Effect of Regenerator Material Configuration on 4K-GM Cryocooler Performance

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ABSTRACT

This paper describes experimental results of a regenerator study made on a 4K-GM cryocooler. The configuration of the regenerator material is one of the important parameters for the improvement of a 4K-GM refrigerator. This study investigated the effect of the configuration of the regenerator material, specifically its diameter and porosity, on the performance of the cooler.

Firstly, the cooling capacity around 6 K was measured for various diameters of lead (Pb) spheres from 0.06 mm to 1.18 mm. Because of the larger heat-transfer area and higher coefficient of heat transfer associated with smaller spheres, they show a higher NTU, which improves the efficiency of the regenerator. But smaller spheres also lead to higher pressure drop in the regenerator, and that reduces the expansion work at the cold end. The study confirmed that an optimal diameter exists when the porosity of the Pb-sphere packed bed is kept constant. However, the noted improvement of cooling capacity with change in diameter was not particularly remarkable.

Secondly, the effect of the bed's porosity on the cooling capacity was measured by mixing two different diameters of Pb spheres. The lower porosity regenerators showed an improvement of cooling capacity in some conditions.

Lastly, based on the experimental results with Pb regenerators, the cooling capacity at 4 K was further investigated using $HoCu_2$ as the regenerator material. The porosity of the packed bed of $HoCu_2$ spheres was also changed by mixing different diameters of spheres. The cooling capacity increased about 14 % when the porosity was decreased from 34 % to 27 %.

INTRODUCTION

Because of their high reliability, easy to use, and low cost, GM cryocoolers are commonly used for cooling cryogenic devices such as superconducting magnets for MRI (Magnetic Resonance Imaging) and Silicon single-crystal pullers, for cryopumping, and so on. In 1990, a two-stage GM cryocooler achieved a cooling temperature of 4 K by using a magnetic regenerator material.[1] The most popular magnetic regenerator materials in commercial use are Er_3Ni and $HoCu_2$. As a result of these advancements, 4K-GM cryocoolers are able to conductively cool superconducting magnets that do not use liquid helium.[2] Since achieving temperatures below

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4 K, substantial effort has been made to obtain even lower temperatures and larger cooling capacities by developing such things as new magnetic regenerator materials[3] and multi-layer structures of regenerator materials[4], and by optimizating for operating conditions.[5]

The study presented here focuses on improving the performance of a 4K-GM cryocooler by examining the diameter of the regenerator material spheres and the porosity of the packed bed of spheres. The smaller the diameters of spheres applied to the regenerator, the larger the heat transfer area will be, and the higher the heat transfer coefficient and NTU (Number of Transfer Unit) will be; thus a higher regenerator efficiency is obtained. But, the smaller spheres make for a larger pressure drop in the regenerator, and this reduces the expansion work at the cold end. The effects of the sphere diameter against NTU and pressure drop have been calculated for the 2nd-stage regenerator of the GM cryocooler used in this study. The expansion volume at the 2nd-stage is 16.1 cm^3 and the operation frequency is 74 rpm. The thermal properties at 25 K for helium gas and Pb are used for the calculation. The high and low operation pressures for the GM cryocooler are 2.0 MPa and 0.8 MPa, respectively. Figure 1 shows the relation between NTU and diameter of Pb spheres, while Fig. 2 shows the pressure drop in the 2nd-stage regenerator. From those figures, two refrigeration losses caused by regenerator inefficiency which is estimated by NTU (Q_{loss}(NTU)) and caused by pressure drop ($Q_{loss}(\Delta P)$) are calculated. Figure 3 shows the dependence of the sphere diameter on the Q_{loss}(NTU) and the $Q_{loss}(\Delta P)$. The sum of the Q_{loss}(NTU) and the $Q_{loss}(\Delta P)$, which is described as the Q_{loss} , is also shown in Fig. 3. A sphere diameter around 0.2 mm shows the lowest Q_{loss} , and it indicates that the optimal diameter for the 2nd-stage regenerator material is around 0.2 mm.

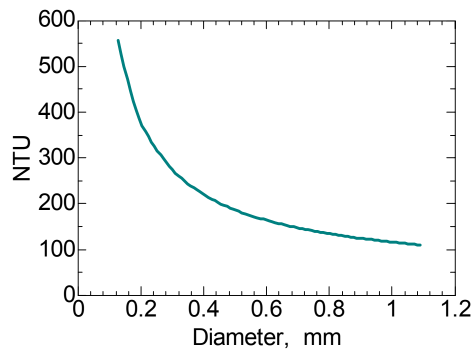

Figure 1. Relation between NTU for the 2nd-stage regenerator and diameter of Pb spheres.

