Superconductivity and Cryogenics
Vol.12, No.2, (2010), pp.25~28

Estimation of Cooldown Time in Cryocooled Superconducting Magnet System

Yeon Suk Choi[*], **Dong Lak Kim and Dong Won Shin**

Korea Basic Science Institute, Daejeon 305-333, Korea

Received 4 March 2010; accepted 26 April 2010

***Abstract*— A cooldown time is one of the major factors in many cryocooler applications, especially for the design of conduction-cooled superconducting apparatus. The estimation of cooldown seeks the elapsed time to cool thermal object by a cryocooler during initial cooldown process. This procedure includes the dimension of cold mass, heat transfer analysis for cryogenic load and available refrigerating capacity of a cryocooler. This method is applied to the specific cooling system for a 3 Tesla superconducting magnet cooled by a two-stage GM cryocooler. The result is compared with that of experiment, showing that the results of proposed method have a good agreement with experiments during initial cooling of superconducting magnet.**

1. INTRODUCTION

Cryogenic cooling technology is one of the critical factors for successful development of any superconducting device. A variety of practical cooling system for superconducting devices has been developed since the discovery of the phenomenon of superconductivity in the early 1900s [1]. For the most part, these systems have utilized the niobium titanium (NbTi) and niobium tin (Nb3Sn), so called low temperature superconductors (LTS), which require a helium temperature environment to achieve their specific properties. In the standard cooling of LTS systems, low temperature helium is effectively used to maintain the system at around 4 K [2].

Recently, many superconducting magnet systems have been required to use cryocoolers as a heat sink, instead of liquid helium, to increase simplicity, compactness and efficiency [3-6]. In a conduction-cooled LTS magnet system, a two-stage cryocooler is employed as a heat sink to cool the superconducting magnet down to the designed temperature, as shown in Fig. 1. A cooldown time is a major factor in conduction-cooled superconducting magnet system. Cooldown time means a time cooling a thermal mass from room temperature to cryogenic temperature within a stipulated amount of time. As users in the field of chemical, biological and medical sciences require the higher magnetic field to improve the quality of images the size of superconducting magnet increases, resulting in the longer cooldown times, even longer than a month.

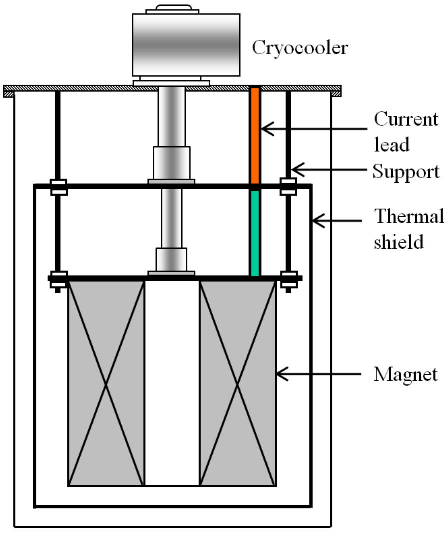

Fig. 1. Schematic of low temperature superconducting magnet cooled by a two-stage cryocooler.

Estimation of initial cooldown time, therefore, is essential in the design of conduction cooling system for superconducting magnets. In this paper, the procedure seeking the elapsed time to cool the thermal object by a cryocooler is presented. The method is applied to the cooling system for a 3 T superconducting magnet cooled by a two-stage GM cryocooler. The effects of cold mass, cryogenic load and refrigeration capacity on the cooldown time are also discussed.

2. NUMERICAL ANALYSIS

2.1. Energy Balance

In the two-stage cooling system, heat can be partly removed at first stage temperature (or shield temperature) as shown in Fig. 2. The energy balances for first and second stage are expressed as

$$\frac{dE_S}{dt} = \frac{d}{dt}\left(\rho V c_p T\right)_S = Q_H - Q_{C1} - Q_L \tag{1}$$

$$\frac{dE_M}{dt} = \frac{d}{dt}\left(\rho V c_p T\right)_M = Q_L - Q_{C2} \tag{2}$$

---

[*] Corresponding author: ychoi@kbsi.re.kr

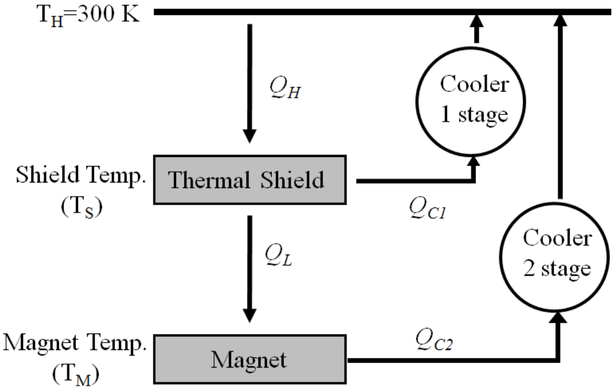

Fig. 2. Energy balance of magnet system by two-stage cooling.

where subscripts S and M denote thermal shield and superconducting magnet, respectively.

