Conduction-Cooling System for Superconducting Magnets at 20–30 K

Ho-Myung Chang and Seung Ill Lee

Abstract—**A cryogenic system is designed and experimentally tested for superconducting magnets conductively cooled at 20–30 K by a cryocooler. Metallic parts are fabricated for the thermal connection between coldhead of a single-stage GM cooler and six magnet bobbins in hexagonal array, and assembled with bolt-joints. The material of all parts is oxygen-free copper with a high RRR value (∼525), and the GM cooler is a newly released model from Sumitomo Heavy Industries. All six bobbins are uniformly cooled down to 13.0 K under no load and can be maintained at 20–30 K under additional thermal load of 26–60 W. It is verified by analytical simulation that this excellent performance is due to the extremely high thermal conductivity of copper conductors and the good thermal contacts by bolt-joints. The conduction-cooling system is a thermally feasible option for 20–30 K magnets, including the wind turbine generators.**

Index Terms—**Conduction-cooling, cryocooler, cryogenics, superconducting generator.**

I. Introduction

CRYOGENIC cooling system for superconducting magnets is designed in a variety of structures, depending on their operating temperature [1], [2]. Some HTS magnets under late development require closed-cycle refrigeration at 20–30 K. For example, 10 MW wind turbine generators have been designed on a basis of 20 K operation by many groups [3]–[5]. The main reason for this low-temperature operation is to take advantage of a larger critical current density of HTS tapes for lighter weight or to make use of less expensive MgB_2 wires.

From the view point of cryogenic design, the 20–30 K magnets are far different from LTS magnets at liquid-helium temperatures (2–5 K) and HTS magnets at liquid-nitrogen temperatures (65–90 K), since no cryogenic liquid is readily applicable. Even though liquid neon or gaseous helium could be used, conduction-cooling systems with a cryocooler have been developed for compactness and simple operation.

In accordance with the potential markets, a few models of single-stage GM cryocoolers are commercially available for refrigeration of 50–100 W at 20–30 K [6], [7]. However, since the cooling capacity of these coolers shrinks sharply as the temperature drops below 20 K, it is crucial to maintain the cold-head temperature above a level such that the cryocooler has the required capacity. In other words, the design goal here is to reduce the temperature difference between the cold-head and magnets for an effective thermal conduction. A great feature of the conduction-cooling is that pure copper could have an extremely high thermal conductivity at 10–30 K, if its residual resistivity ratio (RRR) value is large [8], [9].

The objective of this study is to investigate the thermal effectiveness of a conduction-cooling system for magnets at 20–30 K. It is intended to design and construct an experimental system, with which the upper limit of thermal effectiveness can be demonstrated. Towards this goal, a state-of-the-art GM cryocooler is provided by a leading manufacturer, and thermal conductors are fabricated with highly conductive copper. In parallel with experiment, analytical simulation is performed on the conduction-cooling system for clearly explaining the thermal performance.

II. Experiment

Fig. 1 is a schematic overview of experimental set-up with graphical representation on the assembly of cryogenic parts. The main GM cooler is mounted at the top plate of a vacuum cryostat, and six identical magnet bobbins are vertically placed as hexagonal array around the GM cooler. Thermal conductors are composed of 1) a horizontal disk (100 mm diameter, 15 mm thickness) under the cold-head, 2) a vertical plate (70 mm × 127 mm × 18 mm) under the horizontal disk, 3) four diagonal sheets (200 mm × 50 mm × 3 mm), and 4) 16 U-bent sheets (80 mm × 50 mm × 3 mm) between bobbins. All parts are machined and fabricated with oxygen-free copper and assembled by bolt-joints only (without any soldering). The diagonal and U-bent sheets have a flexible length, where many layers of thin (∼0.2 mm thickness) copper sheets are stacked so that they can be easily bent. The flexible length is important not only for thermal contraction, but also for good thermal contact by bolt-joints, as discussed later. Fig. 2 is a photograph of the assembled cryogenic parts with an enlarged view of the flexible U-bent sheets.

In order to focus on thermal behavior, the magnet bobbins are simply rectangular plates (320 mm × 110 mm × 20 mm) with no HTS windings. For supplying additional thermal load, film heaters are attached on the bobbin surfaces. The entire cold parts are surrounded with a cylindrical radiation shield made with copper shell and aluminum plates. The radiation shield can be optionally cooled by an auxiliary GM cooler. The outer surfaces of cold-head, thermal conductors, magnet bobbins, and radiation shield are wrapped with multi-layer insulation. The

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The authors are with the Department of Mechanical Engineering, Hong Ik University, Seoul 121-791, Korea (e-mail: hmchang@hongik.ac.kr).

