A Novel Approach to Optimize the 2nd Stage Regenerator Configuration of a 4K Gifford-McMahon Cryocooler

S. Masuyama[1], Y. Hiratsuka[2] and T. Numazawa[3]

[1]Oshima National College of Maritime Technology,
Oshima, Yamaguchi, 742-2193, JAPAN
[2]Sumitomo Heavy Industries, Ltd.,
Nishitokyo, Tokyo, 188-8585, JAPAN
[3]National Institute for Materials Science
Tsukuba, Ibaraki, 305-0003, JAPAN

ABSTRACT

This paper presents a novel method to optimize the 2nd stage regenerator configuration to improve the cooling efficiency of a 4K Gifford-McMahon (G-M) cryocooler. In general, it is not easy to find out the optimum regenerator configuration by experiments, because changing it requires simultaneously changing several cryocooler components. From this point of view, we have developed a novel method that can equivalently change the regenerator configuration by using a bakelite rod or cone. The bakelite rod or cone is inserted in the co-axial direction of the 2nd stage regenerator in which a regenerator material of spheres is filled. The inserted bakelite is a dummy volume that has no regenerative effect. Therefore the 2nd stage regenerator configuration can be changed by adjusting the geometry of the bakelite. A conventional two-stage G-M cryocooler of 1W-model has been tested to evaluate the effect of this method. The experimental results prove that inserting the optimized bakelite volume improves the 2nd stage cooling power at 4.2 K as well as the 1st stage cooling power at 40 K.

INTRODUCTION

In order to improve the cooling efficiency of 4K Gifford-McMahon (G-M) cryocoolers, many approaches and modifications, such as development of regenerator material, optimizing the valve timing, and remodeling of several parts, have been carried out since the 1990s. The regenerator, including the regenerator material, has been a key focus because its efficiency is directly linked to the cooling performance. In recent years, some interesting topics have been published. Nakano et al.[1] have developed a magnetic compound of erbium nitride (ErN) as a new candidate regenerator material for 4K cryocoolers. The volumetric specific heat of ErN is larger than that of holmium copper 2 ($HoCu_2$) at temperatures around 4 K, so that the cooling power at 4.2 K can be improved by packing the ErN spheres in the cold side of the 2nd stage regenerator. Xu and Morie[2] presented a calculation result that the performance of a 4K G-M cryocooler is able to be improved by shifting the temperature profile in the 2nd stage regenerator to a higher level by reducing the heat capacity of the regenerator material in the warm side.

Masuyama et al.[3] developed a new filling method for regenerator materials called a co-axial layout. The advantage of the co-axial layout is that the properties of the two regenerator materials are able to be utilized at the same temperature range in the regenerator.

On the other hand, it is not easy to find out the optimum filling weight of regenerator material by experiments. This is because when the filling weight of regenerator material is changed, other components including a regenerator configuration must be remade simultaneously. As an answer of this arduous problem, we presented an improved method in a preceding paper[4] in 2014. This method utilized a bakelite rod as a dummy volume when inserted in the co-axial direction of a 2nd stage regenerator in which $HoCu_2$ spheres are filled. The experimental result showed that the filling weight of $HoCu_2$ is able to be reduce by approximately 10% without a large deterioration of the cooling power of 1W-class at 4.2 K.

This paper describes an approach to optimize the 2nd stage regenerator configuration. This approach derives from the above method which used a bakelite rod. Inserting a bakelite rod in the regenerator is considered to equivalently change the regenerator configuration without remaking other components. Therefore, we can design and test many types of regenerator configurations by only changing the geometry of the bakelite. In this paper, five types of 2nd stage regenerator configurations of a G-M cryocooler have been tested to improve the cooling performance.

G-M CRYOCOOLER AND REGENERATOR CONFIGURATIONS

Two-stage G-M Cryocooler

A conventional two-stage G-M cryocooler, RDK-408D2 (SHI), with a water cooling compressor, C300G (SUZUKISHOKAN), has been tested. The operating frequency of the G-M cryocooler is 1.2 Hz, and the input electric power is 7.3 kW. The initial charging pressure of helium gas is 1.6 MPa. All the experiments have been carried out under these conditions. A schematic diagram of the two-stage G-M cryocooler is shown in Fig. 1. Two calibrated silicon (Si) diode thermometers and two electric heaters are attached to the 1st and 2nd stages. The 2nd stage and cylinder are covered by a radiation shield which is cooled with the 1st stage. The G-M cryocooler is operated in a vacuum condition of less than 10^{-4} Pa.

