Refrigerant circulation system for cooling a HTS coil

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Abstract. When using the superconducting technology industrially, it is not always possible to install a refrigerator near a high temperature superconducting coil for cooling it. In the method using heat conduction cooling, cooling result as expected cannot be obtained due to temperature difference between a refrigerator and a superconducting coil via a heat transfer plate when the distance of the refrigerator and the coil is long. Therefore, a method of cooling a superconducting coil by circulating helium gas has been proposed. Helium gas discharged by a compressor at room temperature is cooled by a pre-cooling heat exchanger, thereafter cooled by a GM refrigerator. The cold helium gas cools the coil and current leads. In this study, the helium circulation cooling system was investigated by using one-dimensional numerical analysis and experiment at different helium gas mass flows.

1. Introduction
Induction heating is widely applied for heating metals because it is a clean, fast and energy-efficient heating method in most cases [1]. Induction heating is a method of heating metals by electromagnetic induction, through heat generated by eddy currents. An induction heater consists of an electromagnet, and an electronic oscillator. When a rapidly alternating magnetic field penetrates the object, eddy currents generates inside the conductor [1]. Metals are heated through Joule heating created by eddy currents. In ferromagnetic materials, heat may also be generated by magnetic hysteresis losses. The frequency of current used depends on the size of object, material type, coupling and the penetration depth.

In conventional aluminium billet induction heating method, a magnetic field is generated in a copper coil, while the copper coil itself also generates heat, and the coil is usually cooled by water-cooled to prevent melting. The heat generation of the copper coil itself causes the largest energy loss in AC induction heating, and the energy efficiency is only 55-60% for 50/60 Hz heaters in the 1 MW class [2]. Therefore, DC induction heating has been examined to improve the energy efficiency. DC induction heating is a high-energy efficient heating method by using a high temperature superconducting (HTS) coil. There is little skin effect, without overheating on the billet surface, thence the billet can be quickly heated to a uniform temperature. The energy efficiency is around 90% [2], main losses of superconducting induction heating system are the motor rotating billet and cooling the superconducting coil.

2. Helium circulation cooling system
In order to achieve use of superconducting induction heating equipment, research and development of superconducting coil cooling system with highly reliable and highly efficient is required. In refrigerant circulation cooling system, cryogenic refrigerant such as nitrogen, helium and neon is circulated inside and outside the cryostat by using a compressor or a pump. In the process, cryogenic refrigerant is precooled by a heat exchanger and further cooled by a GM refrigerator [3]. Finally, cryogenic refrigerant cools the superconducting coil. In this study, helium circulation cooling system was selected to cool a
HTS coil. A helium circulation cooling experimental system was established to confirm the cooling effect of this cooling system. In experiment, a heater was used to replace the HTS coil. Simultaneously, numerical simulation was also used to examine the experimental results.

2.1. Devices of experimental system

The refrigerant circulation cooling experimental system of this study is shown in Figure 1. This system consists of three parts, the refrigerator unit, measurement unit and the helium circulation unit. The helium circulation unit is composed of a cryostat, a circulation compressor, a pre-cooling heat exchanger of 60m (spiral tube-in-tube heat exchanger), a GM refrigerator (RDK-520E), and a heater. In the helium gas path inside of cryostat, there are temperature of five points were measured: surface of cold head; helium gas of inlet and outlet of pre-cooling heat exchanger; helium gas of inlet of heat exchanger on cold head; helium of ahead of heater. These points show in Figure 4.

![Figure 1. Refrigerant circulation cooling experimental system.](image1)

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![Figure 2. Cold head of GM refrigerator (RDK-520E) and cold head wrapped with MLI.](image2)

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![Figure 3. Cryostat TSHE-50S. The capacity is 50L, height is 1.7m, weight is 200kg.](image3)

**Figure 3.** Cryostat TSHE-50S. The capacity is 50L, height is 1.7m, weight is 200kg.
2.2 Results of helium circulation cooling system

In experiment, the temperature of each thermometer was recorded (five red points shown in Figure 4). Moreover, a numerical simulation model was established. The numerical simulation model will be introduced in section 3. In this section, experimental results and numerical simulation results were compared under the same boundary conditions. Boundary conditions of experiment are shown in Table 1. Figure 6~9 show temperature of helium gas along helium path at 0W heat load. And temperature at point ④ at different heat loads are shown in Figure 10.

