Improvement of cooling capacity of 4K GM cryocooler in magnetic fields

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Abstract. 4K GM cryocoolers have been widely used for cooling superconducting magnets, such as, magnets in MRI, NMR, Magnetic field-applied Czochralski (MCZ) and electron accelerator systems. In general, high capacity cryocoolers are required to maintain a stable operation for these systems. Cryocoolers are inevitably exposed to the magnetic fields in these superconducting magnet systems. Therefore, it is important that the cooling capacity can be maintained in magnetic fields. Recently, we measured the cooling capacity of a Sumitomo Heavy Industries, Ltd., (SHI) new 4K GM cryocooler, RDE-412, in magnetic fields up to 3.0 T. It is found that the second stage temperature only increases about 0.3 K and the cooling capacity keeps in the specification of 1.25 W at 4.0 K up to 3.0 T.

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, ErNi, ErNi10.9Co0.1 and HoCu2 [1-2]. In 2000’s, SHI 4K GM cryocoolers were improved furthermore by using ceramic regenerator materials, such as Gd2O2S (GOS) [3-4]. As well known, it is very important that the regenerator is optimized to improve the cooling capacity of a cryocooler. It was reported that the efficiency of a 4K GM cryocooler was improved by about 30% [5].

4K GM cryocoolers have been widely used for cooling superconducting magnets, such as magnets in MRI, NMR, MCZ and accelerator 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 are 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.

In our previous study, the effect of regenerator material GOS on cooling capacities was investigated in magnetic fields. As the results, by using a HoCu2/GOS hybrid regenerator, the cooling capacity of the 4K GM cryocooler can be kept under magnetic fields. In recent, we released a new 4K GM cryocooler, RDE-412, which can provide a cooling capacity of 1.25 W at 4.2 K.

An experimental investigation of the cooling capacity of a RDE-412 cryocooler exposed to a magnetic field was carried out. Some experimental results and discussions are presented in this paper.
2. Experimental system
A RDE-412 cryocooler was used in the experiments. An SHI water-cooled compressor, F50L, was used to drive the cold head. The compressor has a rated input power of about 6.0 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 is 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 0.15 % up to 8.0 T at 4.2 K.

![Figure 1. Experimental setup. (a) A picture of the cold head installed into the superconducting magnet system; (b) schematic diagram of the setup.](image)

Figure 1 (a) shows a picture of the cold head installed into the superconducting magnet system. The magnetic field was applied parallel to the axis of the cold head cylinder. This picture corresponds to the case depicted in Figure 1 (b). In the conducted experiments, the applied magnetic field strength can be up to 3.0 T at the center position of magnetic regenerator constructed out of HoCu$_2$ layer.

3. Experimental results

3.1. The cooling capacity of RDE-412
First, we measured the cooling capacities of a RDE-412 cryocooler in zero magnetic field. RDE-412 4K GM cryocoolers are designed to have a cooling capacity of 53 W at 40 K at the first stage and 1.25 W at 4.2 K at the second stage, respectively. Also, the size is designed to be as same as an SHI conventional 1W 4K GM cryocooler, RDK-408. The cooling capacity of a RDE-412 cryocooler is about 25 % more than that of RDK-408. The improvement of cooling capacity was achieved by optimizing the construction of the regenerators. Figure 2 shows a typical cooling load map of the RDE-412 cryocooler used in the experiment. A typical cooling capacity of 60 W at 48.5 K at the first stage and 1.25 W at 3.8 K at the second stage was achieved. The compressor was operated at 50 Hz and the cold-head was operated at 1.0 Hz.
3.2. The cooling capacity of RDE-412 in magnetic fields

Figure 3 shows the experimental results of the second stage temperature of the RDK-408 and RDE-412 cryocoolers when the cold head was placed in the axial magnetic field. In this figure, the dot line corresponds to the second stage temperature of RDK-408 with heat loads of 1.0 W at the second stage and 40 W at the first stage when the regenerator material was HoCu₂ only. This line was denoted as type (b) line in Figure 3. The dash line corresponds to RDK-408 of using HoCu₂/GOS hybrid regenerator material with same heat loads where GOS replaced about 60 % of HoCu₂ by weight. This line was denoted as type (a) line. The solid line corresponds to the second stage temperature of the RDE-412 with heat loads of 1.25 W at the second stage and 53 W at the first stage. The second stage regenerator of RDE-412 is constructed out of HoCu₂ and GOS. Figure 3 (a) shows that the second stage temperature of RDE-412 only increases slightly and the cooling capacity keeps in the specification of 1.25 W at 4.0 K up to 3.0 T magnetic field. On the other hand, the second temperature of RDK-408 type (a) is over 4.2 K with 1.0 W heat load at 2.0 T magnetic field.

Figure 3 (b) shows the degradation of the second stage cooling capacities by magnetic fields. The second stage temperature in zero field is denoted as 100%, and then the second temperatures in magnetic fields are evaluated as percentage relative to the above temperature. No remarkable reduction of cooling capacity is observed for RDE-412 up to 3.0 T. It is found that the degradation of RDE-412 is the smallest in these experiments. RDE-412 kept the cooling capacity of above 95 % at 2.0 T and above 90 % at 3.0 T.

Owing to the introduction of GOS material and the optimization of the regenerator packing ratio, the second stage cooling capacity of RDE-412 in magnetic fields was greatly improved. The effect of GOS on the second stage cooling capacity in magnetic fields, was reported previously [6].
4. Conclusion

We investigated the cooling capacities of an SHI new 4K GM cryocooler, RDE-412, in magnetic fields. A typical cooling capacity of 60 W at 48.5 K at the first stage and 1.25 W at 3.8 K at the second stage has been achieved in zero magnetic field. The cooling capacity of a RDE-412 cryocooler is about 25% more than that of a SHI conventional 4K GM cryocooler, RDK-408. The second stage temperature of RDE-412 can be kept below 4.2 K with 1.25 W heat load under a magnetic field of up to 3.0 T, and over 95% of the original cooling capacity can be maintained under a magnetic field below 2.0 T.

References

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