

Characteristics of reciprocating speed of a low power consumption 4 K G-M cryocooler

S Masuyama¹, K Kamiya² and T Numazawa²

¹Electronic-Mechanical Engineering Department, National Institute of Technology, Oshima College, Yamaguchi, 742-2193, JAPAN

²National Institute of Materials Science, Tsukuba, 302-0003, Japan

masuyama@oshima-k.ac.jp

Abstract. This study is aiming to develop a low power consumption 4 K G-M cryocooler. As a first step, a two-stage G-M cryocooler with a 2 kW class compressor has been tested. The base model of cold head of two-stage G-M cryocooler is RDK-305D (Sumitomo Heavy Industries). We modified its second stage regenerator materials by filling magnetic materials Gd_2O_2S and $HoCu_2$ spheres. An air-cooled compressor of SA115 (ULVAC CRYOGENICS) that rated input is 1.9 kW at 60 Hz was connected to the cold head. The experimental results showed that the cooling capacity of the second stage of 0.5 W at 4.2 K and the first stage of 25 W at 45 K was achieved with the cold head reciprocating speed of 48 rpm and the compressor electrical input of 2.09 kW. The relative Carnot efficiency of 1.7% at 4.2 K was calculated from the result. A low reciprocating speed of 48 rpm was chosen is to secure the sufficient expansion work in the second expansion space. This is considered an effective method to obtain a large cooling capacity at 4 K by low power compressor.

1. Introduction

The development of magnetic regenerator materials, such as Er_3Ni , $HoCu_2$ and so on, has made it possible to achieve a 4 K level by regenerative cryocoolers since 1990s [1, 2]. An improvement point of the regenerative 4 K cryocoolers is that the efficiency is not satisfactory. A large electrical input is needed to maintain the 4 K level. For example, a 0.5 W model of G-M cryocooler needs approximately 4 kW electrical input [3]. The relative Carnot efficiency is only one percent. In order to improve efficiency, it is considered effective to develop a regenerator material with a large specific heat at around 4 K and a new regenerator structure. New magnetic regenerator material like $Er_xHo_{1-x}N$ [4], and a new regenerator structure like a coaxial pipe regenerator [5], have been developed in the last decade. Unfortunately, no major progress has been obtained by these developments at this time. Further improvement will be expected.

On the other hand, the regenerative cryocoolers, such as two stage G-M and G-M type pulse tube cryocoolers, have been widely used for superconducting application, such as magnetic resonance imaging (MRI) and superconducting magnetic levitation train (MAGLEV) [6, 7]. The 4 K cryocoolers must operate all the time while maintaining the cooling capacity at 4 K level. This means that the power consumption of the 4 K cryocoolers is directly linked to the running cost of that advanced system.

From the above points, a low power consumption 4 K G-M cryocooler has been investigated experimentally in this study. A key point of its development is that a low power compressor should be

used, because the power consumption of the 4 K G-M cryocoolers is occupied mostly by compressor. In this study, a 2 kW class compressor was chosen. The discharged helium mass flow rate from compressor depends mostly on its electrical input power. To compensate the small mass flow rate from the compressor, the reciprocating speed of cold head was controlled to secure the sufficient expansion work in the second expansion space.

2. Experimental Set-up

2.1. Two-stage G-M cryocooler and compressor

A conventional two-stage G-M cryocooler of 0.5 W at 4.2 K model (RDK-305D, Sumitomo Heavy Industries, SHI) and an air-cooled compressor (SA115, ULVAC CRYOGENICS), rating electrical input of 1.9 kW at 60 Hz, were prepared. These cold head and compressor were connected by two flexible hoses, which has an outer diameter of 24.2 mm, and a length of 10 m per hose, with an initial charging pressure of 2.0 MPa. A schematic diagram of the experimental set-up is shown in figure 1. Two calibrated Cernox thermometers (CX-1050, Lake Shore) and two electric heaters were mounted on each stage to measure temperature and cooling capacity. The second stage and cylinder were covered with a radiation shield connected thermally to the first stage. Furthermore, in order to decrease radiation loss, the entire cold head was covered with multi-layer insulation (MLI). The pressure in the vacuum chamber was less than 10^{-4} Pa while the G-M cryocooler was operated. The reciprocating speed of displacer was adjusted by three-phase inverter (Mitsubishi Electric). Two pressure sensors (PGM-50KD, KYOWA) were set to the high- and low-pressure line, respectively. The electrical input power of compressor was measured by power meter (PW3336, HIOKI).