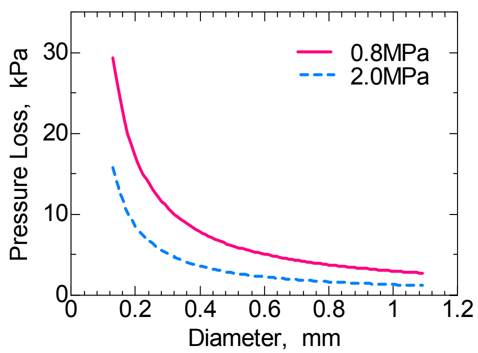

Figure 2. Relation between pressure drop in the 2nd regenerator and diameter of Pb spheres.

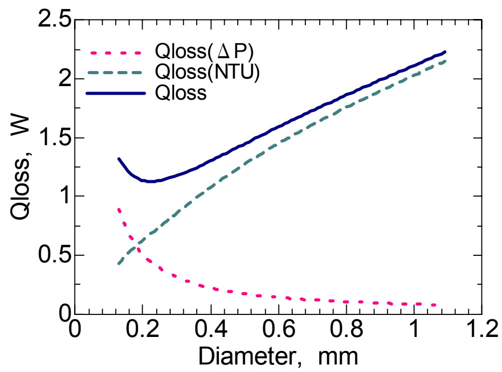

Figure 3. Effect of diameter of Pb spheres on the cooling loss in the 2nd-stage regenerator.

CLASSIFICATION OF SPHERE SIZE

In the present experiments, only refrigerator materials in the 2nd-stage regenerator were changed. The tested regenerator materials are Pb spheres and $HoCu_2$ spheres. The diameter of the spheres was varied. The diameter range of Pb spheres used in this study is from 0.062 mm to 1.18 mm. Those sizes of Pb spheres were classified into 10 categories (A to J) as shown in Fig. 4. For example, the spheres of category A have diameters from 0.062 mm to 0.106 mm and those of category D have diameters from 0.210 mm to 0.250 mm. The porosity of the packed beds of each category of spheres has almost the same value of 37 % to 39 %. In order to vary the porosity of the packed beds, spheres of category D and those of another category were mixed. Figure 5 shows the measured porosity when two of each category are mixed. The characters A to J in this figure indicate the categories of spheres that are mixed with spheres of category D. Though the porosity is about 38 % when a regenerator is made up of a single category, the porosity decreases when two kinds of categories are mixed, and the lowest porosity of 30 % is realized.

EXPERIMENTAL RESULTS

Material Size Dependence

In order to investigate the effect of the regenerator material size on the cooling capacity, six regenerators shown in Table 1 were tested. As shown in Fig. 6, Pb spheres of category E in

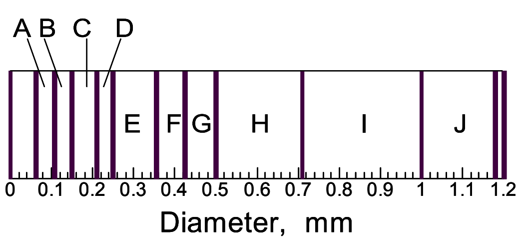

Figure 4. Classification categories for the diameters of the Pb spheres.

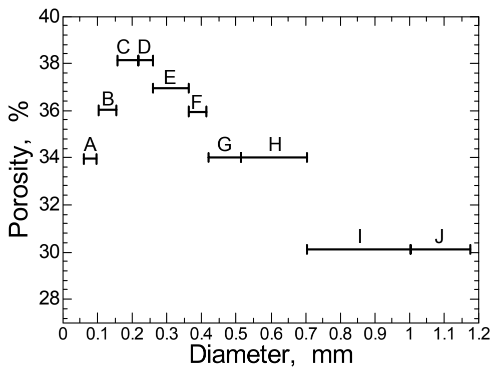

Figure 5. Measured porosity of the packed bed when spheres of category D and another category are mixed.

Table 1. Details of the six tested regenerators used for the investigation of the dependence of cooling capacity on material diameter.

