Improvement of 4 K cooling power by coaxial pipe regenerator for a Gifford-McMahon cryocooler

S Masuyama¹, K Matsumoto² and T Numazawa³

1Department of Electronic-Mechanical Engineering, National Institute of Technology, Oshima College, Yamaguchi, 742-2193, Japan
2Department of Physics, Kanazawa University, Kanazawa 921-8111, Japan
3National Institute of Materials Science, Tsukuba, 302-0003, Japan

masuyama@oshima-k.ac.jp

Abstract. This paper presents the experimental results of 4.2 K cooling power of a Gifford-McMahon (G-M) cryocooler. To improve the cooling power, an original regenerator structure named coaxial pipe regenerator was applied to the second stage regenerator. This structure is that a stainless steel pipe is inserted in the coaxial direction of the second stage regenerator. An effect of the coaxial pipe is considered to rectify the helium flow in the regenerator that leads to an increase in the mass flow rate to the expansion space. Then, an improvement in the cooling power is expected. The second stage regenerator is comprised of three-layer of Pb (warm side), HoCu₂ (middle) and Gd₂O₂S (cold side) spheres of which the volume filling rate is 50, 20 and 30%, respectively. The coaxial pipe is applied to each material layer independently to survey an improvement effect of the cooling power at 4.2 K. These coaxial pipe regenerators were tested with a G-M cryocooler of one-watt model (RDK-408D2, SHI) and a scroll-type compressor (SSC-3700, SUZUKISHOKAN). The three-layer regenerator (without coaxial pipe) obtained the cooling power of 1.70 W. When the coaxial pipe was applied to the Pb layer, the cooling power of 1.79 W was achieved with the electrical input of compressor of 7.06 kW. In contrast, the coaxial pipe of HoCu₂ layer and Gd₂O₂S layer showed no conspicuous improvement. These results prove that the flow condition of helium in the Pb layer significantly affects the 4 K cooling power.

1. Introduction

Obtaining the temperatures below liquid helium region by regenerative cryocoolers, such as Gifford-McMahon (G-M) and G-M type pulse tube cryocoolers, has been easy since magnetic regenerator materials were developed in 1990s [1,2]. From this good advantage, the 4 K cryocoolers are required certainly in order to build advanced cryogenic systems, such as MRI (magnetic resonance imaging), superconducting Maglev (magnetic levitation) train and sensor cooling. On the other hand, much electrical input is needed to maintain the 4 K level, and percent of Carnot is 1% level. Many users and researchers are desiring development of high efficiency 4 K cryocoolers because the cooling efficiency directly links to the running cost of cryogenic systems. A major reason leading to the low efficiency at 4 K is specific heat of high pressure helium increasing steeply at temperatures below 20 K. To compete with this unchangeable thermal property, three representative magnetic materials of Er₃Ni, HoCu₂ and Gd₂O₂S have been used as the second stage regenerator magnetic materials. The second stage regenerator of 4 K cryocoolers needs to maintain the temperature gradient from approximately 50 to 4
K level in its inside. To maintain it, these magnetic materials have been used with metallic materials, lead (Pb) or bismuth (Bi), and are filled as a layer structure to effectively utilize the specific heat depending on the temperature. Simultaneously, the filling quantities are determined in consideration of temperature distribution in the regenerator.

In recent years, Nakagawa et al. have examined a nitride material, Er$_2$Ho$_{1-x}$N$_x$, to survey the possibility as a new regenerator material [3]. The feature of this material is that the peak temperature of specific heat can be controlled from 4.4 to 13 K by varying the composition ratio $x$. The experimental result showed that the cooling power at 4.2 K was confirmed, however, the measured power was smaller than the expected value. This major reason is that a tested second stage regenerator of a G-M cryocooler had a high porosity, where a porosity of regenerator is defined as the total volume of void spaces divided by the regenerator volume. Spherical material synthesized by their own method was filled to the regenerator. The porosity of the tested regenerator was around 0.48 (in general, a porosity of regenerator filled by spheres is about 0.35). The reason of the high porosity is that the synthesized spheres had rough surface with pores which caused during the synthesis process. A high porosity brings generally a low heat capacity that leads to a decrease in the cooling power at 4.2 K.