2.2. Cryogenic Loads

In energy balance equations, Q_H and Q_L are heat leakage from room temperature (T_H) to shield temperature (T_S) and from T_S to superconducting magnet temperature (T_M), respectively. Heat leakage mainly consists of support conduction (Q_k), thermal radiation (Q_r) and heat through current lead (Q_l).

$$Q_H = Q_{k1} + Q_{r1} + Q_{l1} \tag{3}$$

$$Q_L = Q_{k2} + Q_{r2} + Q_{l2} \tag{4}$$

2.2.1. Support Conduction

The heat conduction through mechanical supports is determined as

$$Q_k = N\frac{A}{L}\int_{T_L}^{T_H} k(T)\,dT \tag{5}$$

where N is number of support, A is the cross-sectional area of support and L is the length of support. In Eq. (5), $k(T)$ is temperature-dependent thermal conductivity.

2.2.2. Thermal Radiation

The radiation heat transfer to a body at temperature T_L from the enclosed surface at temperature T_H can be approximately estimated by

$$Q_r \approx \frac{\sigma\left(T_H^4 - T_L^4\right)}{\frac{1-\varepsilon_H}{\varepsilon_H A_H} + \frac{1}{A_L}\left(\frac{1}{\varepsilon_L} + \frac{2N}{\varepsilon_N} - N\right)} \tag{6}$$

where σ is the Stefan-Boltzmann constant, ε is emissivity and A is surface area. N is the number of MLI installed between two surfaces.

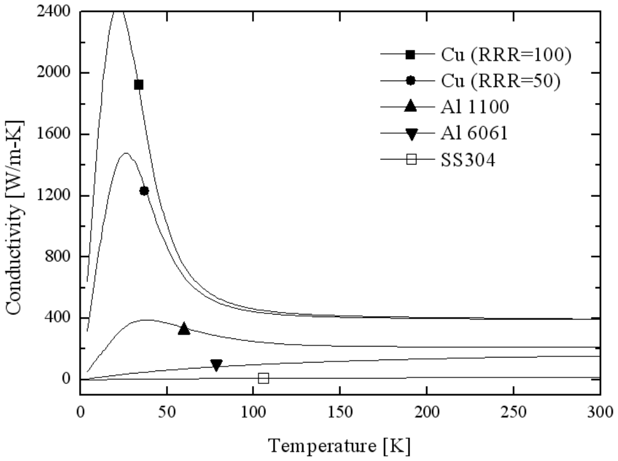

Fig. 3. Thermal conductivity of materials with respect to temperature.

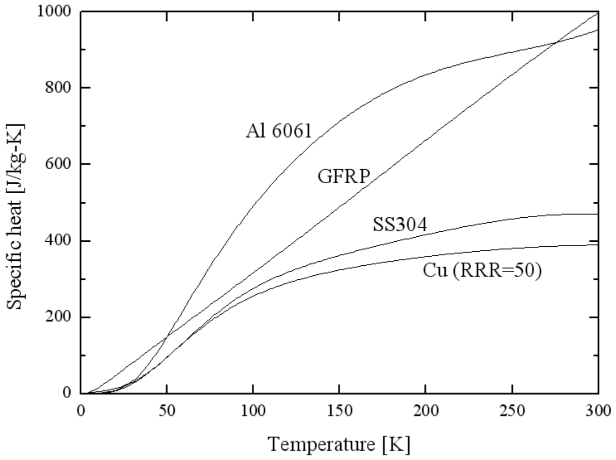

Fig. 4. Specific heat of materials with respect to temperature.

2.2.3. Heat Leak through Current Lead

Heat leak through current lead occurs by heat conduction as well as Ohmic heat generation. During initial cooldown process no current is supplied, thus only heat conduction is considered and Eq. (7) is used for this analysis.

$$Q_l = 2\frac{A}{L}\int_{T_L}^{T_H} k(T)\,dT \tag{7}$$

where A and L denote the cross-sectional area and length of current lead, respectively.

2.3. Temperature-dependent Properties

Thermal conductivity and specific heat of each component in the system are strongly dependent on temperature. Detailed properties of copper, aluminum, stainless steel and GFRP are collected from a number of sources [7-9], with special effort ensuring the consistent

TABLE I
SPECIFICATION OF COOLING SYSTEM FOR 3 T SUPERCONDUCTING MAGNET.

