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Development of zinc-plated regenerator material

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Abstract. An effective way to improve the efficiency of a cryocooler is to improve the efficiency of the regenerator. In general, the heat capacity of materials decreases as temperature decreases. Thus, when temperature is below 40 K, lead or bismuth spheres are often used as regenerator materials. However, the pressure drop in a sphere regenerator is much larger than that in a screen regenerator. To overcome this dilemma, Xu et al. reported that cooling performance at the temperature of less than 40 K was improved when using tin-plated screens at the cold end of the regenerator. However, the reliability of tin at low temperatures is still not verified fully because of its phase transition from a normal β phase to an abnormal α phase, which may result in a significant reduction of the mechanical strength. In this paper, a zinc-plated screen is proposed as another potential alternative. A comparison test was performed with a two-stage GM cryocooler by replacing part of the first stage regenerator material, phosphorus bronze screens, with zinc-plated screens. Compared to a regenerator filled with bronze screens, the cooling capacity of the first stage increased by about 11% at 40 K and 60% at 30 K with these zinc-plated screens. The detailed experimental results are reported in this paper.

1. Introduction

In the 1990s, rare earth material with high heat capacity in the 4 K region was developed and introduced into the regenerators of GM cryocoolers, which in turn made it possible for GM cryocoolers to achieve temperatures around 4 K [1-3].

Since 1995, 4 K GM cryocoolers have been widely used for cooling superconducting magnets, such as magnets in MRI systems. A large amount of power in an MRI system is consumed by the cryocooler. To reduce the power consumption, a high-efficiency cold head was developed and the input power was reduced by about 30% compared to commercially-available 1 W 4 K GM cryocoolers [4-6].

An effective way to further improve the efficiency of a cryocooler is to improve the efficiency of the regenerator. In general, the heat capacity of materials decreases as temperature decreases. Thus, when the temperature is below 40 K, lead or bismuth spheres are often used as regenerator materials in order to achieve a reasonable value of heat capacity. However, the pressure drop in a sphere regenerator is much larger than that in a screen regenerator. To overcome this dilemma, Xu et al. reported that the cooling capacity of the first stage increased by about 14% at 40 K and 90% at 30 K when using tin-plated screens at the cold end of the first stage regenerator [7]. However, the reliability of tin at low temperatures is still not verified fully because of its phase transition from a normal β phase to an abnormal α phase, which may result in a significant reduction of the mechanical strength [8]. Although the phase transition may slow down at helium atmosphere, it takes time to fully verify the reliability. In this paper, a zinc-plated screen is proposed as another potential alternative because zinc does not have such abnormal phase transition. Also, zinc spheres has been used as a regenerator material in 2 K GM cryocoolers [9] and no problem occurred after operated a couple of months. A comparison test was performed with a two-stage GM cryocooler by replacing part of the first stage regenerator material, phosphorus bronze screens, with zinc-plated screens. The detailed experimental results are reported in this paper.

2. Conventional regenerator materials

In general, as seen in figure 1, the heat capacity of materials decreases as temperature decreases. It is well known that lead is a common regenerator material for temperatures below 50 K due to its relatively high heat capacity. Today, lead spheres with a typical diameter of approximately 300 μm are used. However, spheres have a larger pressure drop than screen discs [10]. While high heat capacity regenerator materials still remain important for cryocoolers, low pressure drop regenerator materials are gaining attention due to the rapid growth of research and development of large superconducting apparatus. An effective way to reduce pressure drop without significant impact on the heat capacity is to deposit high heat capacity material onto conventional regenerator materials, such as copper or stainless steel screens.

In 2004, Waldauf et al. [11] reported that the performance of a pulse tube cryocooler was improved with a lead wire mesh. That is, lead was deposited on bronze screens. However, it is difficult to deposit lead on a screen. Also, lead is one of the substances restricted by Restriction of Hazardous Substances (RoHS) directive.

