Experimental investigation on conduction cooling of large diameter superconducting induction heating magnet

Lei Hu¹*, Tao Ma¹, Shaotao Dai¹, Teng Zhang¹ and Bangzhu Wang¹

¹R&D Center for Applied Superconducting Technology, Beijing Jiao Tong University
No.3 Shangyuancun, Haidian District, Beijing, 100044. P.R. China

*Corresponding author e-mail: hulei@bjtu.edu.cn

Abstract: Compared with the traditional high-frequency AC induction heating technology, the high-temperature superconducting DC induction heating technology can greatly improve the diathermy processing efficiency of low resistivity, non-ferromagnetic metal materials. Thermal stability of superconducting magnet is the key to ensure the safe and stable operation of high temperature superconducting induction heating system. Large diameter superconducting magnet is mostly cooled by immersion in cryogenic medium, but there is no precedent for conductive cooling of such magnet in the world. In this paper, we built a conducting cooling experimental platform for superconducting magnet. Temperature sensors arranged in different positions of the magnet are used to monitor the temperature distribution of each part in real time. According to the experimental results, the cooling circuit is optimized and re-tested. And then the conduction cooling experiment of large diameter superconducting magnet is carried out. The experimental results show that the optimized cooling method can sufficiently cool the superconducting magnet.

1. Introduction

Induction heating is essentially the use of electromagnetic induction in the conductor of eddy current heating to achieve the purpose of heating the workpiece, with fast, clean, convenient for surface and local heating, and in most cases energy-saving advantages. Since the 1920s, induction heating technology has been widely used in the melting, heat transmission and quenching of metal materials. Compared with the traditional AC induction heating process, the superconducting DC induction heating device uses superconducting magnet instead of traditional copper cable magnet to produce background magnetic field in the iron core. It has obvious advantages in heating depth and heating efficiency, and can avoid the risk of local temperature overheating or melting that the traditional heating technology may encounter, and provide superior technological conditions for the subsequent extrusion process, thus improving the quality identity of the profile products. At present, relevant research institutions at home and abroad have invested a lot of research work in this area and have been applied in engineering¹-⁴.

Superconducting magnet for induction heating will produce a strong magnetic field during operation, and the magnetic field has a great influence on the current carrying capacity of superconducting tapes, so the superconducting magnet must be cooled to a lower temperature (< 25K) to obtain greater current carrying capacity. There are two cooling methods for superconducting magnet at this temperature: liquid neon immersion refrigeration and conduction refrigeration. For the first method, the design of cryogenic vessels is very difficult, and the cooling method of immersion in cryogenic medium is not suitable for industrial application. Therefore, in this paper, we designed a
conductive cooling scheme for large diameter superconducting magnet to verify the proposed scheme: Firstly, the conduction cooling experiment was carried out on a small diameter superconducting magnet using a refrigerator. Then the conduction cooling structure was optimized and compared with the previous experiment. Finally, a more reasonable cooling method was adopted on the large diameter superconducting magnet.

2. Experimental condition

2.1. 600mm superconducting magnet experiment

We first produced a small superconducting magnet for verification. As shown in figure 1, from the perspective of conduction cooling, the coil skeleton is made of red copper material, and using 1.6 km YBCO superconducting tape. The current leads are separated from the skeleton through the epoxy backing plate. The outer diameter of the superconducting magnet is 600mm and the weight is 40kg.

![600mm diameter superconducting magnet](image)

Figure 1 600mm diameter superconducting magnet

After the magnet is finished, it needs to be tested under the hollow state. The most important factor affecting the current carrying capacity of superconducting tapes at a certain temperature is the magnetic field intensity of the environment in which the tapes are located, especially the vertical magnetic field. Carried out electromagnetic field analysis of this magnet, and the ampere-turns of the design value are loaded. The analysis results are shown below.

![Magnetic field distribution of air core coil](image)

(a) Radial magnetic field  (b) Axial magnetic field

Figure 2 Magnetic field distribution of air core coil

Fig. 2 is the distribution of radial magnetic field and axial magnetic field respectively. Generally speaking, the current carrying capacity of YBCO superconducting tape is most affected by vertical magnetic field, which is called radial magnetic field in this design\(^5\). Magnetic field analysis shows that the maximum vertical magnetic field of superconducting tape is about 0.35T.
The corresponding relation between the critical current and the magnetic field strength of the superconducting tapes used is shown in the above figure. When the applied magnetic field intensity reaches 0.35T and the angle between the magnetic field and the tapes is 90 degrees, the critical current of the tapes decreases to about 25% of the original value. To achieve the required magnetic field strength, the current carrying capacity of the superconducting tapes must reach at least 150A, and the critical current of the superconducting tapes must reach at least 600A. According to the performance of the selected superconducting tapes, the magnet must be cooled to a temperature below 25K to meet this requirement.

The schematic diagram of conduction cooling for 600mm diameter superconducting magnet is shown in figure 4. A refrigerator is used to refrigerate the magnet. In order to distribute the cooling energy evenly on the superconducting magnet, a heat sink structure is adopted in the cold circuit. The refrigerator is connected with the heat sink first, and then a number of soft connections are connected with the magnet evenly from the heat sink. Current lead is an important heat leakage source of superconducting magnet. So in this conduction experiment, we will also deal with the heat leakage of current lead: The current leads are connected with the insulation connection on the heat sink, and then connected with the superconducting magnet through the insulation connection, which can greatly reduce the heat leakage of the current leads.