On the other hand, the ideal helium flow in regenerator is one dimensional (uniform) flow. The porosity of the perfect packing by spheres having the same sphere diameter is 0.26. The standard value of 0.35 is 1.3 times as large as it. This is caused by imperfect packing of spherical material and dispersion of its sphere size. From this, actual second stage regenerators are predicted to have non-uniform flow. The non-uniform flow decreases the mass flow rate in the expansion space leading to a decrease in the PV work. A method to restrict the non-uniform is that a stacked fine mesh is inserted horizontally in a suitable location in regenerator filled by spheres. This effect has been proven experimentally by some researchers [4, 5].

As another method, authors proposed an original regenerator structure that presents in this paper in 2015 [6]. Since then, we have carried out its performance tests, and after that, this structure was named as “coaxial pipe regenerator”. The latest remarkable experimental results, and simulation results of a 4 K regenerator will be presented.

2. Numerical analysis of 4 K regenerator

Figure 1 shows the specific heat of four kinds of regenerator materials as well as those of high pressure helium gas from 0.5 to 2 MPa. From the temperature dependence of regenerator materials, a three-layer layout of Pb, HoCu$_2$, and Gd$_2$O$_2$S produces large cooling power at 4 K level. The volume filling rate of Pb 50%, HoCu$_2$ 20%, and Gd$_2$O$_2$S 30% was decided from our previous studies [7]. To clear the helium behavior in its regenerator, a numerical analysis has been done by using REGEN 3.3 [8]. This software can analysis the regenerator performance such as cooling power, efficiency, pressure drop, etc. at the temperatures from 300 to 4 K. One dimensional helium flow through the regenerator is modeled, and real gas properties of helium are considered. Figure 2 shows a calculation model that has the same

![Figure 1](image1.png)

**Figure 1.** Temperature dependence of specific heat of four regenerator materials and high pressure helium gas.

![Figure 2](image2.png)

**Figure 2.** Calculation model of three-layer of the second stage regenerator.
specification of a tested regenerator (detailed specification will be explained in the section of experimental set-up). The simulated temperature distribution of its three-layer is shown in Figure 3. The cold end temperature (normalized length equal to 1) was fixed at 4.2 K, and the temperature distributions were calculated with three kinds of warm end (normalized length equal to 0) temperatures of 30, 50, and 70 K. From the curves, two features can be understandable. First is the temperature difference between compression (solid line) and expansion (dotted line) processes. Second is existence of a specific area where temperature does not change mostly. Its temperature is close to 4 K level. When the warm end of 30 K, the area is the longest. At 50 K, the area is about half of the whole length, and at 70 K, the area is the shortest. These characteristics are brought from the thermal property of high pressure helium. Similar temperature distribution has been observed experimentally by G-M cryocooler in 1996 [9]. A regenerator of this G-M cryocooler was separated from a displacer to avoid its mechanical movement, and five thermometers were embedded in the regenerator to directly measure the helium temperature distribution.

The specific heat of high pressure helium and the helium density increase steeply below 20 K. Figure 4 presents the helium density distribution in the same three-layer regenerator, which was calculated by combining the temperature distribution shown in figure 3 and the temperature dependence of helium density. The curves show that the helium density has a large difference at the normalized length of about 0.5. The warm end side (left side) has a low density, and conversely the cold end side (right side) has a high density. These results lead to the difference in the kinetic energy of helium gas arising in each layer to maintain the same pressure in the regenerator. A low density area, mainly Pb layer, has a large kinetic energy, and conversely a high density area, mainly Gd$_2$O$_2$S layer, has a small kinetic energy (the HoCu$_2$ layer is the middle of them). Therefore, the helium flow in the low density area is considered to be further non-uniform flow compared with the high density area. Thus the predicted non-uniform flow rate from the density distribution has the relation of Pb layer > HoCu$_2$ layer > Gd$_2$O$_2$S layer.

A regenerator filled with spheres is predicted to have non-uniform flow due to imperfect packing of regenerator material and dispersion of its sphere size. Furthermore, due to the density distribution in each layer from the above simulation results, the helium flow is considered to be further disturbed. To rectify the helium flow, a coaxial pipe regenerator was proposed and tested. The regenerator structure will be explained in the next section.