2nd Stage Regenerator Configurations

Five types of regenerator structures (the part in which regenerator materials are installed) are shown in Figs. 2 through 4. A general two-layer regenerator structure (hereinafter called "normal") with $HoCu_2$ and lead (Pb) spheres is shown in Fig. 2. The cold side is packed with 50% by volume of $HoCu_2$ spheres with a diameter of 0.15-0.35 mm ($HoCu_2$ part), and the warm

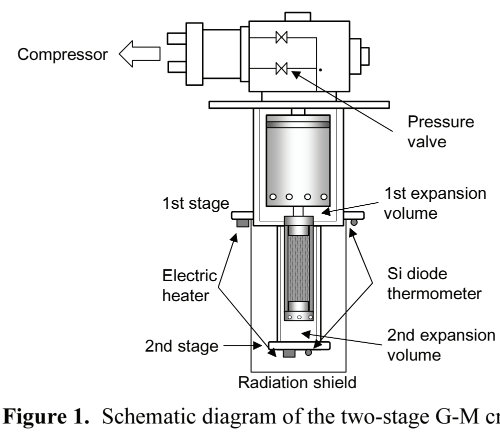

Figure 1. Schematic diagram of the two-stage G-M cryocooler.

side is packed by Pb spheres with a diameter of 0.212-0.3 mm (Pb part). The filling weight of $HoCu_2$ and Pb spheres is 310 and 330 g, respectively. To separate these regenerator materials, a separator, which is made of packed fine wire stainless steel screens, is set in the middle. The total length of the $HoCu_2$ and Pb parts is 14 cm, and the inner diameter of the regenerator is 3 cm, so that the volume of regenerator housing is 99 cm^3. Table 1 gives these dimensions of the 2nd stage regenerator housing.

Two types of regenerator structures with an inserted bakelite rod are shown in Fig. 3: type (a), a regenerator structure with a bakelite rod inserted in the $HoCu_2$ part (hereinafter called "$HoCu_2$-rod"); type (b), a regenerator structure with a bakelite rod inserted in the Pb part (hereinafter called "Pb-rod"). Three sizes of bakelite rods have been tested. The diameters are 0.7, 1.0, and 1.3 cm. The rod length is fixed at 7 cm. In these structures, the helium flow area of a half regenerator length is narrowed.

Two other types of regenerator structures using an inserted bakelite cone are shown in Fig. 4: type (a), a regenerator structure with a bakelite cone inserted in the $HoCu_2$ part (hereinafter called "$HoCu_2$-cone"); type (b), a regenerator structure with a bakelite cone inserted in the Pb part (hereinafter called "Pb-cone"). Three sizes of bakelite cones have been tested. The base diameters are 1.0, 1.5, and 2.0 cm. The height is fixed at 7 cm. In these structures, the helium flow area of a half regenerator length has a taper shape.

The specifications of the bakelite rods and cones are listed in Table 2. Inserting bakelite rods or cones decreases the filling weight of regenerator material and leads to reducing the heat capacity of the 2nd stage regenerator.

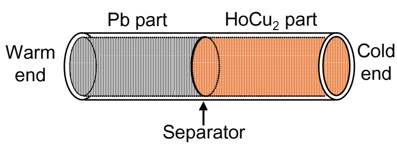

Figure 2. Two-layer configuration with Pb and $HoCu_2$ spheres: normal type.

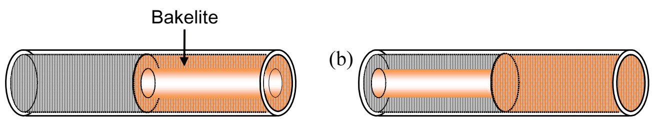

Figure 3. Two-layer configuration inserted bakelite rod: (a) $HoCu_2$-rod, and (b) Pb-rod.

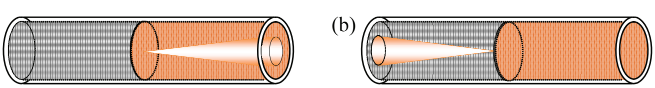

Figure 4. Two-layer configuration inserted bakelite cone: (a) $HoCu_2$-cone, and (b) Pb-cone.

Table 1. Dimensions of the 2nd stage regenerator housing of the Pb part and the $HoCu_2$ part.