In order to observe the accurate cooling of the magnet, we have placed a temperature sensor near the cooler head and farthest away from the cooler head. When the temperature difference between the two sensors is very small, we think the magnet has cooled sufficiently. Conducting cooling experiments on superconducting magnets based on the above experimental system. Based on the above experimental system, conductive cooling experiments of superconducting magnet are carried out. The experimental results show that although the cooler can quickly cool down to about 20K, the magnet temperature is still difficult to achieve the expected 25K. The analysis shows that the cooling capacity of the refrigerator may be due to the cooling of the superconducting magnet and the radiative heat balance between the magnet and the Dewar. Theoretically, the magnet will reach a certain heat balance, but because the distribution and transfer of cooling capacity are very complex, the magnet...
can only be cooled to about 120K (Fig.5) after different connection, adjustment of cooling parts and change of insulation structure, and far from meeting the 25K system requirements.

\[ Q = Q_1 + Q_2 + Q_3 \]  \hspace{1cm} (1)

\( Q_1 \) refers to the conduction of heat leakage through the rod between the magnet and the Dewar. Since the structure of the magnet has been determined, the total amount of heat leakage in this part is fixed. \( Q_2 \) is the convection heat leak of residual gas inside the Dewar. In this experiment, the vacuum of Dewar is kept very high, so we think that the heat leakage value of convection is very small and can be neglected. \( Q_3 \) is the radiation leakage part, which can be calculated from the following formula[8]:

\[ Q_3 = C_0 \varepsilon_F F_1 \left[ \left( \frac{T_2}{100} \right)^4 - \left( \frac{T_1}{100} \right)^4 \right] F_{1-2} \]  \hspace{1cm} (2)

In the formula, \( C_0 \) refers to the radiation constant of the blackbody, generally taken as 5.67x10^{-8} W/m².K⁴. \( F_1 \) is the area of a cryogenic surface, which in this paper refers to the outer surface area of a superconducting magnet. For a designed superconducting magnet, this value is also determined. \( T_2 \) and \( T_1 \) refer to the surface temperature of high temperature and low temperature surface respectively. In this paper, \( T_1 \) is the surface temperature of the superconducting magnet, and the design value is 25K and \( T_2 \) is the temperature of the high temperature surface. In the above experiment, \( T_2 \) is the surface temperature of the Dewar, slightly lower than room temperature, about 300 K. \( F_{1-2} \) is the radiation angle coefficient of the cold surface on the hot surface, generally 1. \( \varepsilon_F \) is the effective radiation coefficient, which is also a fixed value in this experiment.

According to the above analysis, to reduce the radiation leakage of the magnet, only the value of \( T_2 \) can be changed. We have modified the existing conductive cooling structure by adding a cryogenic radiation shield between the low temperature Dewar and the superconducting magnet in order to form a temperature barrier between them and use a refrigerator to cool the cold cryogenic radiation shield (Fig.6). With this modification, \( T_2 \) is changed from room temperature to cryogenic radiation shield temperature after cooling, and the cooling effect of superconducting magnet will be greatly improved in theory.
Cooling experiments were carried out on the modified conductive cooling structure. After 35 hours of cooling, the magnet reached thermal equilibrium, and the surface temperature of the magnet dropped below 25K, which is shown in Fig.7. Because the temperature sensor on the magnet is only attached to the surface of the magnet skeleton, the temperature distribution inside the superconducting coil can’t be judged. It is necessary to judge whether the inner magnet is cooled below 25K by current experiment of the superconducting magnet. According to the above analysis, when the magnet is cooled below 25K, the critical current of the superconducting magnet should be above 150A. so when pass the current 150A, the measuring curve should be stable without inflection point. The experiment of superconducting magnet is carried out and the result is shown in Figure 8. It can be seen from the result that when the test current reaches 150A, the magnet does not break down and other abnormalities occur. The inflection point at the end of the curve is caused by the induced voltage generated inside the magnet after the current is switched off, and is regarded as a normal phenomenon. This shows that the temperature inside the magnet is also lower than 25K, and also proves that the modification of conductive cooling structure is effective.
2.2. 2200mm superconducting magnet experiment

Through the cooling experiment of the 600mm diameter superconducting magnet, the conduction cooling structure is determined, and next we produced a 2200mm diameter superconducting magnet. The system consists of two refrigerators, the superconducting magnet, the cryogenic radiation shield, a cryogenic Dewar and related connectors, and the two cryocoolers respectively refrigerate superconducting magnet and cryogenic radiation shield.

Owing to the large size and heavy weight of the 2200mm superconducting magnet, the whole cooling process lasted 8 days to achieve thermal equilibrium. The temperature sensor shows that the magnet temperature is 25K, which proves that the optimized cooling conduction structure is also feasible for 2200 mm superconducting magnet (Fig.10). In order to judge whether the inner of magnet reaches the temperature, we also carried out the current experiments on the magnet and the experimental results are shown in Figure 11. In order to further test the performance of magnets, we increased the current to 180A in this experiment as shown in Fig.11.
In order to further test the performance of the magnet, we increased the current to 180A in this experiment. The experimental results show that the performance of the magnet is still very stable, and the inner temperature reaches our expected value.

3. Conclusion

The feasibility of conducting cooling method for large diameter superconducting magnets is experimentally studied. We build a conductive cooling platform for 600mm superconducting magnets to find the suitable cooling structure, and then verify the improved cooling structure in 2200mm large diameter superconducting magnet. The experimental results show that conductive cooling is an effective and feasible cooling method for large diameter superconducting magnet. Adding a cryogenic radiation shield to the cooling conduction structure can greatly reduce the heat leakage of the magnet system and help the cooling effect of the magnet.

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