Development of a valved non-lubricated linear compressor for compact 2K Gifford-McMahon cryocoolers

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Abstract. Recently, a new, compact Gifford-McMahon (GM) cryocooler for cooling superconducting single photon detectors (SSPD) has been developed and reported by Sumitomo Heavy Industries, Ltd. (SHI) [1]. It was reported that National Institute of Information and Communications Technology (NICT) developed a multi-channel SSPD system in which two or more channels were mounted on a GM cryocooler, and achieved a world-top-class performance [2]. However, the applications of such SSPD system were restricted due to its relatively large size and power consumption compared with a semiconductor system. Owing to the development of an SSPD system with a portable cryocooler system which can be installed in a vehicle, it is possible to apply such system to the optical communication of AdHoc [3], and to flexibly construct a large capacity optical line in a time of disaster. For such system, the size and power consumption reduction becomes indispensable. The objective is to reduce the total height of the expander by 33% relative to the existing RDK-101 GM expander and to reduce the total volume of the compressor unit by 50% relative to the existing CNA-11 compressor. In addition, considering the targeted cooling application, we set the design temperature targets of the first and the second stages to 1 W and 20 mW of heat load at 60 K and 2.3 K, respectively. In 2015, Hiratsuka reported that a new valved non-lubricated compressor was developed for a 2K GM cryocooler [4]. The cooling performance of a 2K GM expander operated by an experimental unit of the linear compressor was measured, and preliminary experiments were conducted. No-load temperature was 2.19 K, with 1 W and 14 mW heat load, the temperature was 48 K at the first stage and 2.3 K at the second stage, with an input power of about 1.2 kW. After that, the compressor efficiency has been improved by reducing losses, and the compressor input power has been reduced by 25%. The detailed experimental results are discussed in this paper.

1. Introduction

In the conventional optical communication, since only energy is used as a control factor, it is possible to transmit a much large amount of information by utilizing the properties of a wave. On the other hand, because light has the properties of both particle and wave (photon), it is possible to intercept all wiretapping by utilizing these properties. Therefore, the development of detecting single photon arrival at high speed with high sensitivity (single photon detector) is the key technology for quantum cryptography which can catch out completely wiretapping. However, for the current photon detector, a semiconductor APD (Avalanche photodiode) is used. The long distance transmission is extremely difficult for the wavelength band with the limitations, the inadequate dark count noise suppression and the light-receiving sensitivity of the response time limit. As a solution, a superconducting single photon detector (SSPD), which uses superconducting nanowires, enables low noise, high sensitivity and high speed operation. The National Institute of Information and Communications Technology (NICT) has developed a multi-channel SSPD system, in which multiple channels are mounted on a GM cryocooler, and reported that a world-top-class performance was achieved [2]. However, an SSPD system, including the cryocooler, has a relatively large size and power consumption compared to a semiconductor APD system. An SSPD system using a portable cryocooler can be mounted on a vehicle to apply the optical communication in the AdHoc [3]. Also, it becomes possible to flexibly construct a large-capacity optical line for emergency communication in a time of disaster. Thus, it is essential to reduce the size and power consumption of an SSPD system. The objective is to reduce the total height of the expander by 33% relative to the existing RDK-101 GM expander and to reduce the total volume of the compressor unit by 50% relative to the existing CNA-11 compressor unit. In addition, considering the targeted cooling application, we set the design temperature targets of the first and the second stages to 1 W and 20 mW of heat load at 60 K and 2.3 K, respectively. In 2014, Bao reported the development status of a compact expander [1]. In 2015, Hiratsuka reported the development status of a compact linear compressor for a 2K GM cryocooler [4]. The cooling performance of a 2K GM expander operated by an experimental unit of the linear compressor was measured, and preliminary experiments were conducted. The detailed experimental results are discussed in this paper.

2. General designs

The final target specification of the compact 2K GM cryocooler development is shown in Table 1. The target of the cooling performance is, with an electric input of 1.2 kW to the compressor unit, the cooling capacity of the first stage and the second stage is 1 W at 60 K, and 20 mW at 2.3 K, respectively. The target of size reduction is to reduce the volume of the existing CNA-11 compressor unit by about 50% and the height of the current RDK-101 GM cryocooler expander by about 33%. In order to reduce the size of an SSPD system, a compact GM expander which can reach a low bottom-temperature of about 2.3 K, has been developed. The total height of the expander was reduced by 85 mm compared with a commercial 0.1 W 4 K GM cryocooler (figure 1). In addition, although optimization of the internal compositions is one of the ways to reduce the volume of the compressor unit, major design changes are indispensable because the adsorber and the oil separator have almost the same volume as the compressor capsule. Thus, it is considered that an effective way to reduce the total volume is to exclude these parts, i.e. to develop a non-lubricated compressor. In 2015, a prototype capsule of a compact non-lubricated linear compressor for a 2K GM cryocooler has been developed. Figure 2 shows the schematic drawings of the linear compressor capsule.

