Performance estimation of an oil-free linear compressor unit for a new compact 2K Gifford-McMahon cryocooler

Y Hiratsuka, Q Bao and M Y Xu
Technology Research Center, Sumitomo Heavy Industries, Ltd.,
2-1-1, Yato-cho, Nishitokyo-city, Tokyo 188-8585, Japan
E-mail: yoshikatsu.hiratsuka@shi-g.com

Abstract. Since 2012, 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). Also, it was reported that National Institute of Information and Communications Technology (NICT) developed a multi-channel, conduction-cooled SSPD system. However, the size and power consumption reduction becomes indispensable to apply such a system to the optical communication of AdHoc for a mobile system installed in a vehicle. 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 cooling capacity targets of the first and the second stages 1 W at 60 K and 20 mW at 2.3 K respectively. In 2016, Hiratsuka et al. reported that an oil-free compressor was developed for a 2K GM cryocooler. The cooling performance of a 2K GM expander driven by an experimental unit of the linear compressor was measured. No-load temperature less than 2.1 K and the cooling capacity of 20 mW at 2.3 K were successfully achieved with an electric input power of only 1.1 kW. After that, the compressor capsule and the heat exchanger, etc. were assembled into one enclosure as a compressor unit. The total volume of the compressor unit and electrical box was significantly reduced to about 38 L, which was close to the target of 35 L. Also, the sound noise, vibration characteristics, the effect of the compressor unit inclination and the ambient temperature on the cooling performance, were evaluated. The detailed experimental results are discussed in this paper.

1. Introduction
Superconducting single photon detectors (SSPDs), which are under development at the National Institute of Information and Communications Technology in Japan, feature a high count rate, high detection efficiency, low noise (low dark count rate) and short jitter time. Thus, it is expected that they can be a potential alternative to the existing avalanche photodiode (APD) to remarkably improve the communicable distance of quantum cryptography communication [1, 2]. Furthermore, by optimizing the optical cavity structure, it is possible to achieve a high-detection efficiency over a wide wavelength band. Thus, it is expected that such high-performance detectors can be used in various fields, such as biotechnology and medical science. In addition, such a system can be directly cooled by a cryocooler and is expected to continuously operate for a long time. Thus, cryocoolers with high reliability and low temperature (below 2.3 K) are required. However, in comparison to a similar semiconductor detector, the superconducting detector, including the cryostat, is relatively large. Thus, it is essential to reduce the size and power consumption of an SSPD system. With the hopes of filling this spot in the current market,
we launched this development project in 2012. The objective was to reduce the total height of the expander by 33% relative to the existing RDK-101 GM cryocooler, and to reduce the total volume of the compressor unit by 50% relative to the existing CNA-11 compressor. Also, considering the targeted cooling application, the design targets of the first and the second stages cooling capacity were set 1 W at 60 K and 20 mW at 2.3 K, respectively.

In 2014, Bao et al. reported the development status of a compact 2K GM expander with a CNA-11 compressor [3]. In 2016, Hiratsuka et al. reported that an oil-free linear compressor was developed for a 2K GM cryocooler by applying the techniques achieved during previous Stirling cryocooler development to miniaturize the size of the compressor [4]. The cooling performance of a 2K GM expander driven by an experimental unit of the linear compressor was measured. A no-load temperature of less than 2.1 K and the targeted cooling capacity of 20 mW at 2.3 K were successfully achieved with an electric input power of only 1.1 kW. The total volume of the compressor unit and inverter electrical box was significantly reduced to about 38 L. The performance evaluation test of the linear compressor was carried out using a commercially-available RDK-101 expander. Also, the sound noise, vibration characteristics, the effect of the compressor unit inclination and the ambient temperature on the cooling performance, were evaluated. The detailed experimental results are discussed in this paper.

2. Performance of a RDK-101 expander with a linear compressor

As the 2K GM expander used in previous tests was installed in an SSPD system, it was difficult to add heat load to evaluate the cooling performance. Thus, the following experiment was carried out with a commercially-available RDK-101 expander. Figure 1 shows photos of a linear and a CNA-11 compressor unit and figure 2 shows the second stage cooling performance of the expander. As shown in figure 2, a similar cooling capacity of 19.2 mW at 2.3 K was achieved with either a linear or a CNA-11 compressor. Below 2.3 K, a better performance was achieved with a linear compressor. Thus, no-load temperatures of 2.06 K and 2.11 K were achieved with a linear and a CNA-11 compressor, respectively. By contrast, the cooling performances at 4.2 K were 173 mW and 191 mW with a linear and a CNA-11 compressor, respectively. Table 1 shows the operating pressures and the mass flow rates at the second stage temperature of 2.3 K. The lower no-load temperature was achieved with a linear compressor, owing to its higher operating pressures. Theoretically, as operating pressure increases, the lambda point of helium decreases, thus the no-load temperature decreases.