Regenerator No.		I	II	III	IV	V	VI
Hot side	Diameter (mm)	E (0.250-0.355)					
	Porosity (%)	37					
	Weight (g)	355					
Cold side	Diameter (mm)	B (0.106-0.149)	C (0.149-0.210)	D (0.210-0.250)	F (0.355-0.425)	H (0.500-0.710)	J (1.000-1.180)
	Porosity (%)	39	38	38	39	38	39
	Weight (g)	339	346	346	335	350	342

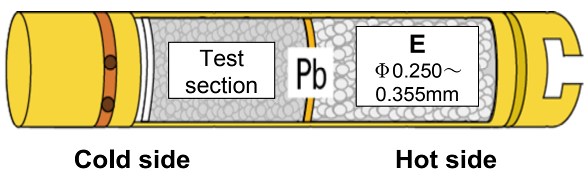

Figure 6. Schematic view of tested 2^{nd}-stage regenerator.

Fig. 4 are filled in the high temperature side for all the regenerators. In the low temperature side, spheres of different categories are filled, keeping the porosity and weight of the material almost constant. The porosity and the weight of the packed bed at the low temperature side are about 38 % and 340 g, respectively. Those are almost the same as those of the Pb spheres filled in the high-temperature side.

The obtained cooling capacity for each regenerator is shown in Fig. 7. The 1st-stage temperature was kept at 45 K and the operation frequency was 74 rpm in this experiment. It is known from this figure that lower than 5 K can be obtained by using only Pb spheres in the

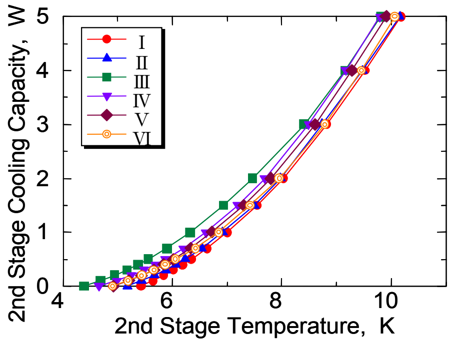

Figure 7. Cooling capacity for each regenerator, the details of which are shown in Table 2.

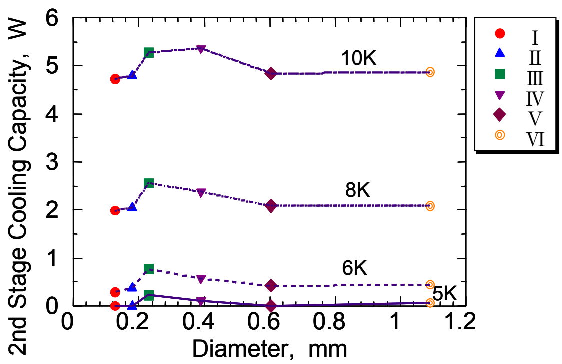

Figure 8. Dependence of cooling capacity on Pb-sphere diameter.

2nd-stage regenerator. This figure also shows that the size of the Pb spheres affects the cooling capacity while the porosity is kept constant.

The dependence of the diameter of the Pb spheres on the cooling capacity is shown in Fig. 8. In this figure, the cooling capacities at 5 K, 6 K, 8 K and 10 K of the 2nd-stage temperature obtained from Fig. 7 are plotted. The regenerator III shows the largest cooling capacity at each temperature. The diameter of Pb spheres filled in this regenerator was 0.21 mm to 0.25 mm (category D). That leads to the lowest heat loss in the 2nd-stage regenerator as indicated in Fig. 3. This result means that an optimal sphere size exists when the porosity of the packed bed is kept constant. However, the improvement in cooling capacity is not particularly remarkable.

Porosity Dependence

The porosity of the packed bed is about 38 % when the regenerator is made up of a single category of spheres, as shown in Table 1. On the other hand, when spheres from two different categories are mixed, the porosity can be decreased. Therefore, in order to investigate the effect of the porosity on the cooling capacity, Pb spheres from two categories were mixed and filled in the low-temperature side of the regenerator. The details of the tested regenerators are shown in Table 2. For the regenerator VII, spheres from category D and category A (smaller than spheres D) were mixed and filled in the low-temperature side. The porosity of the mixed-sphere packed bed is 34 %. For the regenerator VIII, spheres from category D and category J (larger than spheres D) were mixed, and its porosity is 30 %. As with the other regenerators mentioned above, the high-temperature side was filled with spheres E.

Table 2. Details of the tested regenerators for the investigation of the porosity dependence of cooling capacity.

