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Characteristics of a 1.6 W Gifford-McMahon Cryocooler with a Double Pipe Regenerator

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Abstract. This paper focuses on the second stage regenerator of a 4 K Gifford-McMahon (G-M) cryocooler. A three-layer layout of lead (Pb), $HoCu_2$ and Gd_2O_2S spheres in the second stage regenerator derives a good performance at 4 K. After some modifications, we confirmed that the cooling power of 1.60 W at 4.2 K was achieved by using this three-layer layout. A two-stage G-M cryocooler is RDK-408D2 (SHI) and a compressor is C300G (SUZUKISHOKAN) with a rated electric input power of 7.3 kW at 60 Hz. In order to further improve, a double pipe regenerator was applied to the second stage regenerator. As a double pipe, a stainless steel pipe with thin wall was inserted in the coaxial direction into the second stage regenerator. The helium flow in the second stage regenerator is expected to be non-uniform flow because of the distribution of helium density and the imperfect packing of regenerator material. The double pipe regenerator is considered to have an effect of restraining the non-uniform flow. From the experimental results, the second stage cooling power of 1.67 W at 4.2 K and the first stage cooling power of 64.9 W at 50 K were achieved.

1. Introduction

A regenerator has been a key focus influencing the cooling power and efficiency of regenerative cryocoolers because its efficiency is directly linked to the cooling performance. As an unchangeable physical property, a specific heat of pressurized helium gas increases steeply at the temperatures below 20 K that leads to a reduction in the heat exchange between regenerator material and helium gas. The second stage regenerator of 4 K cryocoolers, such as Gifford-McMahon (G-M) and G-M type pulse tube cryocoolers, is not able to avoid it. To suppress the reduction and improve the regenerator efficiency, some methods have been developed since a G-M cryocooler reached to 4 K in the 1990s.

As a major method, magnetic materials that have a large specific heat at around 4 K are filled in the cold-end side of the regenerator in which to increase the heat capacity as a layer layout with a metallic material. Holmium copper ($HoCu_2$) and gadolinium oxysulfide (Gd_2O_2S, GOS) [1, 2] will be considered as representative magnetic materials. In the metallic materials, lead (Pb) has been used for the long term. In recent years, cryocoolers using bismuth (Bi) or zinc (Zn) instead of Pb have been developed. [3]

Another method is that a set of stacked meshes is partially inserted in the second stage regenerator in which sphere material is filled. [4, 5] The experimental results show the cooling power of 4 K and 10 K G-M cryocoolers is improved. It is thought that the non-uniform flow of helium gas in the regenerator is rectified by passing through the stacked meshes.

In 2016, Masuyama and Numazawa introduced a new regenerator structure named double pipe regenerator that was applied to the second stage regenerator with a two-layer layout comprising of Pb and $HoCu_2$ spheres. [6] The cooing power at 4.2 K of G-M cryocooler was improved by 7%.

In this paper, the double pipe regenerator is applied to a three-layer layout comprising of Pb, $HoCu_2$ and GOS spheres. The second stage regenerator structure and detailed experimental results for cooling performance will be presented.

2. Experimental Set-up

2.1. Two-stage G-M cryocooler

A conventional two-stage G-M cryocooler, RDK-408D2 (SHI), was used to survey the characteristics of double pipe regenerator. The cooling power of catalog specifications is 1 W at 4.2 K. A compressor is C300G (SUZUKISHOKAN) with a rated electrical input power of 7.3 kW at 60 Hz. The operating frequency controlled by inverter and the initial charging pressure are 1.2 Hz and 1.6 MPa, respectively. All the experiments have been carried out under these conditions. Figure 1 shows a schematic diagram of the G-M cryocooler and compressor. Silicon (Si) diode thermometers are mounted on the first and second stages. To adjust the stage temperatures, electric heaters are also attached. These data are connected to a PC for data acquisition. A radiation shield, which is cooled with the first stage, covers the second stage and cylinder. The pressure in the vacuum chamber is less than 10^{-4} Pa.

