A Double Pipe Regenerator for a 4 K Gifford-McMahon Cryocooler

S. Masuyama[1] and T. Numazawa[2]

[1]National Institute of Technology, Oshima College, Oshima, Japan
[2]National Institute for Materials Science, Tsukuba, Japan

ABSTRACT

A new regenerator structure named a *double pipe regenerator* was experimentally investigated. This structure was adapted to the second stage regenerator of a 4K Gifford-McMahon cryocooler to improve the cooling efficiency at 4.2 K. The double pipe regenerator consists of a regenerator housing and a stainless steel pipe. This pipe with a thin wall is inserted in the co-axial direction into the regenerator housing. The second stage regenerator was divided into two parts by two kinds of regenerator materials of lead (Pb) and holmium copper 2 ($HoCu_2$) spheres. These filling volume rate were 50%, respectively. Only the Pb part has the double pipe regenerator in consideration of the temperature distribution and helium properties.

The experimental results show that the cooling power was affected by the pipe size and the first stage temperature. The maximum cooling power at 4.2 K achieves 1.33 W with an input electric power of 7.3 kW. This is an improvement in the cooling power by 7%, compared with a conventional two-layer structure. Detailed experimental results will be shown in this paper.

INTRODUCTION

Regenerative 4K cryocoolers, Gifford-McMahon (G-M) and G-M type pulse tube cryocoolers, are widely used for advanced application, such as helium gas liquefaction and superconducting systems. An operation method of these cryocoolers is very easy, because users press the start button only. The cryocoolers are driven by the fixed operating frequency, and get to 4K level automatically. It seems apparently a complete machine. However, the cooling efficiency is insufficient. Much electrical input power is required to maintain the cooling temperatures of 4K level. The coefficient of performance of %Carnot is approximately one percent.

To improve the cooling efficiency, many modifications have been carried out since G-M cryocoolers reached the 4K level in the 1990s. In particular, the regenerator efficiency has been a key focus because this is directly linked to the cooling performance. One effective method is that a material which has a large specific heat at temperatures around 4K is packed in the regenerator. Holmium copper ($HoCu_2$) and gadolinium oxysulfide (Gd_2O_2S) will be considered as representative materials. In recent years, holmium-erbium based nitride has been developed[1,2] as a new candidate for 4K regenerator materials. The specific heat of this nitride is greater than that of $HoCu_2$ at temperatures around 4K.

Another approach with a modified regenerator configuration has been presented by Masuyama et al.[3-5] This approach has a regenerator configuration of a cylindrical form with a constant diameter.

Cryocoolers 19, edited by S.D. Miller and R.G. Ross, Jr.

In general, it is modified by using a bakelite rod. The bakelite rod is inserted in the regenerator as a dummy volume. This method was applied to the second stage regenerator of a 4K G-M cryocooler. The experimental result proved that this method improved the second stage cooling power at 4.2K slightly as well as the first stage cooling power at 40K.

This paper describes a new regenerator structure named a *double pipe regenerator* for the second stage regenerator of a 4K G-M cryocooler. This structure derives from the above method. The double pipe regenerator has a stainless steel pipe inserted into the regenerator. The regenerator structure and experimental results will be presented in this paper.

G-M CRYOCOOLER AND REGENERTAR CONFIGURATIONS

Two-stage G-M Cryocooler

To confirm the effect of the double pipe regenerator, a conventional two-stage G-M cryocooler, RDK-408D2 (SHI), with a water cooled compressor, C300G (SUZUKISHOKAN), were prepared. The operating conditions are as follows: the operating frequency of 1.2 Hz, the input electric power of 7.3 kW, and the initial charging pressure of helium gas of 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 Figure 1. Two calibrated silicon diode thermometers and two electric heaters are attached to the first and second stages, respectively. The second stage and cylinder are covered by a radiation shield which is cooled with the first stage. The G-M cryocooler is operated in a vacuum condition of less than 10^{-4} Pa.

Second Stage Regenerator Configurations

Schematic diagrams of the second stage regenerator (the part in which regenerator materials are installed) are shown in Figs. 2 and 3. A general two-layer regenerator (hereinafter called "two-layer") with $HoCu_2$ and lead (Pb) spheres is shown in Figure 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 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 g 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 are 14 cm, and the inner diameter of the regenerator is 3 cm, so that the volume of the regenerator housing is 99 cm^3. Table 1 gives these dimensions for the second stage regenerator housing.

