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A new approach for low input and high capacity 4 K Gifford-McMahon cryocooler

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Abstract. Regenerative 4 K cryocoolers, such as Gifford-McMahon (G-M) and G-M type pulse tube cryocoolers, are essential for superconducting applications. A significant challenge with these cryocoolers is their low efficiency in reaching 4 K. Typically, an electrical input of 6-7 kW is required to achieve a cooling capacity of approximately one watt at 4 K. To address this challenge, a new operating method has been implemented: a G-M cold head driven by two 2 kW compressors connected in parallel. This approach is based on the observation that the specific mass flow, defined as mass flow divided by electrical input, (g/s)/kW, of lower-input compressors (e.g., 2-kW class) is larger than that of high-input compressors (e.g., 7-kW class). A cooling capacity of 1.7 W at 4.2 K was achieved with an electrical input of 4.2 kW (two 2 kW compressors), compared to 2.0 W with 7.0 kW input (single 7 kW compressor). The relative Carnot efficiency for the G-M cryocooler driven by two compressors was 2.8%, which is 1.4 times higher than that of the single 7 kW compressor. These results demonstrate that this method offers a new approach for developing a low input and high capacity 4 K G-M cryocooler.

1. Introduction

Regenerative 4 K cryocoolers are utilized in various low-temperature systems, including liquid helium recondensation, direct cooling of cryogen-free superconducting magnets, and pre-cooling of dilution cryocoolers [1, 2]. The electrical power required to maintain 4 K temperatures can influence the operating costs of these systems. To achieve high cooling capacity at 4 K, Gifford-McMahon (G-M) and G-M type pulse tube cryocoolers require a large cold head and a high-capacity helium gas compressor. Conventional G-M cryocoolers, requiring 6-7 kW for watt-class cooling at 4 K, exhibit lower efficiency due to the power consumption associated with increased compressor discharge capacity.

In this context, Masuyama S et al. have reported experimental investigations on a 4 K G-M cryocooler with low power consumption in previous studies [3, 4]. This study further develops those investigative reports, aiming to improve cooling performance. To achieve this, we investigated compressor mass flow rate under different electrical inputs and implemented a new approach for the operation of the G-M cryocooler. In this paper, we first describe the experimental setup and measurement methods, then report the experimental results, with a focus on the cooling capacity at 4.2 K, and finally evaluate the effectiveness of the proposed method.

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2. Experimental setup

Four different input compressors, classified by authors as 1, 2, 5 and 7 kW, were tested. Table 1 lists the types of these four compressors and their initial charging gauge pressures. The cooling capacity was measured for each compressor when connected to the same two-stage G-M cold head (SHI Cryogenics Group, RDE-418D4). A schematic diagram of the experimental setup is shown in Figure 1. Two calibrated thermometers and two electric heaters were placed on each cold stage to measure temperature and cooling capacity, respectively. A radiation shield, covering the second cold stage and the cylinder, was fixed to the first stage. The cold head was placed in a vacuum chamber during operation.

The cold head and compressor were connected using two flexible lines, each 10 meters long with a 20 mm inner diameter. Pressure was monitored using two gauges (KYOWA, PGM-50KD) installed on the high- and low-pressure lines. Mass flow was measured on the low-pressure line using a mass flow meter (KOFLOC, HFM-301). Since the 5 and 7 kW compressors exceeding the mass flow meter's full-scale range (approximately 2.8 g/s), two flow meters were used in parallel, as shown in Figure 1. The readings from each mass flow meter were added. The electrical input of the compressor was measured using an electric power meter (HIOKI, PW3336). Stage temperatures, compressor input, mass flow, and pressure were monitored and recorded by a data acquisition PC. To determine the maximum cooling capacity at 4.2 K for each compressor, the operating speed of the cold head (displacer and pressure valve) was controlled using an external inverter. Additionally, a controlled heat load was applied to the first stage via an electric heater to vary the first stage temperatures.

Table 1. Four compressor types and their initial charging pressures.