Parameter		Value	Unit
Central field		3	T
SC wire		NbTi	-
Magnet	ID	80	mm
	OD	103	mm
	Length	170	mm
	Mass	4.6	kg
Mechanical support	Diameter	8	mm
	Length	100	mm
Radiation shield	Diameter	540	mm
	Height	600	mm
Current lead	Material	Copper	-
	Area	100	mm^2
	Length	1300	mm
Vacuum vessel	Diameter	600	mm
	Height	800	mm

values of thermal conductivity and specific heat. Fig. 3 and Fig. 4 show the representative properties of material used in the analysis with respect to temperature.

2.4. Refrigeration Capacity

The two-stage refrigeration can be performed with a two-stage cryocooler. Since the refrigeration at the two stages are coupled each other, the actual refrigeration capacity could be rather complicated. So, we assume that the refrigeration capacities at first and second stage are independent each other. In the analysis, two second-order equations from the refrigeration capacity curve of a two-stage GM cryocooler (RDK-415D, Sumitomo [10]) are used.

3. RESULTS AND DISCUSSION

Temperatures of each component in conduction-cooled superconducting magnet system are estimated by the proposed numerical analysis. The specification of the 3 T superconducting magnet system developed by ourselves is used for accuracy confirmation. Table I shows the specification of conduction cooling system for a 3 T superconducting magnet.

Fig. 5 shows the heat leakage contributed by each cryogenic load as a function of temperature for first stage. As described early, cryogenic load consists of support conduction, shield radiation and thermal leak through current lead. As shown in Fig. 5, heat leakage increases as first stage temperature or shield temperature decreases. As shield temperature decreases, the heat leakage from first stage to second stage decreases, however large capacity of refrigeration at first stage is required to lower the temperature at first stage.

Heat leakage through current lead is larger than the others and is getting dominant as temperature at first stage decreases. When temperature at first stage is 40 K, the amounts of heat leakage by conduction, radiation and current lead are 0.83, 1.4 and 18.3 W, respectively. Heat leak through current lead is sharply increased near 50 K. It is because that the thermal conductivity of current lead material or copper increases near 50 K steeply.

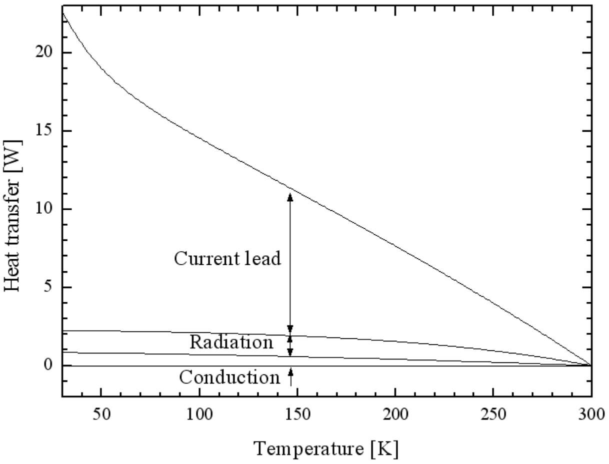

Fig. 5. Heat transfer contributed by each cryogenic load as a function of temperature for first stage.

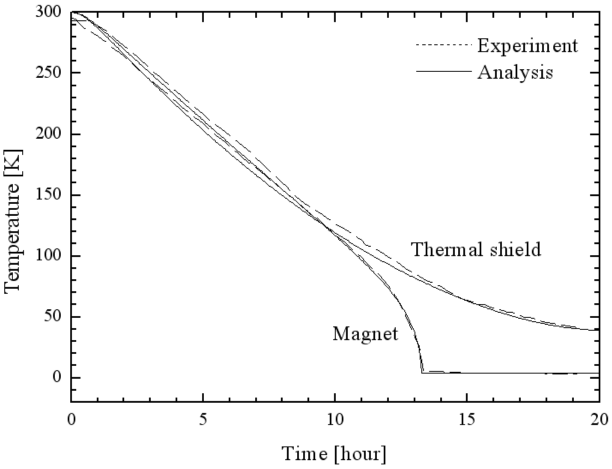

Fig. 6. Temperature history of thermal shield and magnet after turning on cryocooler.

The temperatures of magnet and thermal shield resulting from numerical analysis are plotted and compared with experiments in Fig. 6. It is observed that magnet temperature decreases almost at a constant rate and drops sharply near 50 K. While the temperature of magnet reached 4 K after 13 hours of running, the temperature of thermal shield reached 40 K and then stabilized after 20 hours running of cryocooler. Generally, the refrigeration capacity at first stage is greater than that at second stage in a two-stage cryocooler, thus it is true that the temperature at first stage decreases more quickly than second stage when no thermal load is applied. In our case, the thermal mass of radiation shield is much heavier than that of superconducting magnet, hence the temperatures of thermal shield and superconducting magnet decrease almost same rate down to around 100 K. Comparing the