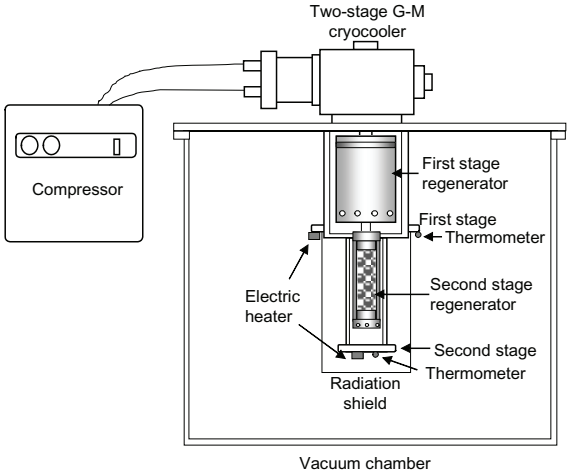

Figure 1. Schematic diagram of the two-stage G-M cryocooler and compressor

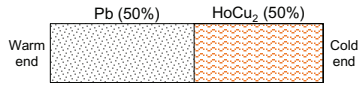

Figure 2. The second stage regenerator of two-layer with Pb and HoCu2 spheres

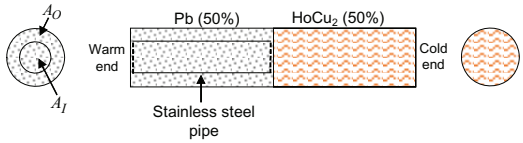

Figure 3. Double pipe regenerator with an inserted stainless steel pipe

Table 1. Dimensions of the second stage regenerator housing of the Pb part and the HoCu2 part.

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

The double pipe regenerator with a stainless steel pipe is shown in Figure 3. The pipe is inserted in the co-axial direction of the Pb part. An photograph of the warm end is shown in Figure 4. In the experiments, three types of stainless steel pipes were prepared (length and thickness are constant). Table 2 presents the specifications of the pipes, the cross-sectional ratio, A_I / A_O, where A_I is the inside area, A_O is the outside area given in Figure 3, and the calculated thermal conduction loss of the pipe. The thermal conductivity of stainless steel from 60 K to 4.2 K was used. The thermal conduction loss of the double pipe regenerator, shown in Figure 3, does exist. However, using a thinner pipe is effective to decrease this thermal loss.

EXPERIMANTAL RESULTS OF COOLING POWER

The cool-down tests of the G-M cryocooler were started from the room temperature. The cool-down characteristics were almost the same for all the regenerator configurations. The cool-down time to the lowest temperature was approximately two hours.

To measure the cooling power, the temperature of the second stage was held at 4.2 K, and the temperature of the first stage was varied by adjusting the electric heater.

Figure 5 shows the results of the cooling power at 4.2 K as a function of the first stage temperature. In the case of the two-layer, the cooling power of 1.24 W remains constant between 40 K and 57 K. With the first stage temperatures of 24 K or 66 K, the cooling power is decreased to 1.1 W.

In the case of double pipe, all the pipes show the same cooling power at 24 K. After that, the cooling power increases with increasing first stage temperature until a peak is reached. Pipe S and L have similar characteristics. The maximum cooling power achieved ia 1.33 W at 50 K. It is an

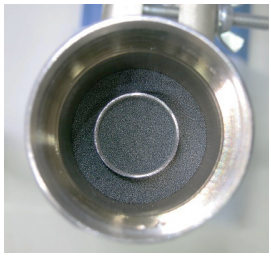

Figure 4. Photograph of the double pipe regenerator viewed from the warm end

Table 2. Specifications of three types of pipes, cross-sectional ratio, and calculated thermal conduction loss of stainless steel pipe.

Pipe type	Outer diameter [mm]	Length [mm]	Thickness [mm]	A_I / A_O	Thermal conduction loss* [mW]
S	10	67	0.5	0.10	44
M	15	67	0.5	0.50	81
L	22	67	0.5	1.1	100

* Thermal conductivity of stainless steel from 60 K to 4.2 K was used.

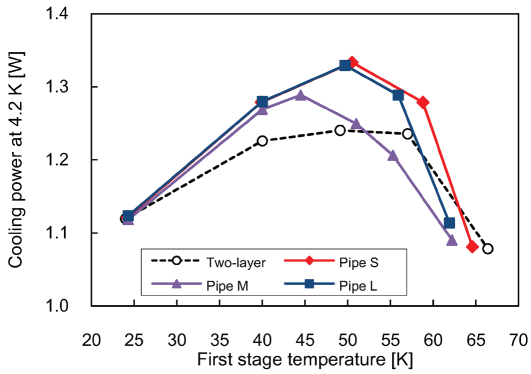

Figure 5. Comparison of the cooling power at 4.2 K for two-layer and double pipe regenerators

improvement by 7%, compared with the two-layer. In contrast, pipe M has a peak power of 1.29 W at 45 K. From the results, the double pipe regenerator is able to improve the second stage cooling power at 4.2 K. The cross-sectional ratio of 0.10 or 1.1 is optimum. Its effect depends on the first stage temperature and the specifications of the pipes. The reason for these intriguing results will be discussed in the next section.