Table 1. Specification of the final designed target.

Item	Object
First stage cooling capacity	> 1 W at 60 K
Second stage cooling capacity	> 20 mW at 2.3 K
Maximum electric input power	1.2 kW AC 100V
Length reduction of expander compared to the existing RDK-101D	33.3%
Volume reduction of compressor unit compared to the existing CNA-11	50.0%
Temperature oscillation displacement	< ±20 mK

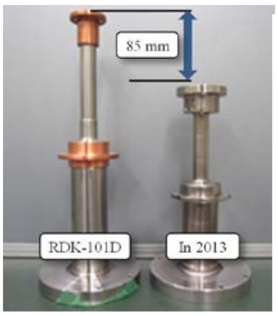

Figure 1. The new prototype expander compared to the SRDK-101D.

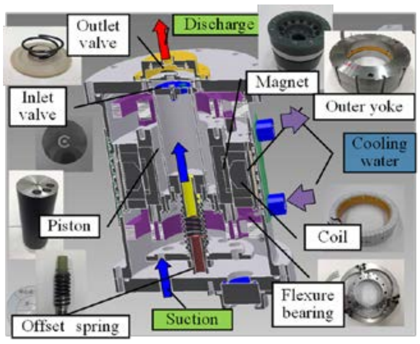

Figure 2. Schematic drawing of a linear compressor capsule.

3. Experimental results and discussions

By reducing the leakage losses of the gap between the piston and the cylinder, the inlet and the outlet valves, the efficiency of the compressor has been further improved after the initial preliminary tests. A compact 2K GM expander was operated w ith the prototype of a compact non-lubricated linear compressor, and the cooling performance was measured. Figure 3 shows an experimental unit of the valved non-lubricated linear compressor. In table 2, the cooling performance test results of a 2K GM cryocooler using a commercial CNA-11 compressor and a linear compressor are shown. Almost the same second stage cooling capacity has been obtained with a linear compressor as with a CNA-11 compressor. The compressor input power is 0.9 kW and the power consumption of the cooling fan, the cooling water pump and the expander valve motor is about 0.1 kW. Thus, the total electric input power of the compressor unit including the inverter loss is about 1.2 kW since the inverter efficiency is about 80%. Figure 4 shows the second stage cooling capacity with respect to the compressor input power. It is possible to increase the cooling capacity by increasing the compressor input power. Figure 5 shows the second stage cooling capacity and the lowest temperature with respect to the initial gas pressure at a compressor input power of 1.0 kW. As the initial gas pressure increases, the lambda point of helium is reduced, thus the lowest temperature is decreased. The cooling capacity at 2.3K reached the maximum at initial pressure of about 1.8 MPa. Figure 6 shows the second stage cooling capacity and the compressor discharge temperature with respect to the inlet cooling water temperature.

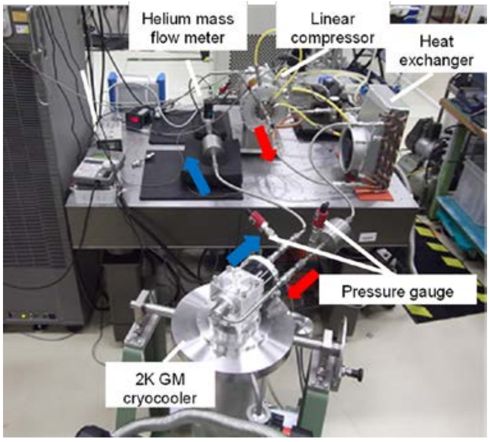

Figure 3. Photograph of an experimental unit for a compact 2 K GM cryocooler

Table 2. Experimental results for a compact 2K GM cryocooler with the linear compressor.

