
Experimental investigation of cooling capacity of 4K GM cryocoolers in magnetic fields

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Abstract

4K GM cryocoolers are inevitably exposed to the magnetic field in MRI systems. The cooling capacity of a 4K GM cryocooler is strongly dependent on the heat capacity of the magnetic regenerator materials, such as HoCu\textsubscript{2}, Er\textsubscript{2}Ni and Gd\textsubscript{2}O\textsubscript{2}S (GOS). In order to clarify the effect of the magnetic field on a cryocooler’s performance, we measured the cooling capacity of Sumitomo Heavy Industries, Ltd. (SHI) 1W 4K GM cryocoolers in magnetic fields up to 2.0 T. It is found that the impact of a magnetic field on the cooling capacity with a HoCu\textsubscript{2}/GOS hybrid regenerator is much smaller than that with a HoCu\textsubscript{2} regenerator.

Keywords: 4K Gifford-McMahon cryocooler; Magnetic regenerator; Magnetic field; HoCu\textsubscript{2}; Gd\textsubscript{2}O\textsubscript{2}S

1. Introduction

Since 1990, the cooling capacity of a 4K GM cryocooler has been significantly improved by the development of magnetic regenerator materials, such as Er\textsubscript{2}Ni, ErNi\textsubscript{0.8}Co\textsubscript{0.2} and HoCu\textsubscript{2}. Kuriyama et al. (1990), Ohtani et al. (1999). In the recent decade, SHI 4K GM cryocoolers have been improved furthermore by using ceramic regenerator materials, such as GOS. Ikeya et al. (2003), Numazawa et al. (2003).

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As well known, 4K GM cryocoolers have been widely used for cooling superconducting magnets, such as magnets in MRI systems. In these systems, 4K GM cryocoolers are set up close to superconducting magnets which generate high magnetic fields. Therefore, 4K GM cryocoolers are exposed to the magnetic field. It is known that the cooling capacity of 4K GM cryocoolers is affected by specific heat degradation of magnetic regenerator materials under magnetic fields. It is especially interesting to understand the magnetic field strength in which 4K GM cryocoolers can be maintained below helium boiling temperature of 4.2 K.

An experimental investigation of the cooling capacity change of 4K GM cryocoolers exposed to a magnetic field was carried out with different regenerator materials such as HoCu₂ and HoCu₂/GOS hybrid. Some experimental results and discussion are presented in this paper.

2. Experimental system

SHI commercial 1W 4K GM cryocoolers were used in the experiments. An SHI water-cooled compressor, CSW-71, was used to drive the cold heads. The compressor has a rated input power of 5.0 kW at a driving frequency of 50 Hz. An SHI cryogen-free superconducting magnet with a bore of 150 mm was used to generate magnetic fields. This magnet was capable of generating up to 10 T at the center position of the coil. The cold head was operated at 1.0 Hz in all experiments. A Cernox (cx-1050) sensor (LakeShore) was used for measuring the second stage temperature. The accuracy of this kind of sensor only slightly depends on a magnetic field and the measurement error is found to be less than 0.1 % up to 2.5 T at 4.2 K.

Fig. 1 shows schematic diagrams of the experimental apparatus. Fig. 1a shows a setup for application of a magnetic field to a cold head. The magnetic field was applied parallel to the axis of the cold head cylinder. Fig. 1b shows a setup for application of a magnetic field perpendicular to the axis of the cold head cylinder. Fig. 2a shows a picture of the cold head installed into the superconducting magnet system. This picture corresponds to the case depicted in Fig. 1a. In the conducted experiments, the applied magnetic field strength can be up to 2.0 T at the center position of magnetic regenerator constructed out of HoCu₂ layer if applied in the axial direction. At the same time, the field strength can be up to 0.45 T at the center position of the same regenerator if applied in the radial direction. For certain reasons, the center position of the magnetic regenerator layer is inevitably located higher than the center position of the superconducting coil in both cases. Therefore, the magnetic regenerator materials are subject for application of not only a magnetic field but also a magnetic field gradient. Fig. 2b shows the results of the calculated magnetic field distribution in the axial direction of this superconducting coil when the intensity of the magnetic field is 5.0 T at the center position of the coil (0.0 mm). Note that in an axial magnetic field, the magnetic regenerators are also exposed to a strong magnetic field gradient (the position indicated to be capital “a” in Fig. 2b). In general, a magnetic material will experience a force generated by a magnetic field gradient. It was previously reported that the cooling capacity was not affected by a gradient in an axial magnetic field. Onishi et al. (1999)

Fig. 1. Schematic diagrams of the experimental apparatus. (a) in axial magnetic field; (b) in radial magnetic field.
The cooling capacity may be reduced by a magnetic field, because the specific heat of magnetic regenerator materials will be varied by a magnetic field. It is guessed that this reduction of the cooling capacity is not dependent on the direction of a magnetic field because the magnetic regenerator materials have an isotropic multi crystal structure. On the other hand, from the viewpoint of magnetic field gradient, the displacer is forced in the radial direction under the electromagnetic force of radially applied magnetic field (the position indicated to be capital “r” in Fig. 2b) acting upon the regenerator materials. Therefore, the cooling capacity loss may increase since the displacer is forced towards one side of a cylinder under the applied magnetic field.