Compressor type	Classification by authors	Supplier	Rated input power at 60 Hz	Initial charging gauge pressure
SA112-C	1 kW	ULVAC Cryogenics	1.3 kW	2.0 MPa
SSC-1100	2 kW	SUZUKI-SHOKAN	1.8 kW	2.0 MPa
F-40L	5 kW	SHI Cryogenics	4.6-5.6 kW	1.6 MPa
SSC-3700	7 kW	SUZUKI-SHOKAN	7.5 kW	1.6 MPa

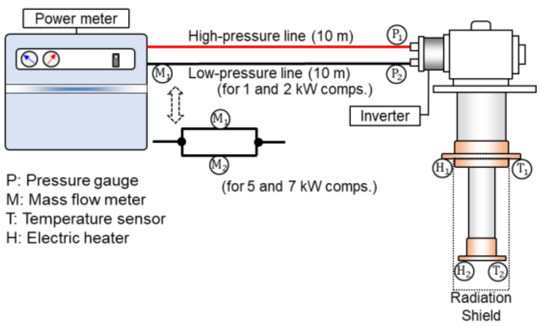

Figure 1. Schematic diagram of the experimental setup and measurement sensor location.

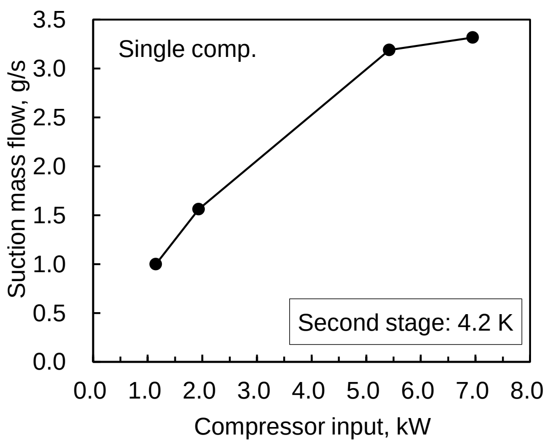

Figure 2. Suction mass flow at 4.2 K results for each compressor.

3. Experimental results

Figure 2 shows the suction mass flow at 4.2 K results for each compressor, demonstrating that the mass flow increases almost proportionally with the compressor input. Figure 3 presents the cooling capacity at 4.2 K as a function of the suction mass flow (the numbers in parentheses indicate the operating speed of the cold head), clearly showing a proportional relationship. Using these results, we calculated a specific mass flow, defined as mass flow divided by compressor input, (g/s)/kW, as shown in Figure 4. Notably, the specific mass flow of lower-input compressors (1 and 2 kW) is higher than that of higher-input compressors (5 and 7 kW).

Based on these findings, we concluded that connecting two 2 kW compressors in parallel offers a promising approach to achieve high capacity 4 K G-M cryocoolers with low input, specifically below 5 kW. Our prediction for the two 2 kW compressors (2+2 kW) is also plotted in Figure 4. In this plot, it was decided that the total compressor input could be doubled (1.9 kW (measured value)×2 = 3.8 kW) while maintaining a specific mass flow of 0.81 (g/s)/kW.

Figure 5 illustrates a schematic of two compressors, along with a photo detailing the cold head, the pressure lines, and two 2 kW compressors. The location of the pressure line joint and the volume of the pressure lines are considered key operational parameters in this method. As a first step, the joint was placed in close proximity to the cold head. This initial setup consisted of 10 m pressure lines from each compressor to the joint, and a 1 m line from the joint to the cold head. The compressor input power was calculated from the sum of the readings from each power meter. Figure 6 shows the relationship between the operating speed of the cold head and the cooling capacity at 4.2 K for two 2 kW compressors. The cooling capacity exhibits a convex curve, demonstrating a maximum cooling capacity of 1.7 W at 60 rpm. The pressure ratio for the single 2 kW compressor (operating speed: 36 rpm) and two 2 kW compressors (operating speed: 60 rpm) were 2.6 and 2.8, respectively, indicating a slight increase.

Figures 4 and 7 present the experimental results of suction mass flow and cooling capacity at 4.2 K for two 2 kW compressors and their corresponding predictions. The prediction of the cooling capacity at 4.2 K shown in Figure 7 was calculated as follows: Given a specific mass flow rate of 0.81 (g/s)/kW and a total input power of 3.8 kW, the resulting mass flow is determined to be 3.1 g/s. Based on the characteristic shown in Figure 3, a mass flow of 3.1 g/s corresponds to a predicted cooling capacity of 1.9 W.