Item	With CNA-11	Measured results
Electric input power	1.2 kW / 50Hz	1.2 kW
1) Compressor input power	-	0.9 kW
2) Expander valve motor	-	0.05 kW
3) Cooling fan and water pump	-	0.05 kW
4) Inverter loss	-	0.18 kW
1^{st} temperature with 1 W	45 K	49 K
2^{nd} cooling capacity at 2.3 K	17 mW	17 mW
No-load 2^{nd} temperature	2.2 K	2.17 K

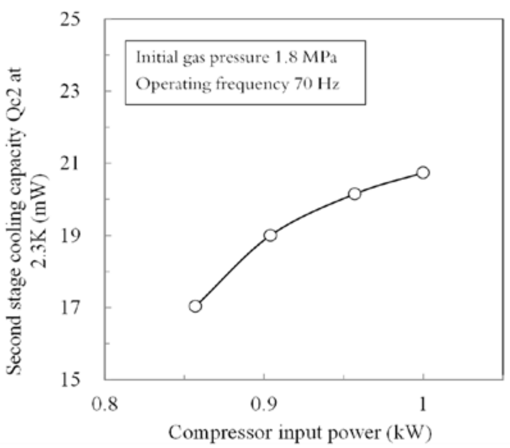

Figure 4. Influence exerted on the second stage cooling capacity by the difference compressor input power.

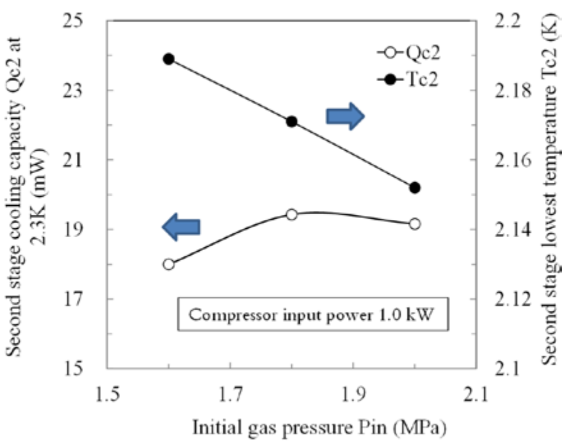

Figure 5. Influence exerted on the second stage cooling capacity and lowest temperature by the difference initial gas pressure.

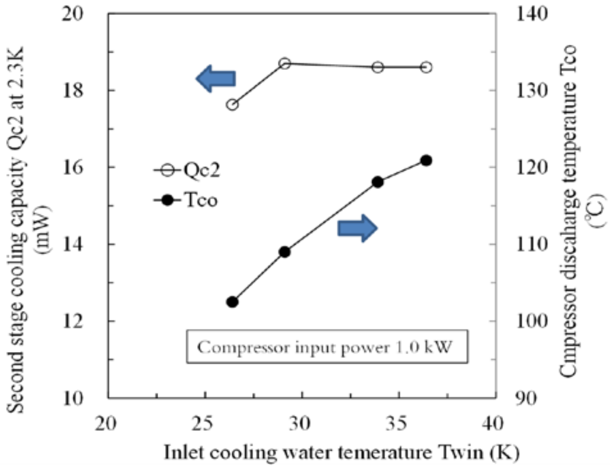

Figure 6. Influence exerted on the second stage cooling capacity and the compressor discharge temperature by the difference inlet cooling. water temperature.

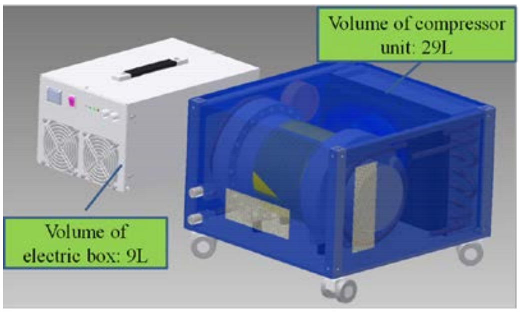

Figure 7. Schematic draw of the compressor unit and the electric box.

The influence of the inlet cooling water temperature on the cooling capacity is negligible although the discharge temperature of the compressor increases as the water temperature increases. A schematic diagram of a compressor unit and the electric box is shown in Figure 7. The volume of the compressor unit is 29 l, while that of the electric box is about 9 l and thus the total volume is about 38 l, which is close to the target of 35 l. The electric box runs at power 100 V. To optimize the performance of the system, PID function for temperature control by the output of the compressor has been installed.

4. Conclusion

An experimental unit of a valved non-lubricated linear compressor for a 2K GM cryocooler, which can be used for cooling superconducting electronic devices, has been developed. Under no-load condition, a low temperature of 2.17 K has been achieved. With 1 W and 17 mW heat load, the temperature was 49 K at the first stage and 2.3 K at the second stage with an electric input power of less than 1.2 kW. The total volume of a prototype unit can be reduced to 38 l. In future, we plan to further improve the efficiency of the compressor, to reduce the size of the heat exchanger and thus reduce the total volume of the compressor.

Acknowledgements

The research results have been achieved by “Development of a Compact Superconducting Single Photon Detector System for Photon-Quantum Information and Communication”, the National Institute of Information and Communications Technology (NICT), JAPAN.

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