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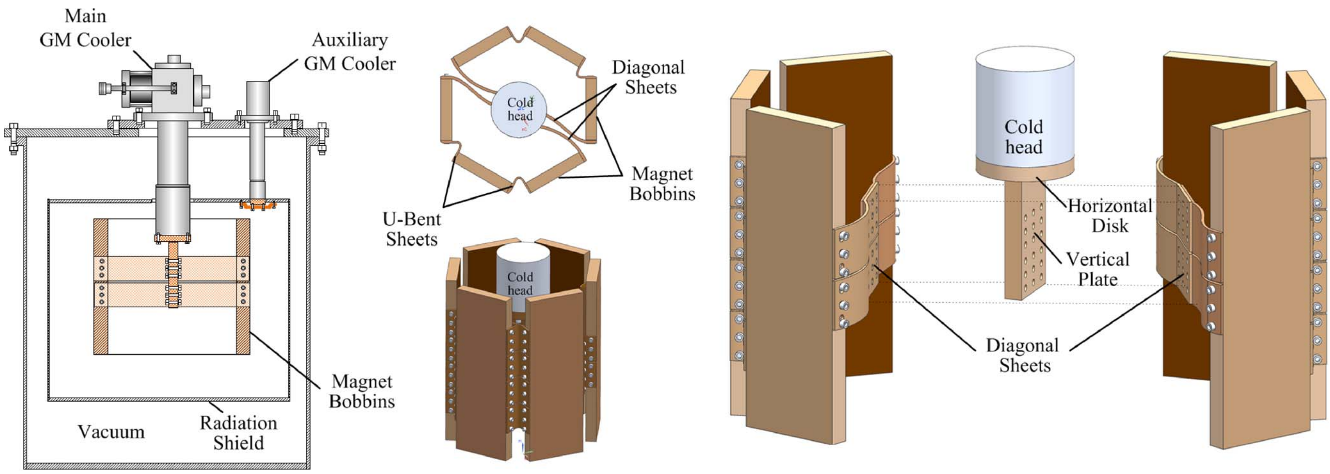

Fig. 1. Schematic overview of experimental set-up and graphical representation for assembly of cryogenic parts, including cold-head of GM cryocooler, thermal conductors (composed of horizontal disk, vertical plate, diagonal sheets, U-bent sheets), and six magnet bobbins in hexagonal array.

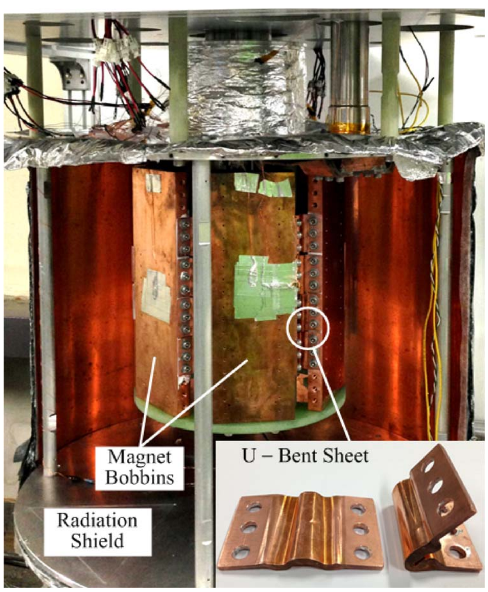

Fig. 2. Photographs of assembled cryogenic parts in radiation shield and U-bent sheets between bobbins (enlarged).

total mass of cryogenic parts including six bobbins and thermal conductors is 44.1 kg.

The main GM cooler is a recently released model (RDK-500B) from Sumitomo Heavy Industries, whose refrigeration capacity is listed as 50 W at 20 K and 95 K at 30 K by the manufacturer [6]. The capacity is actually measured in the experimental set-up (without conductors) and plotted in Fig. 3. The measured capacity is slightly larger than the listed values. The optional auxiliary GM cooler is Cryomech model AL-60. The temperature of radiation shield is measured at 69 K (top) ~78 K (bottom) when cooled by the auxiliary cooler, and 249 K when not cooled.

Temperatures are measured at the cold-head and 14 various locations of conductors, magnet bobbins, and radiation shield. The temperature sensors are silicon diodes (Lakeshore ST-670) and the measured values are recorded every second with two units of data acquisition system (Lakeshore Temperature Monitor 208).