2.2 Second stage regenerator

Three kinds of sphere regenerator materials of Pb (50%), HoCu₂ (20%) and Gd₂O₂S (30%) were filled in the second stage regenerator as a three-layer structure. The values in the parenthesis show the filling rate relative to the space in the second stage regenerator. Figure 2 shows a schematic diagram of the three-layer structure and the sphere diameter of these regenerator materials. The configurations of this regenerator, filling rate and sphere diameter, are appropriate values obtained from previous studies [5, 8]. To separate and fix each material, a separator, which is made of stacked stainless steel meshes, is set to the boundary of each material and both ends of regenerator.

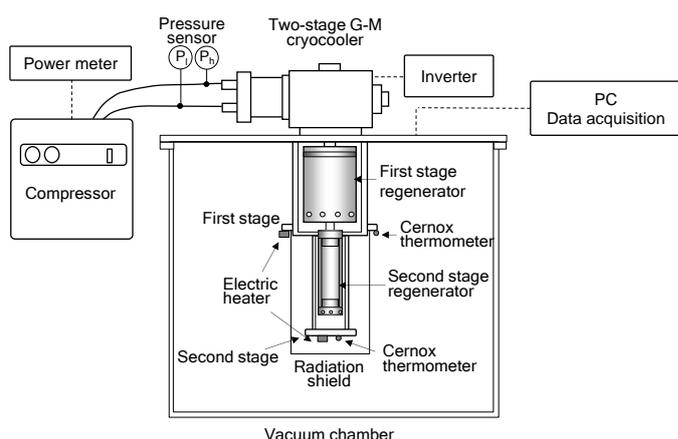


Figure 1. Schematic diagram of the two-stage G-M cryocooler and data acquisition system.

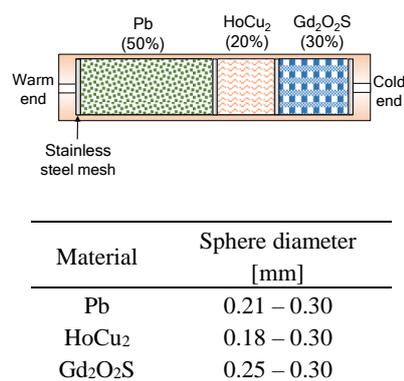


Figure 2. Configuration of the second stage regenerator and sphere diameter of regenerator materials.

3. Experimental results

3.1 Cooling capacity with 2 kW class compressor

The cooling capacity measurement was carried out by adding heat load to each cooling stage. Figure 3 shows the cooling capacity at 4.2 K of the second stage as a function of the first stage temperature of four different reciprocating speed of displacer. The reciprocating speed of 36 and 48 rpm shows almost the same cooling capacity at the measured temperature range, and the cooling capacity is larger than that of 60 and 72 rpm. Figure 4 shows the first stage cooling capacity depending on four different reciprocating speed. The second stage temperature was fixed at 4.2 K. The low reciprocating speed leads to the low cooling capacity. Considering the results shown in figures 3 and 4, the reciprocating speed of 48 rpm is optimum. The cooling capacity of the second and first stages achieved 0.50 W at 4.2 K and 25 W at 45 K, respectively, with the compressor electrical input of 2.09 kW. The relative Carnot efficiency of 1.7% at 4.2 K was calculated from the result.

Figure 5 indicates the lowest temperature of each stage with the first and the second stages heat load by electric heaters of 25 and 0 W, respectively. Decreasing the reciprocating speed lowers the second stage temperature. In contrast, it raises the first stage temperature. The maximum reciprocating speed to maintain below 4 K is approximately 76 rpm. Figure 6 presents the second stage cooling capacity from 0 to 6 W depending on the reciprocating speed, and figure 7 shows an enlarged view of figure 6 less than the cooling capacity of 2.5 W. The constant heat load of 25 W was added to the first stage. The low reciprocating speed of 36 and 48 rpm is effective at below 2 W at 9 K.

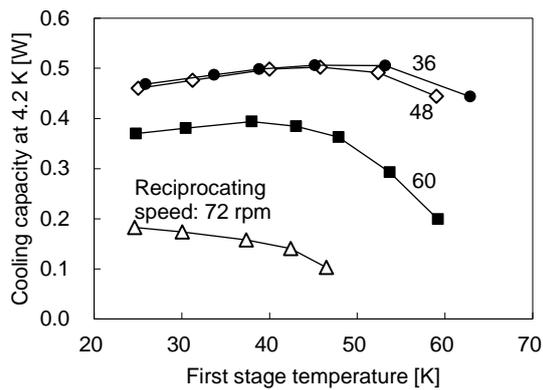


Figure 3. Cooling capacity at 4.2 K of the second stage for four different reciprocating speed.

