Thomson and Stirling-type cryocoolers were not preferable at the 2 K temperature region. Also, pulse tube cryocoolers were not as
Table 1. Development target of a 2K GM cryocooler.

| Item                                         | RDK-101D | Design target |
|----------------------------------------------|----------|---------------|
| First stage cooling capacity at 60 K        | 3 W      | 1 W           |
| Second stage cooling capacity at 2.3 K      | Unreachable | 20 mW         |
| Total length of expander unit               | 442 mm   | under 295 mm  |
| Temperature oscillation displacement        | Over ±30 mK | ≤ ±20 mK     |

compact as GM cryocoolers because of their multiple tube configuration, so they were potentially less attractive from a development point of view. Since we already have design experience with small-size GM cryocoolers (SHI’s RDK-101D, which is the smallest commercially available 4K GM cryocooler), we decided to choose the RDK-101D as the starting point and fulfill the target by making further improvements. More details of the early work and concept design in this project can be found in reference [3].

1.2. Development target
As shown in table 1, the major improvement focus is on the second stage temperature and the total size of the expander. It is known that the measurement accuracy of the superconducting sensor, such as Superconducting Single Photon Detector (SSPD) system, increases greatly as the temperature decreases [2]. Meanwhile, the lowest temperature that can be reached by a GM-type cryocooler is around 2.05 K, since the lambda point is theoretically impossible to break [4]. Therefore, the design target was made to provide sufficient cooling power in that temperature region. It should be noted that the size reduction target is even more challenging because size reduction usually leads to deterioration in the regenerator performance which, in turn, greatly affects the cooling capacity. The temperature oscillation is set to be less than ±20 mK to ensure that it will not affect the performance of the superconducting sensor.

2. Simulation analysis of RDK-101D
2.1. Simulation model and conditions
As the first step in making a prototype unit, a simulation analysis was carried out to estimate the main loss in the current RDK-101D cryocooler. A schematic diagram of the RDK-101D is shown in figure 1.

The simulation method is based on the one-dimensional unsteady finite-volume method (FVM), coupled with helium property calculation subroutine provided by the National Institute of Standards and Technology (NIST). Typical mass conservation, momentum and energy conservation equations are discretized in time and space, being solved simultaneously until an overall conservation is reached in both time and space scale.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{U}) = 0 \tag{1}
\]

\[
\nabla p = F_r = -\frac{f_r}{d_h} \frac{\rho|\vec{U}|^2}{2 |\vec{U}|} \tag{2}
\]

\[
\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho \vec{U} h) + h_f(T - T_s) = 0 \tag{3}
\]

In these equations, \( \rho, U, p, h, \) and \( T \) are the density, velocity, pressure, enthalpy, and temperature of helium. \( f_r \) stands for the Darcy friction factor and \( d_h \) is the calculated hydraulic diameter for
Figure 1. Schematic diagram of a RDK-101D GM cryocooler.

Each area. $h_f$ is the heat transfer coefficient between helium gas and the regenerator material, with the following $T_s$ standing for the regenerator material’s temperature. The momentum equation is significantly simplified since the inertia term is negligible compared to the viscosity resistance in this situation. It should also be noted like most other cryocooler simulators, only the stable operation condition is considered. The details of this simulation method are described in reference [5].

For typical calculations, the cold-head is operated at 1.0 Hz, and the high and low pressures at the inlet of the rotary valve are 2.28 MPa and 0.89 MPa, respectively. The inner diameters of the first and second stage cylinders are 44 mm and 18 mm, respectively. The first stage regenerator is filled with #150 phosphorous bronze screens. The second stage regenerator is filled with lead and HoCu$_2$ spheres. The porosity of the second stage regenerator is assumed to be 0.3 for all calculations. The average sphere diameter is 0.44 mm for lead and 0.33 mm for HoCu$_2$.

Table 2 shows simulation results of the P-V power, the cooling capacity and the losses. The temperatures are assumed to be 45 K at the first stage and 4.2 K at the second stage. The compressor is operated at 50 Hz and the cold head is operated at 1.0 Hz. As shown in table 2, the P-V power is 17.5 W at the first stage and 3.27 W at the second stage. The cooling capacity after considering real gas effect is 17.2 W and 0.56 W, respectively. The cooling capacity after considering real gas effect at the second stage is significantly lower than P-V power because the properties of helium at the second stage are significantly different from those of an ideal gas.

For a GM cryocooler, the cooling power can be calculated as:

$$Q_c = \alpha_T \cdot T \int P dV$$  \hspace{1cm} (4)
Table 2. Simulation analysis result of a RDK-101D cryocooler.

| Item                                | First stage at 45 K (W) | Second stage at 4.2 K (W) |
|-------------------------------------|-------------------------|---------------------------|
| PV power                            | 17.5                    | 3.27                      |
| Cooling capacity after considering  | 17.2                    | 0.56                      |
| real gas effect                     |                         |                           |
| Regenerator loss                    | 3.5                     | 0.24                      |
| Shuttle loss                        | 1.8                     | 0.06                      |
| Pumping loss & thermal conduction   | 3.2                     | 0.20                      |
| loss through walls                  |                         |                           |
| Radiation loss                      | 1.5                     | 0.0                       |
| Net cooling capacity                | 7.1                     | 0.06                      |

can be simply calculated as:

\[ Q_c = \oint PdV \]  \hspace{1cm} (5)

However, near the 2 K region, \( \alpha_T \cdot T \) decreases significantly so the cooling power is much lower than \( Q_c = \oint PdV \). The detail of this effect can be found in [6]. Also it can be explained by the behavior of entropy property near 2 K of helium and has been verified by experiment results of early prototype unit in this work [7]. For both stages, the largest loss is due to the regenerator losses. In addition, unlike a large-size GM cryocooler, the thermal conduction loss and the radiation loss are relatively large and should be reduced in order to further improve the cooling capacity.

