Development of tin-plated regenerator material

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Abstract. To improve the efficiency of a cryocooler, it is vital to improve the regenerator. In general, the heat capacity of materials decreases as temperature decreases. Thus, when temperature is below 50 K, lead spheres are often used as a regenerator material. However, the pressure drop through a sphere regenerator is larger than that through a screen regenerator. To overcome this dilemma, a new, low pressure loss tin-plated screen is proposed. A comparison test was performed with a two-stage GM cryocooler by replacing part of the first stage regenerator material, bronze screens with tin-plated screens. Compared to a regenerator filled with bronze screens, the cooling capacity of the first stage increased by about 14% at 40 K and 90% at 30 K with such tin-plated screens. The ratio of the wire diameter before and after the deposition was also optimized. An optimum cooling capacity of 53.5 W at 40 K was obtained at a diameter ratio of about 1.4. The detailed experimental results are reported in this paper.

1. Introduction
Since 1990, the efficiency of 4 K GM cryocoolers has been continuously improved by optimizing the operation parameter [1-2] and valve timing [3]. 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. Especially at night, more than half of the power is consumed by the cryocooler since no diagnosis is performed. To reduce the power consumption, a high-efficiency cold head was developed and the input power was reduced by about 30% compared to a conventional 1 W 4 K GM cryocooler [4-6]. To improve the efficiency of the cold head, it is vital to improve the regenerator. A new, low pressure loss tin-plated screen is proposed to improve the regenerator efficiency. A comparison test was performed with a two-stage GM cryocooler by replacing part of the first stage regenerator material, bronze screens with tin-plated screens. The detailed experimental results are reported in this paper.

2. Conventional regenerator material
In general, as shown 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. Nowadays, lead spheres with a typical diameter of approximately 300 μm are used. However, spheres have a larger pressure drop than screens discs [7]. In 2004, Waldrauf et al [8] 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.
3. Tin-plated screens

From figure 1, although the heat capacity of tin also decreases as temperature decreases, the heat capacity of tin becomes larger than that of copper at temperatures below 50 K. Maruyama et al suggested that tin alloy could be used as an alternate of lead [9]. To improve the regenerator efficiency, a new, low pressure loss tin-plated screen is proposed. As well known, tin electrolyte deposition is a mature technology and commonly used in food container industry, etc. Tin can be easily deposited on copper or stainless steel screen with a common electrolyte deposition process.

The tin-plated screens were fabricated in the following way: At first bronze screens with 150 mesh and a wire diameter of 66 μm were selected as a basic material. In order to obtain mechanical stability, the basic screens were calendered to a thickness of 92 μm. After cleaning, tin was deposited on the bronze screens. The average thickness of the tin coating layer was about 17.5 μm. The heat capacity of the tin-plated screen is also shown in figure 1. Obviously, the heat capacity of a tin-plated screen is larger than that of a bronze screen at temperatures below 50 K. At 40 K and 1.0 Hz, the penetration depth of tin is about 8.8 mm, which is much larger than the thickness of the coating layer. Thus, the coating layer can be fully functioned as a regenerator material.

A screenview before and after the deposition is shown in figure 2. Figure 2a shows a regular bronze screen and figure 2b shows a screen after the deposition. The average porosity is about 0.57 and 0.46 before and after coating, respectively.

![Figure 1. Specific heat capacity of materials.](image1)

![Figure 2. Screenview before and after electrostatic coating.](image2)
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 tin-plated screens. The cooling capacity of a 4 K GM cryocooler with regular bronze screens and tin-plated screens is shown in figure 3. 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 cylinder 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 side and bronze or tin-plated screens at the cold side. The second stage regenerator is filled with bismuth, HoCu$_2$ and Gd$_2$O$_2$S (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 shown in figure 3, with only bronze screens, the cooling capacity at the first stage was 50 W at 41.4 K or 10 W at 27.4 K. When 261 discs of bronze screens at the cold side were replaced by 157 discs of tin-plated screens, the cooling capacity at the first stage was 50 W at 37.6 K or 30.3 W at 27.7 K. Also, the no-load temperature decreased from 24.6 K to 20.1 K. For comparison, the cooling capacity with 335 g bismuth spheres at the cold side is also shown in figure 3, the cooling capacity at the first stage was 50 W at 39.5 K or 30.3 W at 28.1 K. A comparison of the packing pattern of the first stage regenerator and the estimated cooling capacity at 40 K and 30 K is shown in table 1. As shown in table 1, compared to a regenerator filled with bronze screens, the measured cooling capacity of the first stage increased from 46.9 W to 53.4 W at 40 K and from 19.0 W to 36.4 W at 30 K. The first stage cooling capacity increased by about 14% at 40 K and 90% at 30 K with a regenerator partially filled with tin-plated screens. The performance was improved owing to lower porosity and higher heat capacity. Compared to a regenerator filled with 335 g bismuth spheres which have an average diameter of 0.35 mm, at the cold side, the cooling capacity at the first stage increased from 50.7 W to 53.4 W at 40 K and from 33.9 W to 36.4 W at 30 K. The first stage cooling capacity increased by about 6% at 40 K and 7% at 30 K with a regenerator partially filled with tin-plated screens. Compared to a regenerator filled with bismuth spheres, the effect is only marginal because the heat capacity of tin-plated screens at 30 K is still quite smaller than that of bismuth spheres.

In order to optimize the cooling performance at 40 K, three kinds of tin-plated screens with different tin thickness were tested. The cooling capacity at the first stage with respect to the diameter ratio is shown in figure 4. As shown in figure 4, the optimum ratio of the wire diameter before and after the deposition was about 1.4. At the optimum ratio, a cooling capacity of 53.5 W at 40 K at the first stage was obtained. As the ratio increases, the opening area of the screen decreases thus the pressure loss increases.

![Figure 3. Cooling capacity with different regenerator materials.](image-url)
Table 1. Comparison of the packing pattern of the first stage regenerator and the cooling capacity.

|         | Warm Side       | Cold Side       | Estimated Cooling Capacity at the First Stage at 40K | Estimated Cooling Capacity at the First Stage at 30K |
|---------|-----------------|-----------------|------------------------------------------------------|------------------------------------------------------|
| Case 1  | #150 bronze     | 920 discs       | #150 bronze                                        | Tin-plated                                          |
|         | Tin-plated      | 261 discs       |                                                      |                                                      |
|         |                 |                 | Estimated Cooling Capacity at 40K                  | Estimated Cooling Capacity at 30K                  |
| Case 2  | #150 bronze     | 920 discs       | Tin-plated screen                                  |                                                      |
|         | Tin-plated      | 157 discs       |                                                      |                                                      |
|         |                 |                 | Estimated Cooling Capacity at 40K                  | Estimated Cooling Capacity at 30K                  |
| Case 3  | #150 bronze     | 920 discs       | Bi sphere                                            |                                                      |
|         |                 |                 | 335 g                                                |                                                      |
|         |                 |                 | Estimated Cooling Capacity at 40K                  | Estimated Cooling Capacity at 30K                  |

Figure 4. Cooling capacity at different ratio of the wire diameter before and after the deposition.

5. Conclusions
A new, low pressure loss tin-plated screen is proposed. A comparison test was performed with a two-stage GM cryocooler by replacing part of the first stage regenerator material, bronze screens with tin-plated screens. Compared to a regenerator filled with bronze screens, the cooling capacity of the first stage increased about 14% at 40 K and 90% at 30 K with such tin-plated screens. The ratio of the wire diameter before and after the deposition was also optimized. An optimum cooling capacity of 53.5 W at 40 K was obtained at a diameter ratio of about 1.4.

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