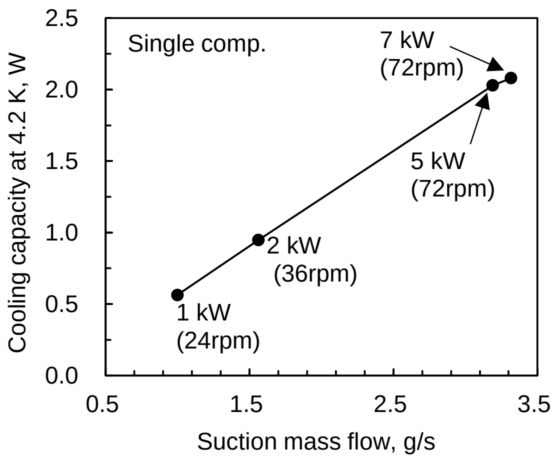

Figure 3. Cooling capacity at 4.2 K as a function of suction mass flow.

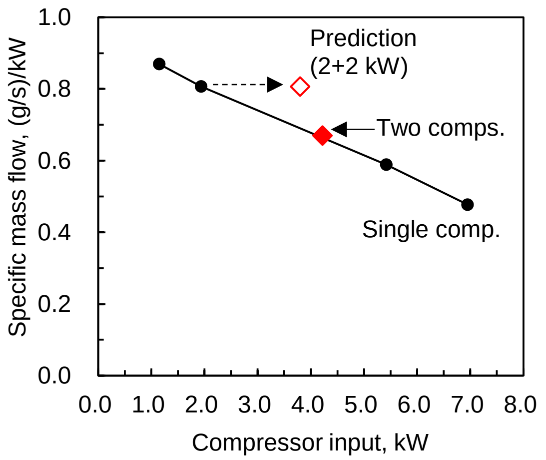

Figure 4. Specific mass flow versus compressor input.

Despite yielding results below predictions, likely due to gas merging losses at the joint and pressure line volume, the operation of the two compressors slightly exceeded the individual compressor performance (as seen in Figures 4 and 7). Specifically, a cooling capacity of 1.7 W was achieved at 4.2 K with an operating speed of 60 rpm and an electrical input of 4.2 kW. The calculated relative Carnot efficiency was 2.8%, which is 1.4 times higher than that of a single 7 kW compressor. Figure 8 shows the first stage cooling capacity at 50 K, with the second stage fixed at 4.2 K. The cooling capacity increases with increasing compressor input. A 1 kW compressor produced no cooling capacity at 50 K, as the lowest temperature of the first stage was 58 K. The opration of the two 2 kW compressors slightly surpassed the individual compressor performance.

Figure 9 shows a comparison of the calculated relative Carnot efficiency between the experimental results (using two 2 kW compressors and a single 7 kW compressor) and commercially available G-M cryocoolers. The dotted line represents the approximate trend for commercially available G-M cryocoolers. It indicates that the two 2 kW compressors have very high efficiency. These results demonstrate that this method is a new approach for developing a low input and high capacity 4 K G-M cryocooler.

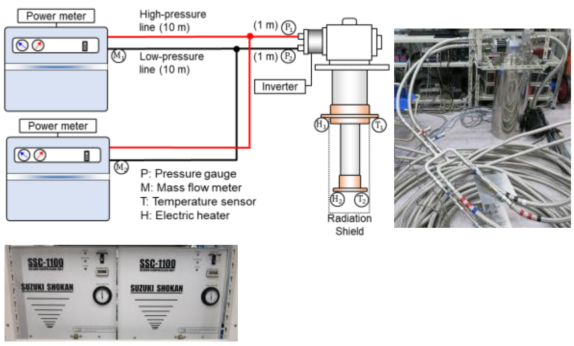

Figure 5. Schematic of connecting two compressors with a photo detailing the cold head, pressure lines, and two 2 kW compressors.

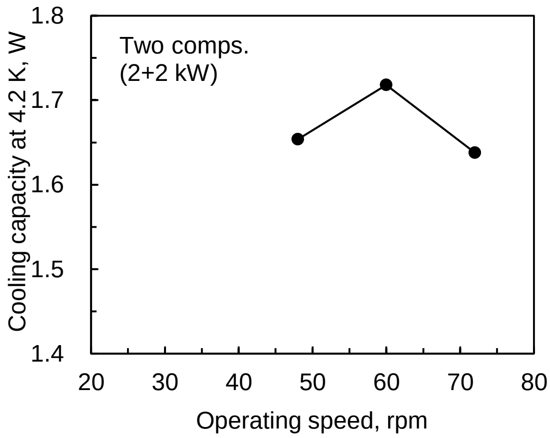

Figure 6. Operating speed of the cold head and cooling capacity at 4.2 K for two 2 kW compressors.