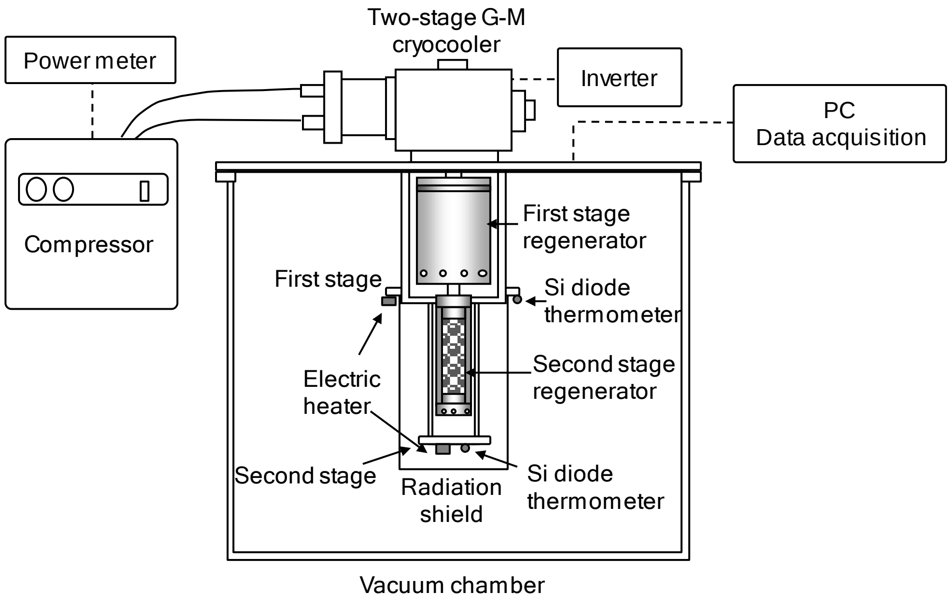

Figure 1. A schematic diagram of the two-stage G-M cryocooler, compressor and data acquisition system.

2.2 Double pipe regenerator

Figure 2 presents two types of the second stage regenerators (the part in which regenerator materials are packed). The regenerator has a length and inner diameter of 140 mm and 35 mm, respectively. Figure 2 (a) shows a three-layer layout (hereinafter called "three-layer") with Pb, $HoCu_2$ and GOS spheres. The volumetric filling ratio of Pb (0.212 - 0.3 mm), $HoCu_2$ (0.15 - 0.3 mm) and GOS (0.25 - 0.3 mm) spheres is 50, 20 and 30%, respectively. Parentheses show a sphere diameter of each material. Figure 2 (b) shows a double pipe regenerator with three-layer layout (hereinafter called "three-layer pipe"). A stainless steel pipe is inserted in the coaxial direction of the Pb part. This pipe has a 10 mm in outer diameter, 0.5 mm in thickness, and 67 mm in length. The specification of the pipe was decided by previous study. [6] Note that thickness is not optimized since thermal conduction loss exists. The calculated thermal conduction loss of the pipe is approximately 44 mW (thermal conductivity of stainless steel from 60 K to 4.2 K was used). Using a thinner pipe is able to reduce the thermal loss.

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. Note that its separator is not shown in Figure 2.

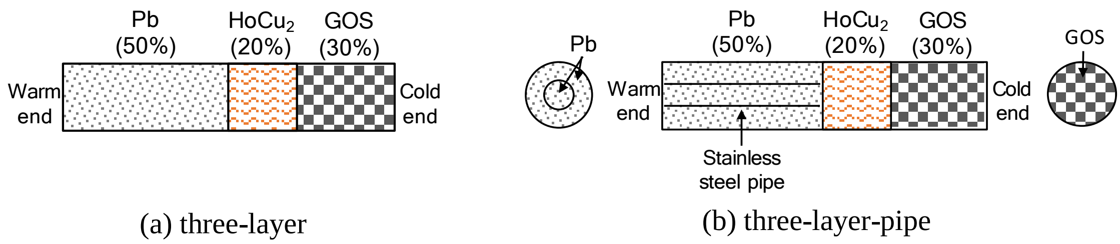

Figure 2. Schematic diagrams of the second stage regenerators: (a) three-layer layout with Pb, $HoCu_2$ and GOS spheres (three-layer), (b) double pipe regenerator (three-layer-pipe). A stainless steel pipe is inserted in the Pb part.