3. Experimental Set-up

3.1 Two-stage G-M cryocooler

A two stage G-M cryocooler of one-watt model (RDK-408D2, SHI) and a scroll type compressor (SSC-3700, SUZUKISHOKAN), rating electrical input of 7.3 kW at 60 Hz, were tested. Figure 5 shows photographs of G-M cryocooler and compressor. An initial pressure of helium of 1.6 MPa, and the
Operating speed of G-M cryocooler of 72 rpm were fixed. Figure 6 shows a schematic diagram of the G-M cryocooler with a vacuum chamber, and data acquisition system. Two silicon (Si) thermometers (DT470 series, LakeShore) and electric heaters were mounted on each cooling stage. These data are connected to a PC for data acquisition. A radiation shield, which was cooled with the first stage, covers the second stage and cylinder. The pressure in the vacuum chamber was less than 10⁻⁴ Pa.

3.2. Second stage regenerator and coaxial pipe regenerator
The second stage regenerator has a diameter of 15 mm, and a length of 140 mm (the part in which regenerator material is filled). Figure 7 shows a schematic diagram of the second stage regenerator of three-layer structure (hereinafter called “Three-layer type”). Three regenerator materials of Pb, HoCu₂ and Gd₂O₂S spheres are filled at the volume rate of 50, 20 and 30% with a porosity of 0.38, 0.35 and 0.39, respectively. Table 1 presents the sphere diameter. To fix and separate each material completely, a stacked stainless steel screen having a thickness of 4 mm is infixed.

Figure 8 shows a schematic diagram of three types of coaxial pipe regenerators: (a) Pb type, (b) HoCu₂ type and (c) Gd₂O₂S type. A stainless steel pipe is inserted in the coaxial direction for the purpose of rectifying the helium flow. The strategy of coaxial pipe regenerator is that the non-uniform flow changes to the uniform flow by coaxial pipe. Then the mass flow rate in the expansion space is expected to

| Table 1. Regenerator materials. |
|--------------------------|
| Material | Sphere diameter [mm] |
| Pb       | 0.21 – 0.30         |
| HoCu₂    | 0.15 – 0.30         |
| Gd₂O₂S   | 0.25 – 0.30         |

Figure 5. Photographs of compressor (SSC-3700) and cold head (RDK-408D2).

Figure 6. A schematic diagram of the G-M cryocooler and data acquisition system.

Figure 7. A three-layer regenerator.

Figure 8. Three types of coaxial pipe regenerators.

Figure 9. The warm end view of the coaxial of Pb type.
increase that leads to an improvement in the cooling power. The coaxial pipe was applied to each layer independently to survey an effect of the cooling power at 4.2 K. The inserted stainless steel pipe has an inner diameter of 9 mm and a thickness of 0.5 mm, and a length is adjusted to fit each layer. The pipe diameter was determined as reference in our paper in 2016 [10]. The three types of coaxial pipe regenerators and the three-layer type have the same filling rate of regenerator materials. Figure 9 shows an image photograph from the warm end view of the coaxial of Pb type.

4. Experimental results

4.1 Cool-down and lowest temperature

The cool-down tests were started from a room temperature without heat load by electric heater. Figure 10 shows the results of typical cool-down curves of the first and second stages. We confirmed that all regenerator types had almost the same cooling characteristics, and cool-down time of about 90 minutes until stage temperature stabilized. The lowest temperatures of four types of regenerators are summarized in figure 11. The lowest temperatures of the first and second stages are about 24 K and 2.4 K, respectively. The large influence on the lowest temperature by having inserted the pipe is not observed. However, the evaluation of these results is difficult because the low lowest temperature does not necessarily bring large cooling power at 4.2 K.

![Figure 10](image1.png)  
**Figure 10.** Typical cool-down curves of the first and second stages.

![Figure 11](image2.png)  
**Figure 11.** The lowest temperatures of the four types of regenerators.

4.2 Cooling power

The cooling power measurement was carried out by adding heat load to each stage. Figure 12 shows the cooling power at 4.2 K as a function of the first stage temperature from 24 K (lowest temperature of the first stage) to 65 K. All regenerator types have convex curve. The maximum cooling power at 4.2 K achieves at the first stage temperature of approximately 50 K.