Figure 6 presents the cooling power at 4.2 K as a function of the first stage power. With the first stage power of 59 W, pipe S and L achieve the maximum cooling power of 1.33 W.

DISCUSSION

In order to clarify the effect of the double pipe regenerator, the phenomena in the second stage regenerator including the helium properties are discussed in this section. Figure 7 shows

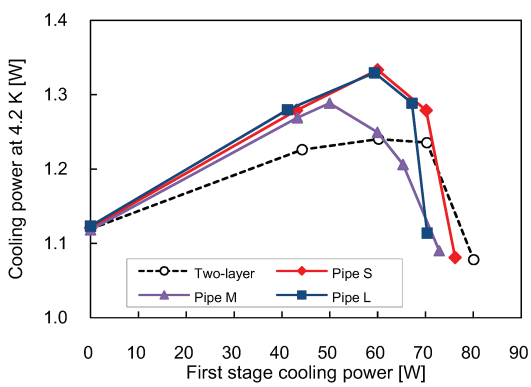

Figure 6. Cooling power at 4.2 K as a function of the first stage cooling power

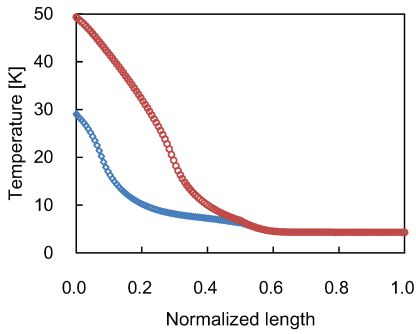

Figure 7. Simulated temperature distribution of the two-layer with Pb and HoCu2 spheres for two warm end temperatures of 30 K and 50 K

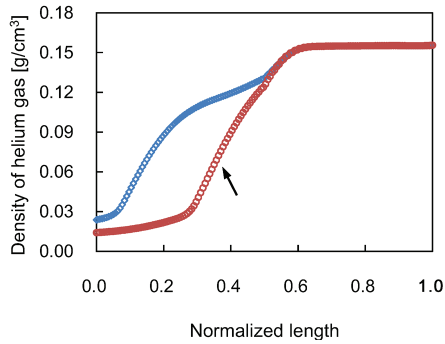

Figure 8. Calculated density of pressurized helium gas for two warm end temperatures

the simulated temperature distribution of the two-layer with Pb (50%) and $HoCu_2$ (50%) spheres. Two temperatures of 30 K and 50 K are considered for the warm end (normalized length equal to 0). The cold end (normalized length equal to 1) temperature is fixed at 4.2 K. Two curves have a large temperature difference at the warm end. In contrast, the cold end has the same characteristics.

From these temperature distributions, the density of helium gas was calculated at a mean pressure of 1.5 MPa. Figure 8 presents the calculation result for the two warm end temperatures. As shown, at a normalized length from 0 to 0.5, the density of the warm end of 50 K is smaller than that of 30 K. After that, two curves are in agreement at a high density. This density distribution means that increasing the warm end temperature from 30 K to 50 K decreases the amount of helium gas in the Pb part. Then, the decreased helium gas flows to the expansion volume through the $HoCu_2$ part. This effect leads to an improvement in the cooling power. Too high a warm end temperature, however, causes an increase in the enthalpy loss in the regenerator. As a result, the cooling power is decreased.

According to the experimental results shown in Figure 5, the cooling power increases from 24 K to 50 K for the two-layer and double pipe (pipe S and L) configurations are 11% and 19%, respectively. This difference is thought to be due to a disturbed flow of helium, which is not one-dimensional flow in the regenerator. From the density distribution, the disturbance in the Pb part is larger than that in the $HoCu_2$ part. In the case of the two-layer, the helium flow from the Pb part to the $HoCu_2$ part is suppressed by the disturbance. In contrast, in the case of the double pipe, the inserted pipe is considered to act as a rectifier which reduces the disturbance.

Figures 5 and 6 show the size effect of pipes. From the results, we propose a distribution of helium flow patterns which are divided into three in the Pb part as shown in Figure 9. The outer area has a disturbed flow because of the reflection from the wall. The middle area has an effective flow for regeneration. The inner area has a slow flow. In this inner area, the regenerative effect is considered to be small over the cycle.