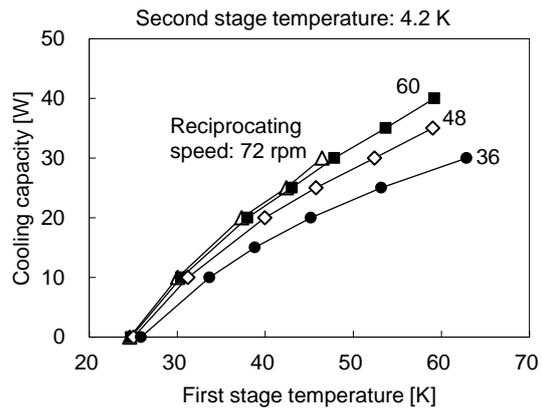


Figure 4. First stage cooling capacity depending on four reciprocating speed.

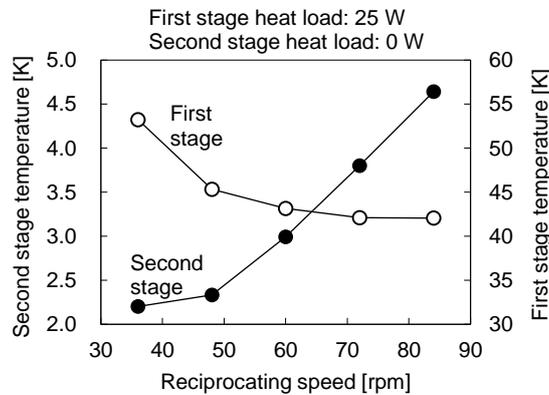


Figure 5. Change of lowest temperature of the first and second stages.

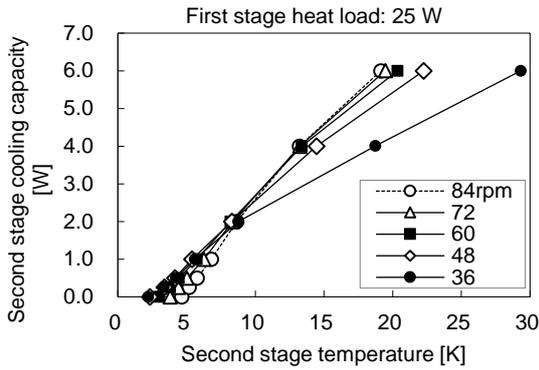


Figure 6. Second stage cooling capacity with the heat load 0-6 W.

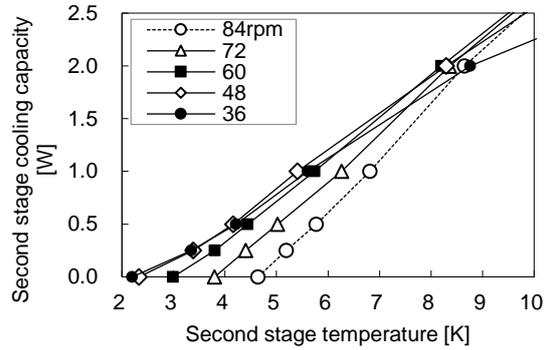


Figure 7. Enlarged view of figure 6 less than the cooling capacity of 2.5 W.

3.2 Comparison of 2 kW class and 5 kW class compressors

A cold head of RDK-305D has been released by SHI in combination with a 5 kW (60 Hz) class compressor, F-40H/L. We compared cooling performance of RDK-305D, of which the second stage regenerator material was modified described in former section, connected two compressors of SA115 and F-40L, independently. Note that the initial charging pressure of SA115 and F-40L was 2.0 and 1.6 MPa, respectively. Figure 8 shows the measured cooling capacity at 4.2 K of the second stage. The constant heat load of 25 W was added to the first stage. The cooling capacity of F-40L increases at high speed side where that of SA115 decreases. Its maximum capacity has reached 0.97 W. A low reciprocating speed, such as 36 and 48 rpm, is needed to secure the sufficient expansion work in the second expansion space by connecting a low power compressor.

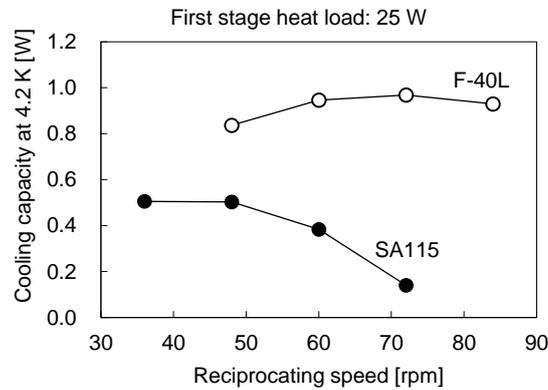


Figure 8. Comparison of cooling capacity at 4.2 K for SA115 (2 kW class) and F-40L (5 kW class) compressors.