The Pb type shows the largest cooling power over the measured temperature range except the high temperature side of around 65 K. Its maximum cooling power achieves to 1.79 W with the electrical input of compressor of 7.06 kW. The percent of Carnot at 4.2 K is 1.8%. Compared to the three-layer type of 1.70 W, the cooling power of the Pb type improves by 5%. The characteristics of other two types of the coaxial pipe regenerators, compared with the three-layer type, are that the Gd$_2$O$_2$S type has no effect of an improvement, or rather deterioration, and the HoCu$_2$ type has a rather improvement effect at more than 50 K. From the results, the flow condition of helium in the Pb layer significantly affects the 4.2 K cooling power (detailed analysis regarding the cooling power characteristics will be described in the section of discussion).

Figure 13 presents the first stage cooling power as a function of first stage temperature. The second stage was fixed at 4.2 K. The first stage cooling power does not almost depend on the regenerator types. The cooling power of 68 W at 50 K was achieved.
Figure 12. Experimental results of the cooling power at 4.2 K as a function of first stage temperature.

5. Discussion

In this section, the results of 4.2 K cooling power are discussed. To clarify the calculated results of the helium density distribution shown in figure 4, and the effect of the coaxial pipe regenerator, the amount of gas in the regenerator (three-layer type) was calculated by following equation:

\[
m = \int_0^{0.5} \alpha_{Pb} \rho(T)Adx + \int_{0.5}^{0.7} \alpha_{HoCu2} \rho(T)Adx + \int_{0.7}^{1} \alpha_{Gd2O2S} \rho(T)Adx
\]

where \(m\) is the mass of gas, \(\alpha\) is the porosity, \(\rho(T)\) is the helium density, \(T\) is the temperature, and \(A\) is the cross-sectional area of regenerator. Figure 14 shows the calculated results of the averaged amount of gas and kinetic energy (values in parentheses) of gas in the regenerator of three kinds of warm end temperatures. From the figure, two interesting features were found out. Firstly, the total amount of gas decreases with increasing warm end temperature. Secondly, the amount of gas and kinetic energy differ in each layer. This behavior of helium gas has been already predicted by the results of figure 4. The calculation results shown in figure 14 reveal the amount of gas and kinetic energy in each layer concretely.

The coaxial Pb type shown in figure 12 represents a large improvement in the 4.2 K cooling power except high temperature side of the first stage temperature. From figure 14, the amount of gas in Pb layer is the smallest in all the temperature range, and the kinetic energy in Pb layer is the largest at two warm end temperatures of 30 and 50 K, compared with two magnetic layers. This means that the non-uniform flow rate is large from 30 to 50 K. Then the helium flow is rectified by coaxial pipe. As a result, the mass flow rate in the expansion space is increased that leads to an improvement in the cooling power. On the other hand, the cooling power at the high temperature side is decreased. This reason is that there is no effect of the coaxial pipe due to kinetic energy being small. Thus the cooling power is almost the same as that of the three-layer type at around 65 K.

The coaxial HoCu\(_2\) type has a rather improvement in the cooling power at more than 50 K, compared with the three-layer type. In this temperature range, the amount of gas is decreased and the kinetic energy is increased in HoCu\(_2\) layer. These effects lead to an increase in the mass flow rate by coaxial pipe. In contrast, the amount of gas and the kinetic energy do not change at below 50 K. Therefore, the cooling power of HoCu\(_2\) type is almost the same as that of three-layer type.

The cooling power of the coaxial Gd\(_2\)O\(_2\)S type and the three-layer type are almost the same in all the temperature range. This reason is that the amount of gas and the kinetic energy in Gd\(_2\)O\(_2\)S layer do not change. However, it seems that the coaxial pipe is interfering with the helium flow from rather deterioration of the cooling power.
6. Summary
An original regenerator structure named coaxial pipe regenerator was applied to the second stage regenerator of a G-M cryocooler as an improvement method of the cooling power at 4.2 K. The second stage regenerator was comprised of three-layer structure of Pb, HoCu$_2$ and Gd$_2$O$_2$S spheres. The coaxial pipe regenerator was applied to each material layer independently to survey its effect. An effect of coaxial pipe is that the non-uniform flow caused by low density of helium gas and imperfect packing of regenerator materials is rectified. From the experimental results, applying the coaxial pipe regenerator to the Pb layer led to an improvement in the cooling power at 4.2 K. In contrast, the coaxial pipe of HoCu$_2$ layer and Gd$_2$O$_2$S layer showed no conspicuous improvement effect. These results prove that the flow condition of helium in the Pb layer, which is a low amount gas and a high kinetic energy area, significantly affects the 4 K cooling power.

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