3. Experimental results

3.1 Cooling power measurement

The two-stage G-M cryocooler was operated form room temperature. After approximately two hours, the temperature of each cooling stage stabilized. The lowest temperature of three-layer and three-layer pipe was 2.56 K and 2.58 K, respectively. Then the cooling power was measured by adding heat load by electric heater.

Figure 3 shows a comparison of the cooling power results for three-layer and three-layer pipe. The first stage temperature was varied from 24 K (lowest temperature of the first stage) to 67 K while the second stage was producing the cooling power at 4.2 K. As shown, the cooling power of the three-layer is divided into three part with increasing, flat, and decreasing areas. The maximum cooling power of the three-layer was 1.60 W. The temperature range of the flat area is from 47 K to 57 K at which its maximum power is maintained.

In contrast, the three-layer pipe shows a convex curve. The cooling power that is more than 1.60 W is produced in the temperature range where the three-layer keeps flat area. The effect of the double pipe

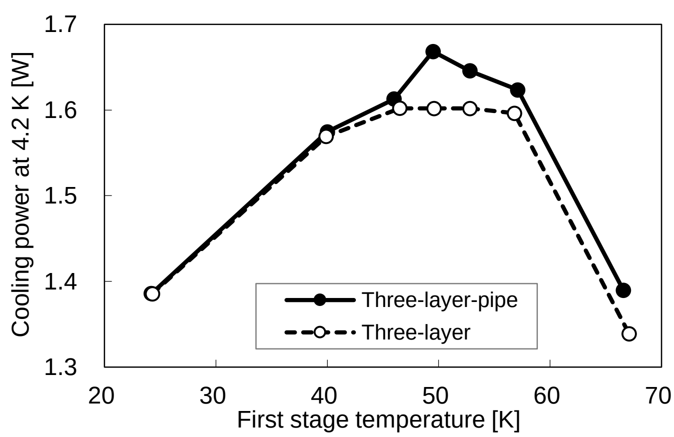

Figure 3. Comparison of the cooling power at 4.2 K for three-layer and three-layer pipe.

regenerator is appearing clearly. The maximum cooling power of 1.67 W at 4.2 K achieved at the first stage temperature of 50 K. The cooling power characteristics will be explained at "Discussion" section.

Figure 4 presents the first stage cooling power. The second stage was fixed at 4.2 K. The three-layer and three-layer pipe have almost the same cooling power. At 50 K, the cooling power of 64.9 W was achieved. The electrical input power of the compressor measured by power meter was 7.37 kW.

3.2 Efficiency evaluation

To evaluate the efficiency of cryocoolers, percent of Carnot has been often used. The calculated percent of Carnot at 4.2 K is 1.6%. In 2015, Green has presented the following equation to estimate the efficiency η for two-stage cryocoolers [7] :

$$\eta = \frac{1}{P_{com}}\left(Q_1\frac{300-T_1}{T_1}+Q_2\frac{300-T_2}{T_2}\right)\times 100 \qquad (1)$$

where Q_1 is the first stage cooling power that produces at temperature T_1. Q_2 is the second stage cooling power that produces at temperature T_2, simultaneously. P_{com} is the electrical input power of