The helium flow in the two-layer consists of the flow mixed by these three patterns that leads to a disturbed flow. In the case of the double pipe regenerator, the cooling power of pipe S and L is larger than that of pipe M at a first stage temperature of 50 K. It is thought that pipe S and L are inserted in the boundary layer of each area shown in Figure 9. Pipe S separates the inner and middle areas, and pipe L separates the outer and middle areas. Consequently, the helium flow is rectified that leads to an improvement in the cooling power. On the other hand, pipe M is inserted in the middle area. The divided middle areas, caused by inserting the pipe, mix the outer and inner areas and the effective flow area is decreased. This flow pattern makes a small improvement in the cooling power.

Compared with the Pb part, the whole area of the $HoCu_2$ part is considered to be an effective flow due to the high density of helium gas. To prove this proposal, a development of a measurement method regarding the helium flow patterns in the regenerator will be required.

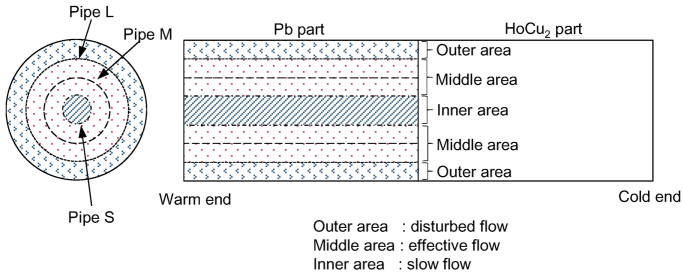

Figure 9. Proposed distribution of helium flow patterns in the Pb part

SUMMARY

A double pipe regenerator was developed to improve the cooling efficiency of a 4K G-M cryocooler. Three types of stainless steel pipes were inserted in the second stage regenerator to confirm its performance. The experimental results showed that the maximum cooling power of 1.33 W was achieved. It is an improvement in the cooling power by 7%, compared with the two-layer. The characteristics of the double pipe regenerator show that the cooling power depends on the first stage temperature, and the optimum cross-sectional ratio is 0.10 or 1.1. From these results, we proposed the helium flow pattern in the Pb part. The Pb part without the pipe has a disturbed flow. The inserted pipe is considered to act as a rectifier to reduce this disturbance.

The double pipe regenerator was proven to be an effective method to improve the cooling power with the two-layer (Pb-$HoCu_2$), and we will test it with a three-layer (Pb-$HoCu_2$-GOS) as a next step.

ACKNOWLEDGMENT

This study was supported by MEXT KAKENHI Grant-in-Aid for Scientific Research (C) 15K06693 and the NIFS Collaborative Research Program (NIFS15KECA034).

REFERENCES

1. Nakano T., Masuyama S., Hirayama Y., Izawa T., Nakagawa T., Fujimoto Y., Yamamoto T.A., Irie T., Nakamura, E. and Yamamoto, T. A., "ErN HoN Spherical Regenerator Material for 4K Cryocoolers," *Applied Physics Letters*, Vol. 101, No. 25 (2012), pp. 19081-19084.

2. Shoda K., Miyauchi T., Kobayashi H., Nakano T., Nakagawa T., Yamamoto T.A., Masuyama S., Fujimoto Y., Takata H., Kuriiwa T., and Yamamoto K., "Regenerator Material of Rare Earth Nitride ($Ho_xEr_{1-x}N$) for a 4K-GM Cryocooler," *Journal of Cryogenics and Superconductivity Society of Japan*, Vol. 50 (2015), pp. 132-136, (in Japanese).

3. Masuyama S., and Hiratsuka Y., "Effects of an Inserted Bakelite Rod in the 2nd Stage Regenerator of a Gifford-McMahon Cryocooler," *Journal of Cryogenics and Superconductivity Society of Japan*, Vol. 48 (2013), pp. 358-363, (in Japanese).

4. Masuyama S., Nagao T., and Numazawa T., "Magnetic Regenerator Material Economizing Method for 4K Gifford-McMahon Cryocoolers using Bakelite Rod," *Adv. in Cryogenic Engineering*, Vol. 59, Amer. Institute of Physics, Melville, NY (2014), pp. 1162-1168.

5. Masuyama S., Hiratsuka Y., and Numazawa T., "A Novel Approach to Optimize the 2nd Stage Regenerator Configuration of a 4K Gifford-McMahon Cryocooler," *Cryocoolers 18*, ICC Press, Boulder, CO (2015), pp. 271-276.