Regenerator No.		VII	III	VIII
Hot side	Diameter (mm)	E (0.250-0.355)		
	Porosity (%)	37		
	Weight (g)	355		
Cold side	Diameter (mm)	A+D A(0.062-0.106) D(0.210-0.250	D (0.210-0.250)	D+J D(0.210-0.250) J(1.000-1.180)
	Porosity (%)	34	38	30
	Weight (g)	372	346	396

The cooling capacities at 5 K, 6 K, 8 K and 10 K obtained using regenerators IV, VII and VIII are shown in Fig. 9. The 1st-stage temperature and the operating frequency were kept at 45 K and 74 rpm, respectively. The regenerator III has the largest cooling capacity among the regenerators packed with Pb spheres of a single category, as shown in Fig. 8. The regenerator VIII shows a slightly larger cooling capacity at 8 K and 10 K compared with those for the other regenerators. This figure suggests that a lower porosity regenerator can make an improvement of cooling capacity in some conditions.

Based on the experimental results with Pb regenerators, the 4-K cooling capacity was also investigated using spheres of $HoCu_2$ magnetic regenerator material. The porosity of the $HoCu_2$ packed bed was also changed by mixing different diameters of spheres. Table 3 shows the details of the regenerators that contain $HoCu_2$ spheres in the low-temperature side. The porosity of the $HoCu_2$ packed bed of the regenerator X is smaller than that of the regenerator IX. The high-temperature side was filled with the Pb spheres from category E for both regenerators.

The obtained cooling capacities of the regenerators IX and X are shown in Fig. 10. The 1st-stage temperature and the operation frequency were kept at 37 K and 53 rpm, respectively. 2nd-stage temperatures less than 3 K were obtained for both regenerators. It is also known from this figure that the cooling capacity for the smaller porosity regenerator was larger than that for the larger porosity regenerator. The cooling capacity at 4 K for the regenerator X was 0.67 W. This value was 14 % larger than that for regenerator IX (0.59 W).

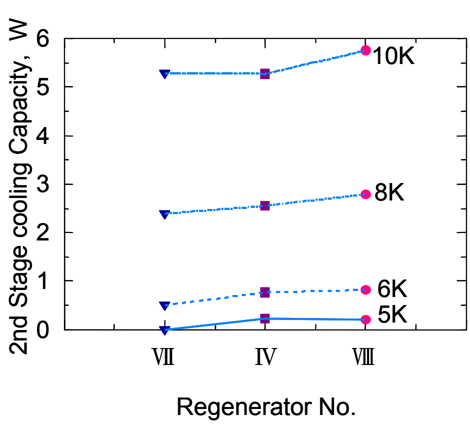

Figure 9. Cooling capacity at 5 K, 6 K, 8 K and 10 K obtained from regenerators IV, VII and VIII

Table 3. Details of the regenerators that contained $HoCu_2$ spheres in the low-temperature side.

Regenerator No.			IX	X
Hot side	Pb	Diameter (mm)	E (0.250-0.355)	
		Porosity (%)	37	
		Weight (g)	355	
Cold side	$HoCu_2$	Diameter (mm)	0.149-0.210	0.062-0.106 0.250-0.355
		Porosity (%)	34	27
		Weight (g)	231	254

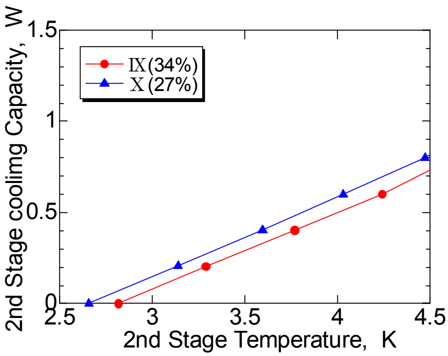

Figure 10. Cooling capacity for regenerators that contain $HoCu_2$ spheres.

CONCLUSIONS

The effect of regenerator configuration, such as material diameter and porosity, on cryocooler performance has been investigated. It was confirmed that an optimal diameter of the Pb spheres exists when the porosity is kept constant. But, the improvement of cooling capacity with diameter is not particularly remarkable. The effect of the porosity on the cooling capacity was also measured by mixing two different diameters of Pb spheres. It is suggested that the lower porosity regenerators can make an improvement of cooling capacity in some conditions. Cooling capacity at 4K was also investigated using $HoCu_2$ magnetic regenerator material. The cooling capacity increased about 14% when the porosity was decreased from 34 % to 27 %.

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