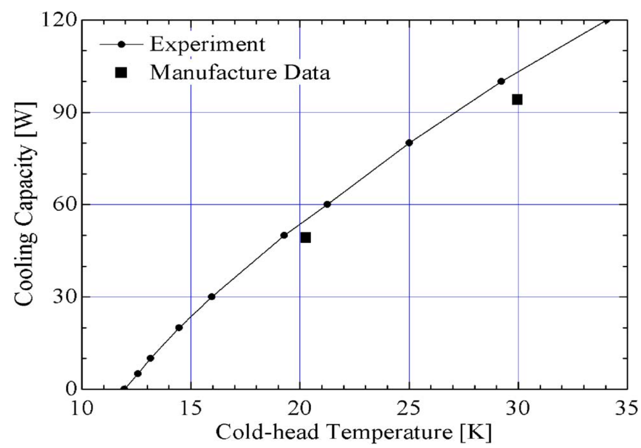

Fig. 3. Measured refrigeration capacity under the experimental setup as a function of cold-head temperature in comparison with the manufacturer's listed values for main GM cryocooler (Sumitomo Heavy Industries Model RDK-500B).

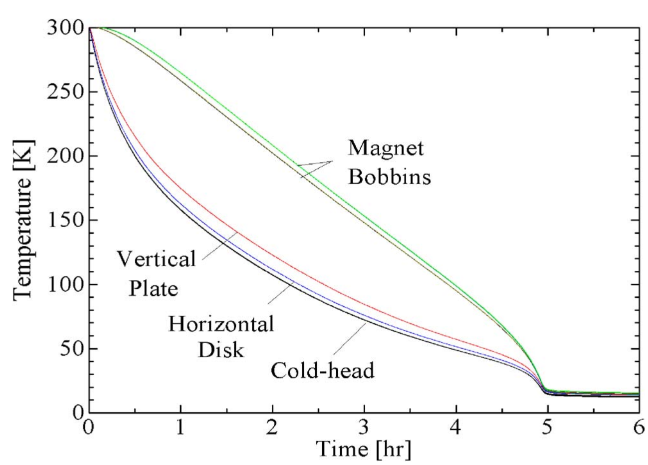

Fig. 4. Measured temperature history for cool-down process.

III. Results and Discussion

Fig. 4 is the measured temperature history for the cool-down process when both GM coolers are employed. For beginning hours, the cold-head temperature drops quickly, but the bobbin

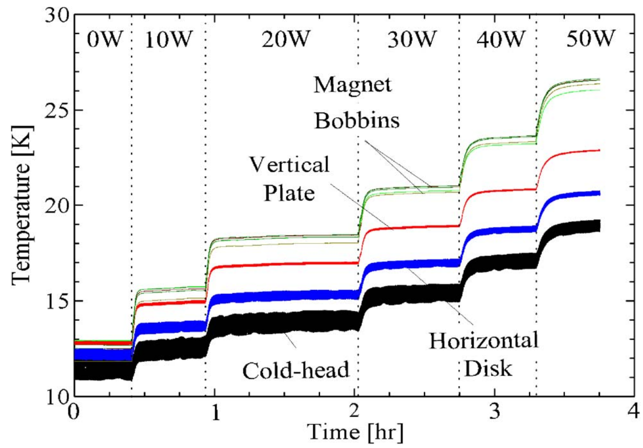

Fig. 5. Measured temperature followed by stepwise increase of heater power.

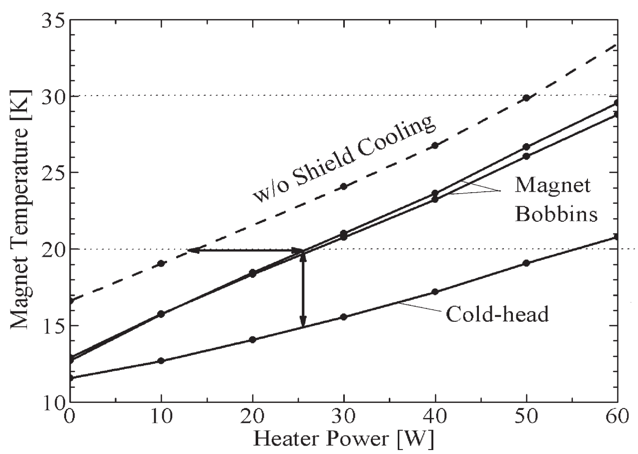

Fig. 6. Measured temperature at bobbins and cold-head versus heater power.

temperatures decrease gradually, so the temperature difference becomes as large as 120 K. At temperatures below 50 K, however, the difference diminishes mainly due to increased thermal conductivity of copper conductors as discussed below. The reason for even quicker decrease around at 20–30 K is the reduced heat capacity of cold parts. It takes approximately 5 h to reach the steady state.