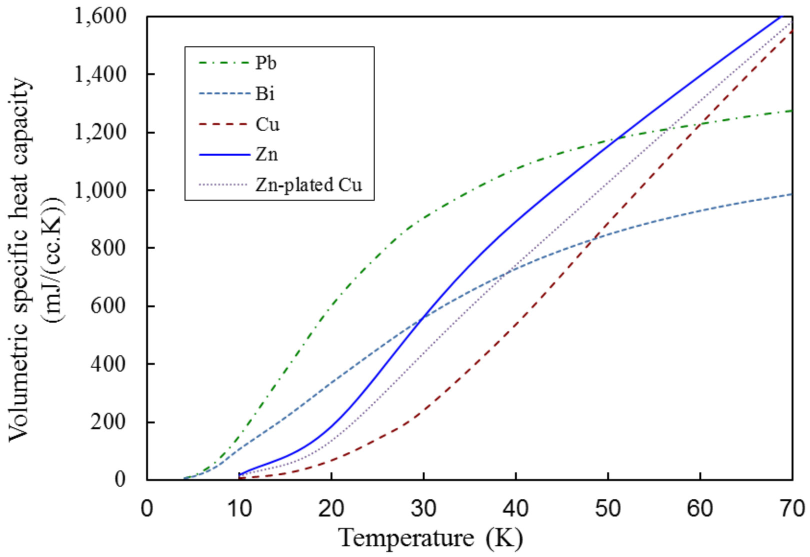


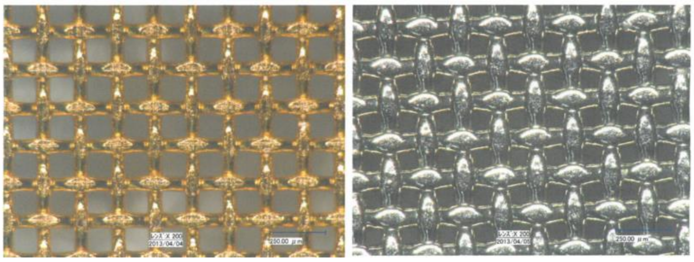
Figure 1. Specific heat capacity of materials.

3. Zinc-plated screens

As seen in figure 1, although the heat capacity of zinc also decreases as temperature decreases, the heat capacity of zinc becomes larger than copper below 70 K. To improve the regenerator efficiency, a low pressure loss zinc-plated screen is proposed as a new potential alternative. As is well known, zinc electrolyte deposition is a mature technology commonly used in the construction industry. Zinc can be deposited easily on copper or stainless steel screen using a common electrolyte deposition process.

The zinc-plated screens were fabricated in a process similar to tin-plated screens [7]. First, bronze screens with 150 mesh and a thickness of 132 μm were selected as a base material. Then, to obtain a high mechanical stability, the base screens were calendered to a thickness of 92 μm. Finally, after cleaning, zinc was deposited on the bronze screens. The average thickness of the zinc coating layer was about 21.5 μm. The heat capacity of the zinc-plated screen is also shown in figure 1. Obviously, the heat capacity of a zinc-plated screen is larger than that of a bronze screen at temperatures below 70 K. At 40 K and 1.0 Hz, the penetration depth of zinc is about 8.9 mm, which is much larger than the thickness of the coating layer. Thus, the coating layer can fully function as a regenerator material.

Figure 2a shows a regular bronze screen, and figure 2b shows a screen after the deposition. The average porosities are about 0.57 and 0.37 before and after coating, respectively.



(a) (b)

Figure 2. Screenviews before and after electrostatic coating. (a) Before and (b) after.

4. Experimental results

A comparison test was performed with a two-stage GM cryocooler by replacing part of the first stage regenerator material, bronze screens, with zinc-plated screens. The first stage cooling performance of a 4 K GM cryocooler with regular bronze screens and zinc-plated screens is shown in figure 3. Also, a comparison of the packing pattern of the first stage regenerator and the measured cooling capacity at 40 K and 30 K is shown in table 1. The compressor is an F-70 compressor from Sumitomo Heavy Industries, Ltd. The cold head is operated at 1.0 Hz, and the compressor is operated at 50 Hz. The static charging pressure is 1.38 MPa. The inner diameters of the first and the second stage cylinders are 82 mm and 35 mm, respectively. The stroke of the displacer is 25 mm. The first stage regenerator is filled with 150 mesh bronze screens at the warm end and bronze or zinc-plated screens at the cold end. The second stage regenerator is filled with bismuth, $HoCu_2$ and Gd_2O_2S (GOS) spheres. The heat load at the second stage was kept at 1.0 W while the first stage load was varied at the range of 0 W to 65 W. As seen in figure 3 and table 1, with bronze screens, the cooling capacity at the first stage was 50 W at 41.4 K and 10 W at 27.7 K. When 100 discs of bronze screens at the cold end were replaced by 54 discs of zinc-plated screens, the cooling capacity at the first stage was 50 W at 38.8 K and 30 W at 30.0 K. Also, the no-load temperature decreased from 24.8 K to 22.2 K. When the zinc-plated screens were increased to 151 discs, the cooling capacity at the first stage was 50 W at 40.9 K and 30 W at 29.2 K. Also, the no-load temperature decreased to 19.6 K. As seen in table 1, compared to a regenerator filled with bronze screens, the measured cooling capacity of the first stage increased from 46.6 W to 51.6 W at 40 K and from 18.7 W to 30.0 W at 30 K. The first stage cooling capacity increased by about 11% at 40 K and 60% at 30 K with a regenerator filled with 54 discs of zinc-plated screens. When the zinc-plated screens were increased to 151 discs, the measured cooling capacity of the first stage was 48.6 W at 40 K and 31.4 W at 30 K. Compared to a regenerator filled with bronze screens, the first stage cooling capacity increased by about 4% at 40 K and 68% at 30 K with a regenerator filled with 151 discs of zinc-plated screens. The performance was improved owing to lower porosity and higher heat capacity. For reference, the cooling capacity with a regenerator filled with 335 g bismuth spheres at the cold end of the first stage regenerator is also shown in table 1. The cooling capacity was 50.5 W at 40 K and 33.9 W at 30 K at the first stage [7]. Compared to a regenerator filled with bismuth spheres, the performance was slightly worse because the heat capacity of zinc-plated screens below 40 K is still much smaller than that of bismuth spheres.