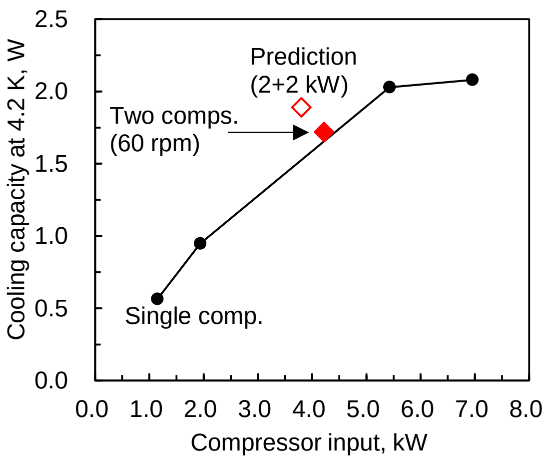

Figure 7. Cooling capacity at 4.2 K versus compressor input.

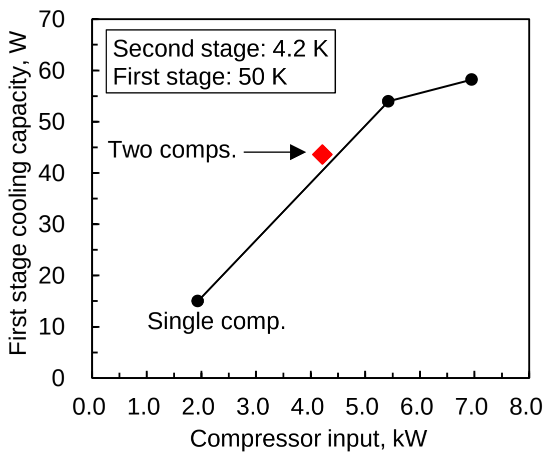

Figure 8. Fist stage cooling capacity at 50 K, with the second stage fixed at 4.2 K.

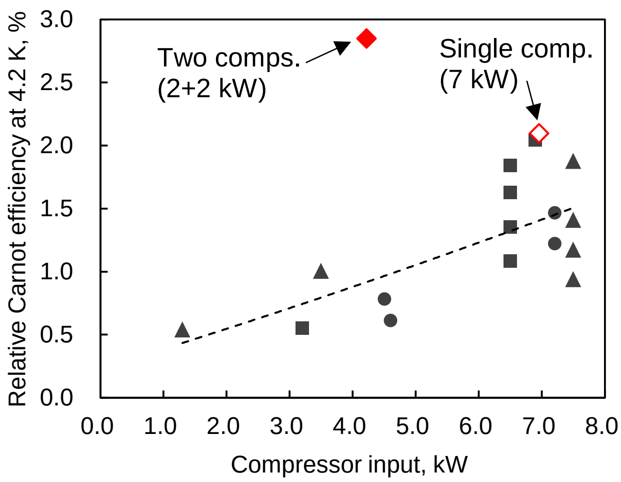

Figure 9. Comparison of the relative Carnot efficiency at 4.2 K between the experimental results and commercially available G-M cryocoolers (specifications for ●, ▲, and ■ are based on references [5], [6], and [7], respectively).

4. Summary

This study aimed to develop low input and high capacity 4 K G-M cryocoolers. To achieve this goal, we focused on the observation that lower-input compressors exhibit a higher specific mass flow than higher-input compressors. As a new operating method, a two-stage G-M cold head driven by two 2 kW compressors connected in parallel was tested. The experimental results showed that a cooling capacity of 1.7 W at 4.2 K was achieved with an electrical input of 4.2 kW. The calculated relative Carnot efficiency at 4.2 K for the G-M cryocooler driven by two 2 kW compressors was 2.8%, which is 1.4 times higher than that of the single 7 kW compressor. These results demonstrate that this method is a promising candidate for a new operating method for 4 K GM cryocoolers.

Acknowledgments

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