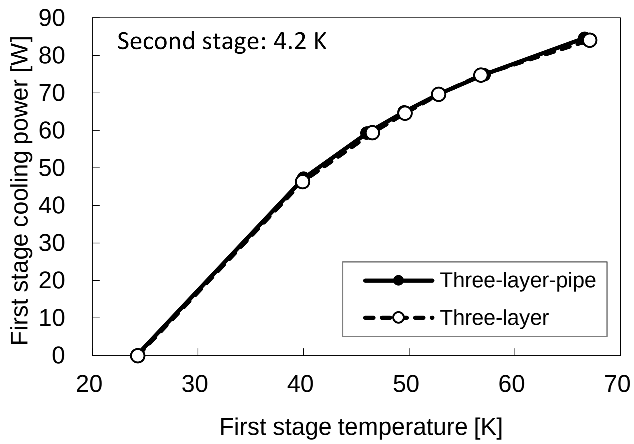

Figure 4. Comparison of the first stage cooling power for three-layer and three-layer pipe.

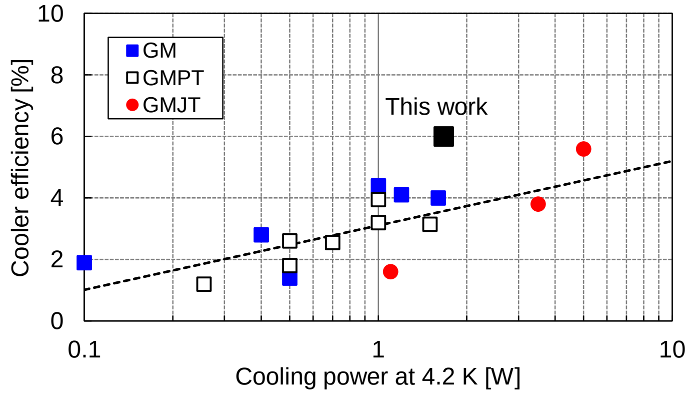

Figure 5. The efficiency of 4 K cryocoolers as a function of the cooling power at 4.2 K (GM: Gifford-McMahon, GMPT: GM type pulse tube, GMJT: GM with J-T valve). [7]

the compressor. Substituting the experimental results of the double pipe regenerator at 4.2 K and 50 K into Equation (1), one obtains the efficiency of 6.0%. Green also summarized the efficiency of 4 K cryocoolers with different types as well as the fitting curve shown in Figure 5. The efficiency of 6.0% of this work was also plotted. It is clear that the efficiency of this work is higher than that of other cryocoolers at the same cooling power.

4. Discussion

In this section, the effect of double pipe regenerator is revealed by characteristics of the second stage regenerator including the helium properties, where we assumed that the temperatures of the first stage and the warm end of the second stage are the same. Figure 6 shows the temperature distribution of the three-layer at three warm end (normalized length equal to 0) of 30 K, 50 K and 70 K by using regenerator software of REGEN3.3 [8] which is based on one dimensional equations. The cold end (normalized length equal to 1) was fixed at 4.2 K. From Figure 6, we calculated the helium density at a mean pressure of 1.5 MPa shown in Figure 7. The density of the warm end of 30 K is larger than that of 50 K at a normalized length of 0 to 0.5. After that, two curves are in agreement at a high density. This means that increasing the warm end from 30 K to 50 K decreases an amount of helium gas in the regenerator. The decrease in the helium gas increases the mass flow rate at the cold end that leads to an improvement in the cooling power. The increase in the mass flow rate, $\Delta\dot{m}$, is given by

$$\Delta\dot{m} = \alpha f_r V_r \int_0^1 (\rho_{30K} - \rho_{50K}) dx = 0.87 \text{ g/s} \tag{2}$$

where α is the porosity, f_r is the operating frequency, V_r is the regenerator volume, ρ is the helium density, the subscripts of 30 K and 50 K refer to the warm end, and x is the normalized length. The

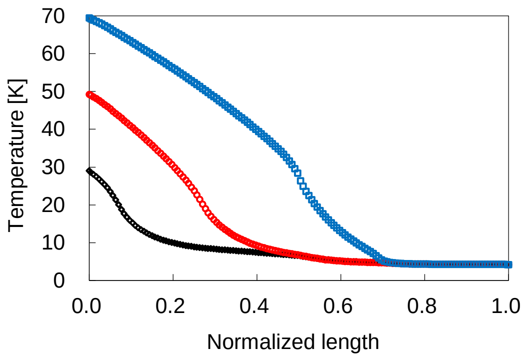

Figure 6. Simulated temperature distribution of the three-layer of Pb, $HoCu_2$ and GOS for three warm end temperatures of 30 K, 50 K and 70 K.