In experiment, when heat load on coil was zero, the temperatures of coil (at point ④) were substantially the same under different helium gas mass flows. When heat load gradually increased, a large mass flow had a better cooling effect (the temperature of coil was lower). However, the temperatures of coil in experiment were higher than simulation results. Because the space of cryostat was narrow, which caused various devices contacting to bring heat intrusion. The narrow cryostat was replaced to a bigger cryostat, new experiment will be carried out.

**Figure 4.** Five temperature test points.

**Figure 5.** 60m pre-cooling heat exchanger (tube-in-tube). Full length is 120m. Weight is 28.1kg. The unit of numbers in the figure is mm.

**Figure 6.** Temperature of helium gas along helium path. The abscissa shows helium path starting from inlet of cryostat end to outlet of cryostat. Five black marks mean experimental results, black line means simulation values. Helium gas mass flow is 0.15g/s, and heat load on heater is 0W.

**Figure 7.** Temperature of helium gas along helium path. Helium gas mass flow is 0.52g/s, and heat load on heater is 0W.
Figure 8. Temperature of helium gas along helium path. Helium gas mass flow is 1.13g/s, and heat load on heater is 0W.

Figure 9. Temperature of helium gas along helium path. Helium gas mass flow is 1.43g/s, and heat load on heater is 0W.

Figure 10. Temperature at point ④ (coil) in experiment and simulation. Heat load is added to the heater showing in Figure 4.

Table 1. Boundary conditions of experiment.

| Helium mass flow (g/s) | 0.1~1.5         | Discharge pressure (MPa) | 1.5          |
|------------------------|-----------------|--------------------------|--------------|
| Heat load on heater (W) | 0~30            | Room temperature (K)     | 296          |

3. One-dimensional numerical analysis model

According to the first law of thermodynamics, energy equation in numerical analysis of helium circulation cooling system shows in Equation (1). In this study, a program code C++ which was created to solve energy equation numerically by the difference method.

\[
\rho c_p \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} \right) = \frac{\partial p}{\partial t} + u \frac{\partial p}{\partial x} + k \frac{\partial^2 T}{\partial x^2} + \frac{4}{3} \mu \left( \frac{\partial u}{\partial x} \right)^2 + \frac{Q}{A d x}
\]  

(1)

Where \( \rho \) is density of helium (kg/m³), \( c_p \) is specific heat at constant pressure of helium (J/(kg·K)), \( T \) is helium temperature (K), \( u \) is helium flow velocity (m/s), \( Q \) is the amount of heat exchanger per unit
\( W \), \( A \) is cross-sectional area of helium flow path \((m^2)\), \( k \) is thermal conductivity of helium \((W/(m \cdot K))\), \( \mu \) is viscosity coefficient of helium \((Pa \cdot s)\)[4].

On the left side of Equation (1), the first term is the temporal change of temperature. The second term is the spatial change of temperature due to the movement of fluid. On the right side, the first and second term are work by pressure. The third term represents heat conduction in the direction of the flow, and the fourth term represents heat generation due to fluid viscosity friction.

In numerical analysis of helium circulation cooling system, the pre-cooling heat exchanger, heat exchanger on cold head, heater are modelled, and helium gas temperature of every part is calculated by solving energy equation.

4. Cooling current leads by helium circulation system

Superconducting coils are usually energized by current supplied from a power source at room temperature. A power source must be connected to a HTS coil by a pair of current leads. Current leads are usually the dominant source of extraneous heat leak into the cryostat. In order to reduce heat intrusion from current leads into the coil, the helium circulation cooling system cools current leads after cooling the coil. The numerical simulation results are shown in Figure 11.

In helium circulation cooling system, it was verified that it was better to cool current leads and a HTS coil simultaneously than only cool the coil by numerical simulation. This is because when current leads are cooled, which prevents heat intrusion from the current leads into the coil. Therefore, the coil can reach a lower temperature.

![Figure 11. Temperature at point ④ (coil) in numerical simulation. Solid lines mean without cooling current leads, dotted lines mean with cooling current leads. Heat load is sum heat added to the coil and current leads. Heat load on current leads are constant value 20W, and heat loads on the coil are 0, 5, 10, 15W, respectively. Pressure of helium gas is 1.7MPa.](image)

5. Conclusion

The feasibility of helium circulation cooling system was verified by experiment. In experiment, when heat load on coil was zero, the temperatures of coil (point ④) were substantially the same under different helium gas mass flows. When heat load gradually increased, a large mass flow had a better cooling effect (the temperature of coil was lower).

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