Figure 9 shows the measured gauge pressure at high- and low-pressure lines and figure 10 presents the pressure ratio calculated from figure 9. The high- and low-pressure of SA115 are higher than that of F-40L. Contrarily, the pressure ratio of SA115 is approximately 37% smaller than that of F-40L. For both compressors, the pressure ratio decreases with increasing reciprocating speed. The high speed operation affects the cooling capacity when the operating with a low power compressor as shown in figure 8. In contrast, a large pressure ratio, however, does not necessarily bring to large cooling capacity. The reason is that the pressure ratio rising too high leads to the helium gas is bypassed inside compressor

resulting a reduction in a discharged helium gas from compressor. A decrease in the cooling capacity of F-40L at low speed operation, shown in figure 8, is considered to be due to the above reason.

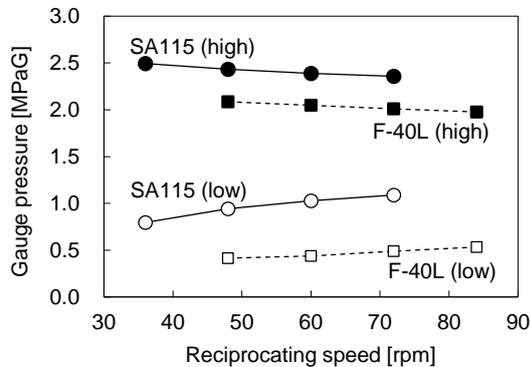


Figure 9. Results of pressure measurement at high- and low-pressure lines.

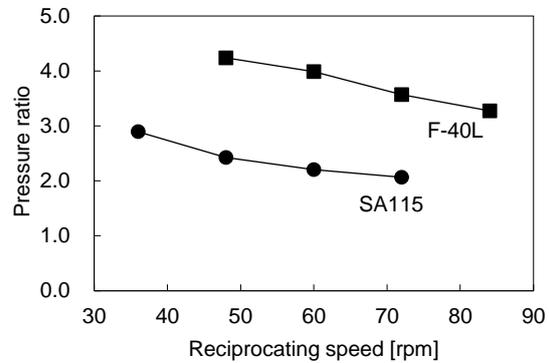


Figure 10. Comparison of pressure ratio for two types of compressors.

4. Summary

To develop a low power consumption 4 K G-M cryocooler, a two-stage G-M cryocooler with a 2 kW class compressor has been tested. The second stage regenerator materials was modified by authors. The experimental results showed that the cooling capacity of the second stage of 0.5 W at 4.2 K and the first stage of 25 W at 45 K was achieved by the cold head reciprocating speed of 48 rpm and the compressor electrical input of 2.09 kW. The relative Carnot efficiency of 1.7% at 4.2 K was calculated. A low reciprocating speed, such as 36 and 48 rpm, is needed to secure the sufficient expansion work in the second expansion space. This is considered an effective method to obtain a large cooling capacity at 4 K by low power compressor. As a point to note, a low reciprocating speed leads to a reduction in the first stage cooling capacity.

5. References

- [1] Sahashi M, Tokai Y, Kuriyama T, Nakagome H, Li R, Ogawa M and Hashimoto T 1990 *Adv. Cryog. Eng.* **35B** pp 1175-1182
- [2] Kuriyama T, Hakamada R, Nakagome H, Tokai Y, Sahashi M, Li R, Yoshida O, Matsumoto K, and Hashimoto T 1990 *Adv. Cryog. Eng.* **35B** pp 1261-1269
- [3] SHI Cryogenics Group home page (<https://www.shicryogenics.com/products/cryocoolers/>)
- [4] Arita A, Takahashi K, Shiraiishi T, Fujieda S, Nakagawa T, Yamamoto T.A, Seino S and Masuyama S 2021 *Journal of Physics* **1857** 012009 pp 1-6
- [5] Masuyama S, Matsumoto K and Numazawa T 2021 *Journal of Physics* **1857** 012007 pp 1-7
- [6] Radebaugh R 1997 *Proc. 16th Int. Cryog. Eng. Conf.* pp 33-44
- [7] Kondo Y, Terai M, Nishikawa Y and Sugiyama O 2005 *Cryocoolers* **13** pp 681-687
- [8] Masuyama S and Numazawa T 2018 *Mat. Sci. and Eng.* **278** 012041 pp 1-6

Acknowledgments

This study was supported by JST-Mirai Program, Grant Number JPMJMI18A3, Japan.