The cooling performance of the second stage of a 4 K GM cryocooler with bronze screens and zinc-plated screens is shown in figure 4. As seen in figure 4, the second stage temperature with 1.0 W heat load decreased by about 0.04 K when the bronze screens at the cold end were replaced by zinc-plated screens. The performance was improved owing to lower porosity at the cold end of the first stage regenerator. Thus, less gas was trapped in the void volume of the first stage regenerator, and more gas flowed into the second stage.

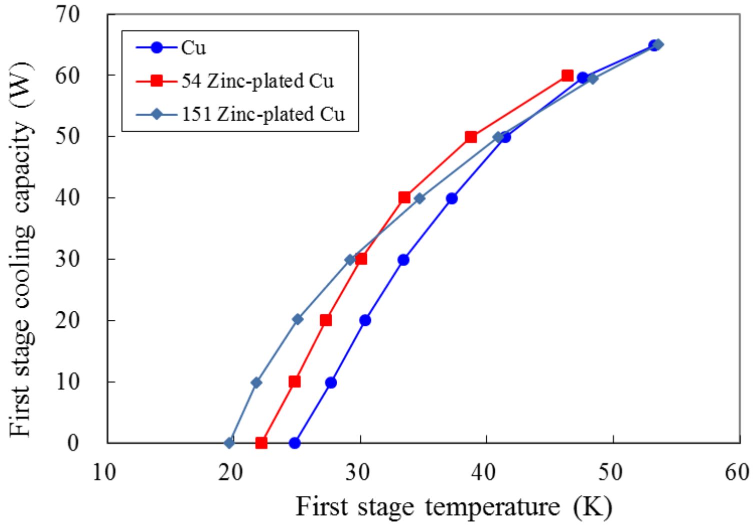


Figure 3. Cooling performance of the first stage with different materials at the cold end of the first stage regenerator.

Table 1. Comparison of the packing pattern of the first stage regenerator and the cooling capacity.

	Warm End		Cold End		Measured First Stage Cooling Capacity (W)	
					at 40K	at 30K
Case 1	#150 bronze	1097 discs	#150 bronze	100 discs	46.6	18.7
Case 2	#150 bronze	1097 discs	Zinc-plated screen	54 discs	51.6	30.0
Case 3	#150 bronze	945 discs	Zinc-plated screen	151 discs	48.6	31.4
Case 4	#150 bronze	920 discs	Bi sphere	335 g	50.5	33.9

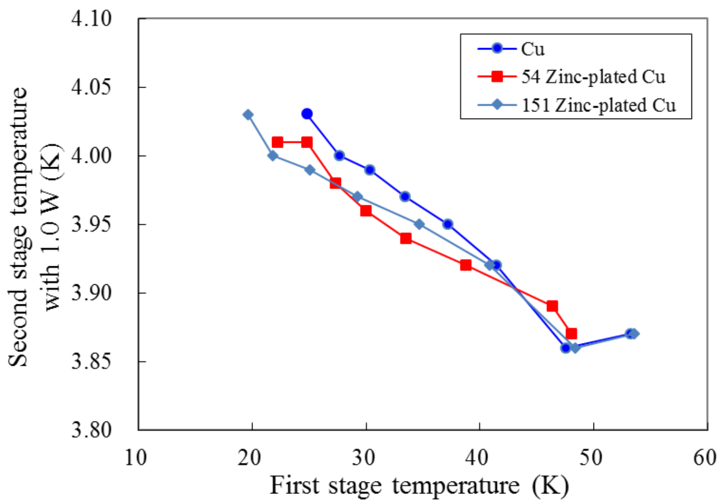


Figure 4. Cooling performance of the second stage with different materials at the cold end of the first stage regenerator.

5. Conclusions

A new, low pressure loss zinc-plated screen is proposed for cryogenic cooler applications. A comparison test was performed with a two-stage GM cryocooler by replacing part of the first stage regenerator material, bronze screens, with zinc-plated screens. Compared to a regenerator filled with bronze screens, the cooling capacity of the first stage increased by about 11% at 40 K and 60% at 30 K with these zinc-plated screens.

6. References

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