3. Critical technologies to improve cooling capacity

3.1. Regenerator materials

As a key component in a GM cryocooler, the regenerator should be carefully designed to meet the performance requirement. However, in this project, the length of the cylinder is limited to under 67% of the current product. Such a length reduction in the temperature gradient direction usually leads to severe deterioration in regenerator performance. To reconcile this problem, new materials were introduced to the second stage regenerator.

As shown in figure 2, the new compact designed second stage regenerator is slightly shorter than the original design and a new three-layer filling pattern was introduced. On the warm end...
end, bismuth was replaced by zinc, and on the cold end, a new ceramic magnetic material, Gd$_2$O$_2$S (GOS), was introduced. The heat capacity data of these new materials are shown in figure 3 and figure 4.

According to the design, the hot end temperature of the second stage regenerator is 15-35 K, where the heat capacity of bismuth is higher than that of zinc. In general, higher heat capacity material improves the regenerator’s performance, but in this case, we find that lower heat capacity helps to reduce the amount of helium gas trapped in the hot end region, which will actually improve the P-V power. To clarify this point, the temperature profile inside the second stage is extracted from past simulation of 4 K GM cryocoolers. All operating conditions were kept the same, except that the material property in the second stage regenerator hot end is switched between bismuth and zinc, respectively, to reveal the difference.

In figure 5, the temperature on the hot end became slightly higher in the case of zinc, presumably due to the lower heat capacity of zinc compared to bismuth. Therefore, the helium density in that region should in turn become lower, and as a result, more helium gas is pushed into the expansion space and more P-V power is obtained. This phenomenon is first explained by Xu, et al in a simulation analysis of 4 K GM cryocoolers [8].

As for the cold end, a ceramic magnetic material, GOS, is introduced to improve the performance near the 2 K region. From figure 4, the heat capacity of GOS is much higher than that of HoCu$_2$ in the 2 K region. Further information about GOS can be found in [9].

3.2. Thermal conduction reduction

As presented in the simulation analysis result, thermal conduction and pumping losses are important for small size GM cryocoolers because the ratio of them increases in compact designs. For a RDK-101D cryocooler, those two losses account for 40% of the first stage cooling power and over 300% for the second stage.

To reduce the thermal conduction loss, a new step-wise structure was introduced to the new prototype unit. For simplicity, only a schematic drawing of the first stage cylinder is shown in figure 6. The conduction heat flux from room temperature to the first stage (or from the first stage to the second stage) can be estimated by the simple thermal conduction equation at stable condition,
\[ \dot{Q} = -k \int \nabla T \cdot d\vec{A} \]  

Since the cross-section area was reduced with the new step-wise cylinder wall structure, the heat flux was reduced while the mechanical strength was retained.

4. Prototype unit and experiment results

4.1. Latest prototype unit

The latest prototype unit was made in 2014 and is shown in figure 7. The total length of the cylinder is 99 mm shorter compared with that of a RDK-101D cryocooler. In addition, the synchronous motor is replaced by a smaller stepping motor, which provides the same torque.
power to drive the scotch yoke and the rotary valve. As a result, the motor housing is also shortened by about 42 mm. The total length of this prototype unit is 299.7 mm, which is 67.8% of a RDK-101D GM cryocooler. The experiment discussed below was operated by this prototype unit.

4.2. Cooling capacity confirmation and result
Typical experiment was carried out to confirm the cooling capacity of the prototype unit. The basic experiment setup of the prototype unit was a typical GM cryocooler system, which consists of a compressor and an expander. 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 with helium gas up to 2.05 MPa at 293 K. The power supply for the compressor is 100 V/50 Hz AC and the cold head operating frequency is 1 Hz. As shown in figure 8, the

![Figure 8. Experiment setup of the prototype unit.](image)
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. The temperature on the heat flanges of the first and the second stages were measured by a PtCO sensor (Chino) and a Cernox (cx-1050) temperature sensor (Lakeshore) respectively.

Under no-load conditions, the stable temperature of the first and the second stages was 46.3 K and 2.22 K, respectively. Detailed load-map and cool-down data are still under collection and will be reported in the near future. The interested reader is referred to reference [10] for the detailed load-map of last year’s prototype unit. Note that the cooling capacity of this year’s prototype unit might be slightly different but should be similar in principle.

5. Conclusions
A new, compact GM cryocooler has been developed for cooling small-scale superconducting devices which need a lower temperature than that of commercially available GM cryocoolers. The expander cylinder was shortened by 99 mm, and the housing assembly was shortened by over 42 mm. The overall length of a prototype unit was reduced to 299.7 mm. Under no-load conditions, the stable temperature of the first and second stages was 46.3 K and 2.22 K, respectively.

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