After the coldest steady state is reached, the heaters on the magnet bobbins are switched on. Fig. 5 is a plot of measured temperature followed by stepwise increase of heater power up to 50 W. The cold-head temperature looks like a thick curve, as it actually oscillates at the reciprocating frequency of GM displacer. This oscillation is clearly the effect of temperature swing of working helium inside, because the heat capacity of cold-head shell diminishes below 20 K. It is noted that the temperature difference between magnet bobbins and cold-head becomes larger as the heater power is increased.

In order to highlight the key points of experimental results, the measured temperatures at bobbin and cold-head are plotted as a function of heater power in Fig. 6. When the heater power is zero, all six bobbins are uniformly cooled to 13.0 K, and the temperature difference between bobbins and cold-head is only 1.3 K. A main reason for this excellent performance is the great thermal conductivity of copper conductors. To verify this, a short sample is cut and its electrical resistance is

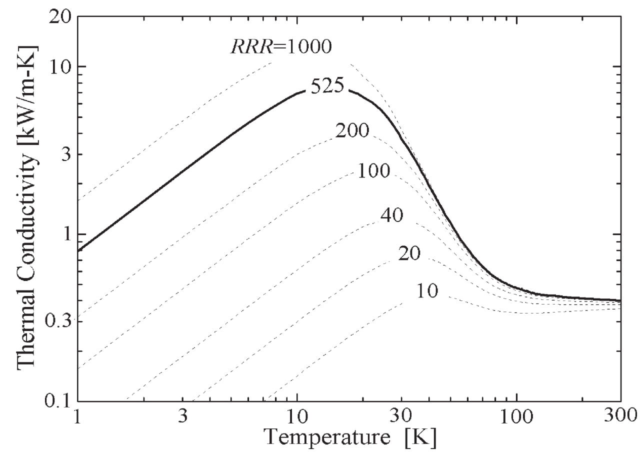

Fig. 7. Thermal conductivity of copper with $RRR = 525$ versus temperature.

measured at 298 K and 4.2 K (in liquid helium) in collaboration with the Korea Basic Science Institute. The RRR value is estimated at 525, for which thermal conductivity reaches a peak (~8 kW/m-K) at 10–20 K, as plotted in Fig. 7 [8], [9].

As the heater power increases, the temperature difference between bobbins and cold-head also increases, because a large temperature difference is necessary for the increased cooling load. For an operation of this system at 20 K, the thermal load should be 26 W or less, and the cold-head temperature should be 15 K or less, as indicated by the vertical arrow in Fig. 6. About 13 W heat load would result from radiation, if no auxiliary GM cooler is employed for shield (dotted curve), as indicated by the horizontal arrow. Similarly, for an operation at 30 K, the thermal load should be 60 W or less, and the cold-head temperature should be 21 K or less.

In parallel with the experiment, the temperature distribution is calculated with commercial software (NX Nastran 7.5). The purpose of the analytical efforts is to verify two uncertain but important factors in conduction-cooling design.

The first is the thermal contact resistance for metallic interfaces [10]. The bolt-joints of the experimental system are classified as two types: 1) between solid parts (cold-head~horizontal disk~vertical plate) and 2) between flexible and solid parts (vertical plate~diagonal sheets~bobbins~U-bent sheets~bobbins). The contact resistance is estimated from the measured temperature and heat data, which is 40 and 2.9 m^2-K/kW for the two types, respectively. The machined surface roughness is less than 6.3 μm. The second factor is the radiation heat flux on cold surfaces. The cryogenic parts are modeled as radiation-network between enclosed surfaces [10]. The heat flux on the outer surface of bobbins is estimated to be 0.15 W/m^2 from the model and measured heat data.

The estimated values are used as boundary conditions for the thermal analysis. Fig. 8 shows some calculated isotherms on the cold parts in comparison with measured temperatures (boxed numbers) and the temperature profile on meshed bodies when the heater power is 30 W. The analytical and experimental data are in a fairly good agreement.