3. Experimental results

3.1. In axial magnetic fields

Fig. 3a shows the experimental results of the second stage temperature readings when the cold head was placed in the axial magnetic field with heat loads of 1.0 W applied at the second stage and 40 W applied at the first stage. In this figure, the dash line corresponds to the second stage temperature when the regenerator material was HoCu$_2$ only. This line was also denoted as type (a) line. The solid line corresponds to that of using HoCu$_2$/GOS hybrid regenerator material where GOS replaced about 60% of HoCu$_2$ by weight. That line was denoted as type (b) line. In zero magnetic fields, for both types of regenerator materials, the temperature of the second stage reaches about 3.85 K. The latter indicates that the cooling capacity is the same. In magnetic fields, below 0.6 T, no obvious reduction of cooling capacity is observed for both types of regenerator materials. But in magnetic fields above 0.8 T, the cooling capacity with regenerator material outlined by type (a) line reduces as magnetic field increases.
On the other hand, no remarkable reduction of cooling capacity is observed for regenerators with material outlined by type (b) line. Using GOS as a magnetic regenerator material, the cooling capacity reduction is suppressed, and the temperature can be kept at about 4.2 K within magnetic field of up to 2.0 T.

The cause of cooling capacity reduction with regenerator materials denoted by type (a) line can be explained by a decrease of the specific heat of HoCu2 while exposed to a magnetic field above 0.8 T Onishi et al. (1999). On the other hand, the specific heat of GOS decreases more slowly than that of HoCu2 Numazawa et al. (2003). And also, the specific heat of GOS has a peak slightly above 4.2 K. Therefore, it is considered that the extra regenerator loss, caused by specific heat degradation of HoCu2, can be suppressed to some extent. Fig. 3b shows the experimental results of the minimum second stage temperature readings when the unit was placed in axial magnetic fields with no heat load at the second stage and 40 W at the first stage. As magnetic field increases, the cooling temperature can be maintained by type (b), but cannot be maintained by type (a) regenerator materials. It should be noted here that for type (a) regenerator material placed in 2.0 T magnetic field, the second stage cannot maintain the temperature below helium boiling temperature of 4.2 K, even with no heat load condition on the second stage. The magnetic regenerator material GOS is indispensable for condensing helium under high magnetic fields.

3.2. In radial magnetic fields

Fig. 4 shows the experimental results of the second stage temperature readings when the unit was placed in the radial magnetic fields with heat load of 1.0 W at the second stage and 40 W at the first stage. In this case, the magnetic field applied cannot be above 0.45T due to restrictions applied to the devices. It was estimated for the magnetization of HoCu2 by Gratz et al. (1982) that the displacer is forced in the radial direction by about 1 kgf of electromagnetic force at 0.45 T when type (a) regenerator material is used. Therefore, unlike the case of an axial magnetic field, a friction heat loss may be generated between the displacer and the cylinder due to the displacer reciprocation motion. However, no significant reduction of cooling capacity was observed at the magnetic field of up to 0.45 T for both types of regenerators. As to the reduction of cooling capacity caused by an increase of a magnetic field, it can be expected to be similar to the results obtained for the regenerators in axial magnetic fields.

3.3. Discussion of AC magnetic noise

Finally, it is considered that the intensity of AC magnetic noise may be generated due to the fluctuation of magnetization of magnetic regenerator materials when 4K GM cryocoolers are operated in an external magnetic field with magnetic field gradient. Especially, the primary factors of AC magnetic noise are as follows:

1. The intensity of magnetic field at the position of a magnetic regenerator fluctuates with the reciprocation of the displacer. Accordingly, the magnetization of the magnetic regenerator fluctuates.
2. The temperature of magnetic regenerator fluctuates when the cryocooler is operated. Accordingly, the magnetization of magnetic regenerator fluctuates in an external magnetic field.
The amount of noise in two types is compared by the magnetization of magnetic regenerator materials reported in previous papers Numazawa et al. (2003), Gratz et al. (1982) and numerical calculation results. The temperature of magnetic regenerators may be in the range of 4~10 K in the operated cryocooler. In low magnetic fields, the magnetic susceptibility (dM/dH) of GOS is less than that of HoCu₂. Accordingly, the amount of magnetic noise caused by the reciprocating motion of the displacer in an external magnetic field will be less when GOS is used. In low magnetic fields, the temperature dependence of magnetization (dM/dT) of GOS is less than that of HoCu₂ in the temperature range of 4~10 K. Accordingly, in both cases, the amount of magnetic noise caused by the magnetism fluctuation of the magnetic regenerator will be less when GOS is used. These properties are useful especially for an MRI system.

4. Conclusion

By using HoCu₂/GOS hybrid regenerator, the cooling capacity of the SHI 1W 4K GM cryocooler can be kept under a magnetic field of up to 2.0 T. Especially, the magnetic regenerator material GOS is necessary for maintaining the second stage below helium boiling temperature of 4.2 K within a magnetic field of up to 2.0 T. Moreover, it is considered that the amount of magnetic noise caused by an operated cryocooler will be lower. With this kind of cryocooler, it is possible that superconducting magnet systems, such as MRI, can be more compact. And also, it can be used for cooling a superconducting magnet system which generates a high magnetic field.

References