Regenerator housing	Inner diameter [cm]	Length [cm]	Cross-sectional area [cm^2]	Volume [cm^3]
Pb part	3	7	7.1	49.5
$HoCu_2$ part	3	7	7.1	49.5

Table 2. Specifications of the bakelite types of rods and cones.

Bakelite type	Diameter [cm]	Length [cm]	Cross-sectional area [cm²]	Volume [cm³]
	0.7	7	0.38	2.7
Rod	1.0	7	0.79	5.5
	1.3	7	1.3	9.3
Bakelite type	**Base diameter [cm]**	**Height [cm]**	**Cross-sectional area of base [cm²]**	**Volume [cm³]**
	1.0	7	0.79	1.8
Cone	1.5	7	1.8	4.1
	2.0	7	3.1	7.3

EXPERIMANTAL RESULTS

The cool-down tests of the GM cryocooler were started from room temperature. The cool-down characteristics were almost the same for all the regenerator configurations. The temperatures of the 1st and 2nd stages were fixed at 40 K and 4.2 K by adjusting electric heaters, respectively. Then, cooling power measurements were made.

Figure 5 shows the results of the cooling power measurements of the bakelite rod configurations ($HoCu_2$-rod and Pb-rod) as well as the normal type. The horizontal axis is the volume of the inserted bakelite rod. Therefore, the bakelite volume of 0 cm^3 shows the cooling power of the normal configuration. According to the figure, the cooling power of the normal configuration at 4.2 K and 40 K achieves 1.28 W and 44.0 W, respectively. In the case of the $HoCu_2$-rod, when a bakelite volume of 2.7 cm^3 is used, the cooling power of the 1st and 2nd stages is the same as the normal. After that, the 2nd stage cooling power decreases with increasing bakelite volume, whereas the 1st stage cooling power improves to 46.2 W. In the case of the Pb-rod, the 2nd stage cooling power is improved with a bakelite volume of 5.5 cm^3. Its cooling power reaches 1.30 W. When the bakelite volume is 9.3 cm^3, the cooling power is decreased to 1.26 W. However, its rate of reduction is less than with the $HoCu_2$-rod. The 1st stage cooling power with the Pb-rod improves with increasing bakelite volume.

Figure 6 shows the results of the cooling power measurements of the bakelite cone configurations ($HoCu_2$-cone and Pb-cone). In the case of $HoCu_2$-cone, the 2nd stage cooling power decreases with increasing bakelite volume. Its reduction rate is larger than the $HoCu_2$-rod.

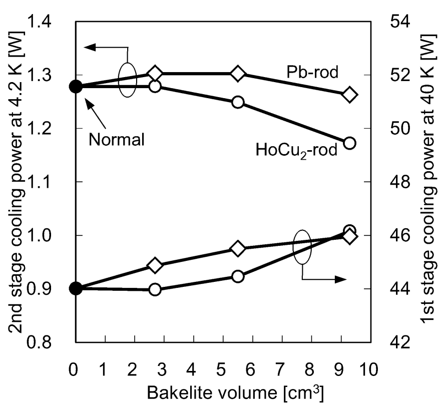

Figure 5. Comparison of the cooling power at 4.2 K and 40 K for the $HoCu_2$-rod and the Pb-rod.

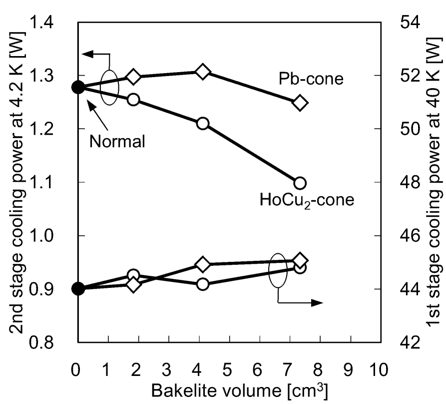

Figure 6. Comparison of the cooling power at 4.2 K and 40 K for the $HoCu_2$-cone and the Pb-cone.

In the case of the Pb-cone, the 2nd stage cooling power improves by a bakelite volume of 4.1 cm^3, and then decreases. The maximum attainable cooling power is 1.31 W. This characteristic is similar to the Pb-rod type. The 1st stage cooling power of the $HoCu_2$-cone and Pb-cone improves with increasing bakelite volume.