Based on the results above, a concept design is graphically shown in Fig. 9 for conduction-cooled magnets at 20–30 K,

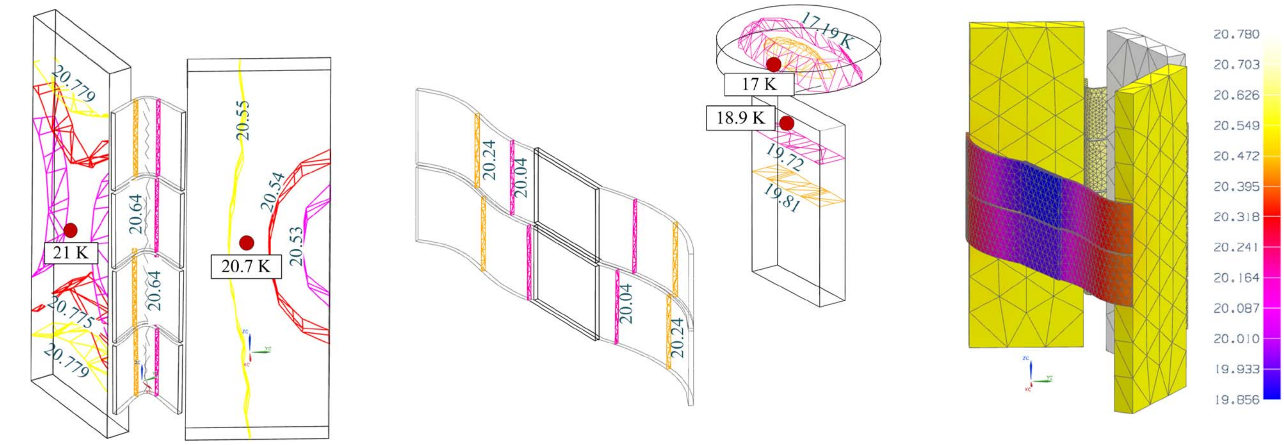

Fig. 8. Calculated isotherms on conduction-cooling parts with measured temperatures (boxed values) and temperature profile when the heater power is 30 W.

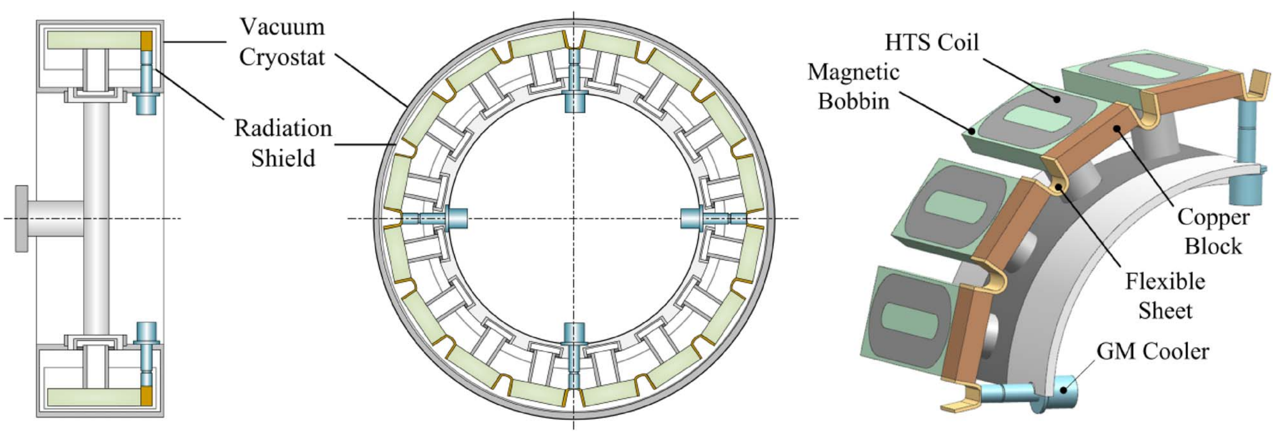

Fig. 9. Graphical representation on concept design of conduction-cooling system for 20–30 K rotor magnets of 10 MW-class wind turbine generator.

applicable to 10 MW-class wind turbine generator [3]. The GM coolers are on board a rotating cryostat in radial direction, and the number of coolers is 4∼6, depending on the operating temperature (20–30 K) and cooling load (200–250 W).

Finally, it is important to state that the effect of magnetic field should be considered in practical magnet cooling. The thermal conductivity of copper may be depressed by intensive magnetic fields [11] and extra thermal load may be added due to AC loss and bolt-joints. Further study and design efforts are needed on these issues as next steps.

IV. Conclusion

An effective conduction-cooling system is designed and experimentally tested for superconducting magnets at 20–30 K. It is successfully demonstrated that six bobbins are uniformly cooled down to 13.0 K under no load and maintained at 20–30 K under additional thermal load of 26–60 W. The key reasons for this effective thermal performance are 1) exceptionally high thermal conductivity of copper at 10–20 K and 2) good thermal contacts with flexible conductors, as well as 3) large cooling capacity of state-of-the-art GM cooler. Conduction cooling is a thermally feasible option for 20–30 K magnets.

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