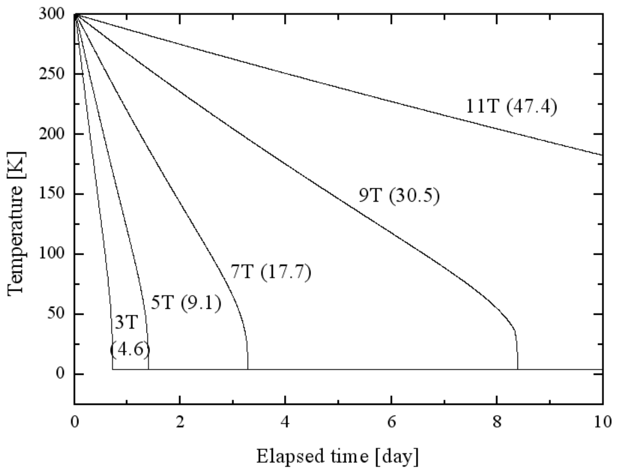

Fig. 7. Effect of magnetic field or magnet mass on initial cooldown time (corresponding mass of magnet in parenthesis, unit: kg).

experiments, the results of numerical analysis had some variation within 3% at beginning of initial cooldown. In general, the numerical analysis, however, had a good agreement with experiments and estimated exact cooldown times.

There appear to be a growing need for large-scale magnet to obtain high magnetic field. The size of magnet increases with magnetic field. The size of magnet is collected from the previous researches [4],[5],[11],[12]. Process of calculation for magnet temperature is repeated utilizing developed numerical program for various magnet sizes. Fig. 7 shows the temperature profile of magnet during initial cooldown process for several sizes of magnet. As shown in Fig. 7, the cooldown time increase with magnet size or magnetic field. It takes more than 8 days to cool the 9 T superconducting magnet down to 4 K using a two-stage cryocooler. More cryocooler or tentative thermal link between a magnet and first stage of cryocooler is one option to shorten initial cooldown times.

4. CONCLUSION

Cooldown time is successfully estimated by numerical analysis, taking into account the dimensions of superconducting magnet, heat transfer for cryogenic loads and refrigeration capacity of a cryocooler. This method is applied to the specific cooling system for 3 T superconducting magnet, showing that the results of proposed method have a good agreement with experiments. The effect of magnet mass on initial cooldown time is significant, therefore additional technique is required to shorten cooldown time when the magnetic field is high.

ACKNOWLEDGMENT

This work is supported by the KBSI Grant D30110.

REFERENCES

[1] A. C. Rose-innes and E. H. Rhoderick, *Introduction to Superconductivity*, Pergamon Press, 1978.

[2] S. W. Van Sciver, *Helium Cryogenics*, Plenum Press, 1986.

[3] Y. S. Choi, D. L. Kim, B. S. Lee, H. S. Yang and T. A. Painter, "Conduction-cooled superconducting magnet for material control application," *IEEE Trans. App. Supercond*., vol. 19, pp. 2190-2193, 2009.

[4] S. Katano, N. Minakawa, T. Hasebe and J. Sakuraba, "New cryocooler-cooled superconducting magnet: a 13.5 T high-field split-pair coil magnet for neutron scattering," *Physica B*, vol. 385-386, pp. 1300-1302, 2006.

[5] K. Watanabe and K. Takahashi, " Cryogen-free hybrid magnet for magnetic levitation," *Physica C*, vol. 386, pp. 485-489, 2003.

[6] H. Morita, M. Okada, K. Tanaka, J. Sato, H. Kitaguchi, H. Kumakura, K. Togano, K. Itoh and H. Wada, "10 T conduction-cooled Bi-2212/Ag HTS solenoid magnet system," *IEEE Trans. App. Supercond*., vol. 11, pp. 2523-2526, 2001.

[7] N. J. Simon, E. S. Drexler and R. P. Reed, "Properties of copper and copper alloys at cryogenic temperature," *National Institute of Standard and Technology*, Washington D.C., pp. 7-16, 1992.

[8] CRYOCOMP, version 3.06, a program distributed by Cryodata, Inc. Louisville, CO.

[9] Cryogenic Material Properties, NIST, [Online] Available: http://www.cryogenics.nist.gov/

[10] Sumitomo Product Documentation, Sumitomo (SHI) Inc., Allentown, PA, [Online] Available: http://www.shicryogenics.com

[11] K. Watanabe, S. Awaji, J. Sakuraba, K. Watazawa, T. Hasebe, K. Jikihara, Y. Yamada and M. Ishihara, "11T liquid helium-free superconducting magnet," *Cryogenics*, vol. 36, pp. 1019-1025, 1996.

[12] M. Urata, K. Koyanagi, T. Kuriyama, K. Yamamoto, S. Nakayama, T. Yazawa, S. Nomura, Y. Yamada, H. Nakagome, "A 10 T cryo-cooled superconducting magnet with 100 mm room temperature bore," *Physica C*, vol. 216, pp. 209-211, 1996.