From the above experimental results, changing the regenerator configuration influences the cooling performance directly. Two types of regenerator configurations of Pb-rod and Pb-cone are able to improve the 2nd stage cooling power at 4.2 K. The optimum bakelite volume is approximately 5 cm^3 — that is one tenth of the Pb part regenerator volume. On the other hand, although the cooling power at 4.2 K of the $HoCu_2$-rod is smaller than that of the Pb-rod, the $HoCu_2$-rod has a merit that is able to reduce the filling weight of $HoCu_2$ without a large deterioration of the cooling power at 4.2 K. When the bakelite volume is 9.3 cm^3, the filling weight of $HoCu_2$ is decreased from 310 g (normal type) to 254 g.

NUMERICAL ANALYSIS

Inserting a bakelite rod or cone into the regenerator reduces the filling weight of regenerator material and leads to a decrease in the heat capacity. In general, a decrease in the heat capacity of the regenerator is considered to deteriorate the cooling performance. However, the experimental results are not in agreement with this consideration.

In this section, in order to clarify the effect of the bakelite, a numerical analysis is presented. The basic first-order-model equations and the calculation method are explained in Refs. [5, 6]. The numerical model of the regenerator configuration is of the Pb-rod type, and the specifications of the G-M cryocooler are the same as the experimental conditions. The calculated results are presented in Figs. 7 and 8. The pressure difference at the expansion volume of the 1st and 2nd stages and the helium flow rate at the pressure valve are plotted as a function of the bakelite volume shown in Fig. 7. The pressure difference at the expansion volume of the 1st and 2nd stages increases with increasing bakelite volume. In contrast, the helium flow rate at the pressure valve decreases with increasing bakelite volume. From these results, inserting a bakelite rod has two positive effects for the cooling performance: an increase in pressure ratio that leads to an improvement in the PV work at the expansion volume, and suppression of the helium flow rate in the regenerator that leads to an improvement in the regenerator efficiency. We confirmed that the calculated results of the Pb-cone have similar characteristics to the Pb-rod.

The cooling power of the 1st and 2nd stages is presented in Fig. 8 in which the calculated results are compared with the experimental results. The curves of calculated results do not show an improvement in the cooling power like the experimental results. However, deterioration also

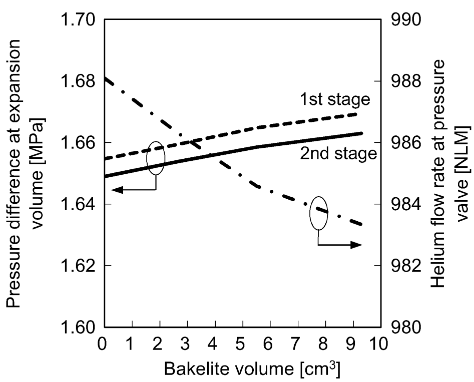

Figure 7. Calculated pressure difference at expansion volume and helium flow rate at pressure valve as a function of the bakelite volume for the Pb-rod.

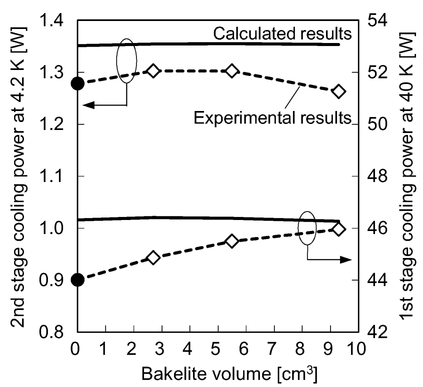

Figure 8. Comparison of the cooling power at 4.2 K and 40 K for calculated and experimental results of the Pb-rod.

does not show. It seems that the two positive effects of the bakelite rod are eliminated by the decreased heat capacity of regenerator.

The implementation of the numerical analysis is able to qualitatively evaluate the effect of the inserted bakelite. As a next step, we will need to derive an improved optimum configuration using the numerical analysis.

SUMMARY

As a novel approach to optimize the 2nd stage regenerator configuration, a few types of bakelite rods and cones were inserted in the 2nd stage regenerator of a 4K G-M cryocooler. This approach is able to equivalently change the regenerator configuration so that different configurations can be quickly evaluated. The experimental results prove that the Pb-rod and Pb-cone types are able to improve the 2nd stage cooling power at 4.2 K as well as the 1st stage cooling power at 40 K. The optimum bakelite volume of approximately 5 cm^3 that is one tenth of the Pb part regenerator volume was established. This approach has been shown to be an effective and easy experimental method to establish the optimum regenerator configuration for 4K cryocoolers.

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