![Figure 1. Photos of a linear and a CNA-11 compressor unit.](image)

**Table 1.** Operating pressures and mass flow rates at the second stage temperature of 2.3 K.

|                      | CNA-11 | Linear compressor |
|----------------------|--------|-------------------|
| Input power (kW)     | 1.1    | 1.1               |
| High pressure $P_h$ (MPa) | 2.24 | 3                   |
| Low pressure $P_l$ (MPa) | 0.73 | 1.2               |
| $P_h/P_l$            | 3.07   | 2.5               |
| $P_h - P_l$ (MPa)    | 1.51   | 1.8               |
| Mass flow rate (g/s) | 1.2    | 1.16             |

![Figure 2. Cooling performance of a RDK-101 expander using a linear or a CNA-11 compressor unit.](image)
Figure 3 shows the influence of the ambient temperature on the second stage cooling performance. The second stage cooling performance gradually increased until the ambient temperature reached 28°C, and then decreased. As the room temperature increased from 20°C to 32°C, the outlet temperature of the pump went up from 38°C to 55°C. The inlet temperature of the cooling water was not measured, but from the results of previous tests, it was estimated to be about 10°C lower than the outlet temperature. Since the upper limits of the ambient temperature for both the pump and the inlet cooling water temperature are 40°C, it is desirable for the ambient temperature to be lower than 28°C.

As the cryocooler is installed in a small space, it is essential to shorten the length of the gas hose connecting the compressor and the expander. Figure 4 shows the influence of the length of the gas hose on the cooling performance. With a CNA-11 compressor, as the hose length decreases, the cooling performance also decreases, but with a linear compressor, the performance change is relatively small. In Figures 2 and 4, there is a slight difference in the cooling capacity (error) at the second stage, but the tendency of the influence on the cooling capacity due to the difference in gas hose length between the linear compressor and the CAN-11 compressor does not change.

3. Influence of compressor inclination on cooling performance
By increasing the inclination freedom of the compressor unit, various new market applications can be considered. Figure 5 shows the influence on the temperature of the first and the second stages when the compressor unit was rotated by 90°. As seen in the figure, there is almost no influence on the cooling performance by the rotation of the compressor unit. Unfortunately, it was impossible to rotate to 180°.
due to a structure problem. The structure will be modified in the future so that the compressor can be rotated by 180°.

4. Sound noise and vibration measurement
Since the developed linear compressor unit consists of only a single piston, a sound noise due to vibration exists. Therefore, the sound noise and vibration of the compressor unit were measured. Figures 6, 7 show an experimental setup of the sound noise of a CNA-11 and a linear compressor unit. So, figures 8, 9 show the sound noise measurement results (A weigh) of a CNA-11 and a linear compressor unit. Figures 10, 11 show the vibration measurement results at the compressor side of the supply hose (high pressure) for a CNA-11 compressor.

Figure 6. Experimental setup of the sound noise of a CNA-11 compressor unit.

Figure 7. Experimental setup of the sound noise of a linear compressor unit.

Figure 8. The sound noise measurement results (A weigh) of a CNA-11 compressor.

Figure 9. The sound noise measurement results (A weigh) of a linear compressor unit.

Figure 10. The vibration measurement results at the compressor side of the supply hose (high pressure) for a CNA-11 compressor.

Figure 11. The vibration measurement results at the compressor side of the supply hose (high pressure) for a linear compressor unit.
unit, respectively. The sound noise of a linear compressor is somewhat higher than that of a CNA-11. This large sound noise frequency is a multiple of 70 Hz, which is the compressor operating frequency. Thus, it is considered that the sound noise is caused by the knocking sound of the valve and the vibration of the gas transfer tube. Measures to reduce this sound noise will be investigated in the future.

Further, figures 10, 11 show the vibration measurement results of a linear and a CNA-11 compressor unit, respectively. The vibration was measured at the compressor side of the high pressure (supply) hose. It can be seen that the vibration of a linear compressor unit (maximum 2.2 G) is still higher than that of a CNA-11 unit (maximum 0.75 G), and should be further reduced in the future.

5. Short-term operation test
Short-term operation was performed to confirm the reliability of the compressor unit with a RDK-101 expander. The results are shown in figure 12. During a continuous operation of about one month, it was found that although the second stage temperature was stable and remained at the same temperature of 2.06 K, the first stage temperature gradually rose. The reason for such a performance degradation will be further investigated by performing a longer test. After that, the performance with the recently-developed compact 2 K GM expander will be evaluated, also.

6. Conclusion
The performance evaluation test of a linear compressor was carried out using a commercially-available RDK-101 expander. Also, the sound noise, vibration characteristics, the effect of the compressor unit inclination and the ambient temperature on the cooling performance, were evaluated. When temperature was lower than 2.3 K, an improved cooling performance was achieved compared to a CNA-11 compressor. Moreover, it was confirmed that during a continuous operation of about one month, the second stage temperature was stable and remained at the same temperature of 2.06 K.

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