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Thermal stability analysis of a superconducting magnet considering heat flow between magnet surface and liquid helium

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A B S T R A C T

This paper represents a numerical calculation method that enables highly-accurate simulations on temperature analysis of superconducting magnets considering the heat flow between the magnet and liquid helium during a quench. A three-dimensional (3D) superconducting magnet space was divided into many cells and the finite-difference method (FDM) was adopted to calculate the superconducting magnet temperatures governed by the heat transfer and joule heating of the each cell during a quench. To enhance the accuracy of the temperature calculations during a quench, the heat flow between the superconducting magnet surface and liquid helium, which lowers the magnet temperatures, was considered in this work. The electrical equation coupled with the governing thermal equation was also applied to calculate the change of the decay of the magnet current related to the joule heating. The proposed FDM method for temperatures calculation of a superconducting magnet during a quench process achieved results that were in good agreement with those obtained from an experiment.

1. Introduction

A quench is an undesirable phenomenon that occurs when part of the superconducting magnet is converted to the resistive state. When a quench occurs in the superconducting magnet, a particular hot spot spreads out due to the large electric current and the magnet temperature increases. This forces the surrounding regions into the resistive state and leads to more joule heating in a chain reaction. Therefore, a whole part of the magnet changes to a resistive state in several seconds. A quench protection system is necessary for preventing damage to the superconducting magnet from excessive joule heating. In the design process of the quench protection system, the maximum temperature of the superconducting magnet is an important factor. That is, the parameters of the protection system circuit are determined according to the maximum magnet temperature, and the wrong estimation of the temperature leads to the failure of protection for the magnet [1–3]. This is why accurate calculation of the magnet temperature is so important. There have been many studies to calculate the maximum temperature of a low temperature superconducting (LTS) magnet during a quench and these studies have suggested many advanced theories about the quench analysis [4–10].

In previous studies related to the LTS magnet immersed in a liquid coolant, the thermal effect of the coolant was ignored to simplify the numerical calculations (adiabatic conditions) [11,12]. However, consideration of the cooling effect of liquid coolant is necessary to improve the accuracy of numerical calculations in some cases. In this paper, we suggest a highly reliable quench simulation technique considering the effect of liquid helium during a magnet quench. The three dimensional mathematical model for quench analysis is used to predict the temperature with high accuracy; the joule heating, heat transfer in three directions (x,y and z directions) and heat flux to the liquid helium are all considered to calculate the temperature profiles. An LTS magnet is divided into small unit cells in three-dimensional space. Each cell has four values: the x-coordinate position, the y-coordinate position, the z-coordinate position and the temperature. The key features of the proposed numerical method are the following: (1) Thermal conduction in all-directions (between turns and layers, along the longitudinal direction) are considered at 3D space, (2) the governing thermal equation coupled with the electrical equation are discretized to estimate temperature, (3) the heat flow effect of liquid helium considering heat transfer regimes (natural convection, nucleate boiling and film boiling) is considered. To verify the feasibility of the proposed numerical simulation, the calculated results were compared with the LTS magnet quench experiments and the results were in good agreement with the experimental results. We also verified the effect of the wire material properties and the parallel resistance on the magnet temperature profiles. These calculation results demonstrated that the proposed analysis method should be an effective simulation model for a quench analysis.

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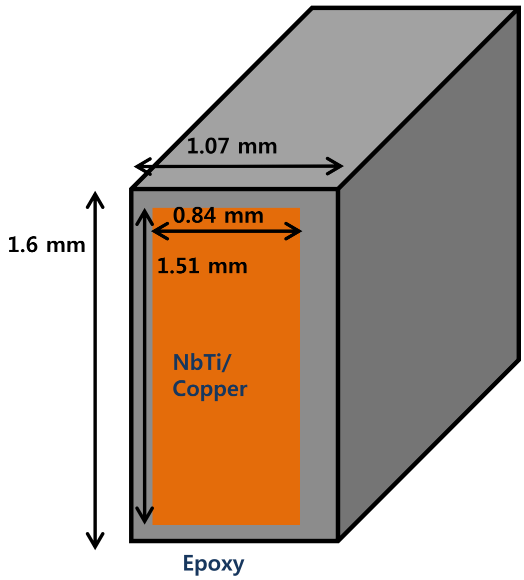

Fig. 1. Structure and dimensions of the LTS wire.

Furthermore, the proposed method will be applied to the design of the LTS magnet for an electro-magnetic property measurement system, which will be developed by the Korea Basic Science Institute (KBSI).

2. Finite difference method of simulation on thermal analysis during a quench with consideration of the heat flow between the LTS magnet surface and liquid helium

2.1. Structure of an LTS magnet

A single turn of the LTS wire consists of a mixture of a superconducting material of NbTi and copper, an insulator (epoxy) that surrounds the NbTi and copper composite. Fig. 1 shows the structure and dimensions of the superconducting wire. Before the quench occurs, current flows through only the NbTi, which has zero resistance. After the quench occurs, however, the NbTi part has a large resistance and the current flows through not the NbTi part but the copper part. In that case, joule heat generated by copper resistance is transferred to adjacent superconducting wires and the hot spot temperature is increased. Fig. 2 shows the three-dimensional (3D) structure of an LTS magnet cooled by liquid helium. The grid of the magnet represents the superconducting wires. The LTS magnet is divided into many unit cells in a 3D grid. Each cell has 3D coordinate values (X, Y, and Z) and a temperature value. Heat transfer among the adjacent cells, heat flow to the liquid helium and joule heat of each cell determine the temperature of that cell.