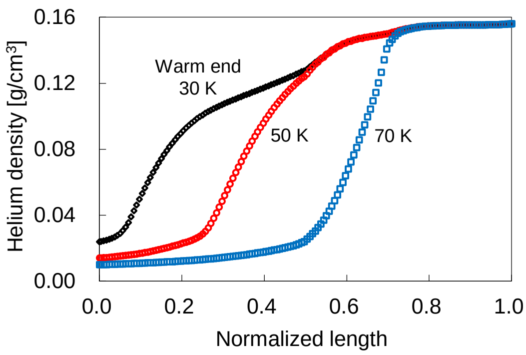

Figure 7. Calculated helium density by temperature distribution from Figure 6 for three warm end temperatures of 30 K, 50 K and 70 K.

Table 1. Comparison of calculated mass flow rate at the cold end by REGEN3.3 and measured cooling power at 4.2 K for three-layer and three-layer pipe.

Regenerator type	Calculated mass flow rate at the cold end [g/s]			Measured cooling power at 4.2 K [W]	
	Warm end temp.		Increase in mass flow	Warm end temp.	
	30 K	50 K	(30 K → 50 K)	30 K	50 K
Three-layer	5.70	6.25	0.55	1.45	1.60
Three-layer pipe (double pipe)	5.70	6.52	0.82	1.45	1.67

increase in the mass flow rate of 0.87 g/s was estimated. This mass flow rate can be achieved when the helium is uniform flow (one dimensional flow) in the second stage regenerator.

Next, we calculated the mass flow rate at the cold end by REGEN3.3 to reproduce the measured cooling power at 4.2 K. It was performed at two warm end temperatures of 30 K and 50 K. The calculated results are summarized in Table 1. In the case of the three-layer pipe (double pipe), the increase in the mass flow rate from 30 K to 50 K is 0.82 g/s which agrees closely with the estimated value of 0.87 g/s from Equation (2). In the case of the three-layer, the increase in the mass flow rate is 0.55 g/s. The helium flow in the second stage regenerator is expected to be non-uniform flow because of the distribution of helium density and the imperfect packing of regenerator material. Consequently, the mass flow rate at the cold end is decreased. The value of 0.55 g/s shows that the influence of non-uniform flow in the three-layer is larger than that of the three-layer pipe. The effect of non-uniform flow is considered to be large in the Pb part due to low helium density. Thus, the double pipe regenerator is able to restrain the non-uniform flow, then increase the mass flow rate at the cold end.

On the other hand, the cooling power at 4.2 K deteriorates with too high warm end temperatures exceeding 70 K. It can predict from the cooling power results shown in Figure 3. As shown in Figure 7, the helium density of the warm end of 70 K occupies a long length with lower density at the warm side in the regenerator. It indicates that the heat exchange between regenerator material and helium gas will be insufficient. Thus, regenerator loss becomes large that leads to a decrease in the cooling power.

5. Summary

To improve the efficiency and cooling power at 4.2 K of a G-M cryocooler, a double pipe regenerator was applied to the second stage regenerator comprising of Pb, $HoCu_2$ and GOS spheres. The second stage cooling power of 1.67 W at 4.2 K and the first stage cooling power of 64.9 W at 50 K were achieved. The experimental results prove that the double pipe regenerator is able to improve the second stage cooling power at 4.2 K. The regenerator analysis shows that the double pipe regenerator is able to restrain the non-uniform flow, then increase the mass flow rate at the cold end. This effect becomes large at the first stage temperature of around 50 K.

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Acknowledgments

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