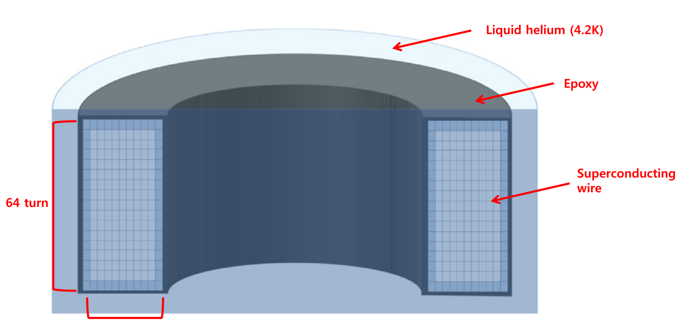

Fig. 2. Structure of the LTS magnet.

2.2. Mathematical models for temperature calculation

The power density equation governing the LTS magnet temperature analysis can be expressed by

$$C(T)\frac{\partial T}{\partial t} = \nabla\cdot[k_{cd}(T)\nabla T] + \rho_{cd}(T)J_{cd}{}^2(t) - qA_{surf} \tag{1}$$

In Eq. (1), the left side of the equation represents the time rate of change of thermal energy density of the conductor, where *C(T)* is the heat capacity per unit volume of the conductor. In the right side of the equation, the first term represents thermal conduction into the conductor, where $k_{cd}(T)$ is the thermal conductivity of the conductor.

The second term describes the joule heat of the conductor, where $\rho_{cd}(T)$ is the composite electrical resistivity and $J_{cd}(t)$ is the current density. The last term represents the heat transfer between the liquid helium (4.2 K) and the outer layers (epoxy, stycast 2850 FT), where q is the heat flux to liquid helium and *Asurf* is the surface area [13–15]. Note that q value is changed according to the liquid helium state.

Eq. (1) needs to be modified to be applied to the proposed model. Because the inner cell of the magnet is not adjacent to the liquid helium, the last term of the right side of Eq. (1) can be ignored. The discretized power density numerical equation of the inner cell (*i*th cell) is as follows:

$$C_i\frac{\Delta T_i}{\Delta t} = \frac{R_i I_i^2}{V_i} + \sum_{j=1}^{6}\frac{K_{ij}A_{ij}(T_i - T_j)}{l_{ij}V_i} \tag{2}$$

The first term of Eq. (2) describes the joule heat and second term represents the thermal conduction into the *i*th cell from the six adjacent cell s, where R_i is the resistance, I_i is the current, V_i is the volume, C_i is the heat capacity, k_{ij} is the thermal conductivity between the *i*th and adjacent *j*th cell, A_{ij} is the area between the *i*th and adjacent *j*th cell and l_{ij} is the distance between the *i*th and adjacent *j*th cell. Unlike the inner parts, heat flux to the liquid helium should be considered at the outer parts (insulation layers, no joule heat) as shown in Eq. (3).

$$C_i\frac{\Delta T_i}{\Delta t} = \sum_{j=1}^{5}\frac{K_{ij}A_{ij}(T_i - T_j)}{l_{ij}V_i} + qA_{surf} \tag{3}$$

The last term of the Eq. (3) describes the heat flow between the liquid helium and the outer cells, where q is the heat flux to liquid helium, A_{surf} is the surface area between liquid helium and the outer epoxy layer. Since the heat flux q is dependent on the liquid helium state, three different steady-state regimes were considered in this research: (1) Natural convection, (2) Nucleate boiling and (3) Film boiling [14–16]. The three different state regimes in a heat flux with respect to temperature difference are shown in Fig. 3. The different heat flux q can be expressed as shown in Eqs. (4)–(7).

At transient regime,

$$q_{Trans} = a_{Trans}(T_S^{nTrans} - T_b^{nTrans}) \tag{4}$$

At natural convection,

$$q_{NC} = a_{NC}(T_S - T_b) \tag{5}$$

At nucleate boiling,

$$q_{NB} = a_{NB}(T_S - T_b)^n \tag{6}$$

At film boiling,

$$q_{FB} = a_{FB}(T_S - T_b), \tag{7}$$

where T_S and T_b are temperature of the outer cell and adjacent liquid helium, respectively. a_{Trans}, n_{Trans}, a_{NC}, a_{NB}, a_{FB} and n are the heat transfer parameters [15,16].

Fig. 4 shows the heat transfer mechanism of the LTS magnet.

There are two directions in thermal conduction between two adjacent cells as shown in Fig. 4. b: the longitudinal direction and the transverse direction. Thermal conduction in the longitudinal direction