Concept of a cryogenic system for a cryogen-free 25 T superconducting magnet

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Abstract

A cryogen-free 25 T superconducting magnet using a ReBCO insert coil that generates 11.5 T in a 14 T background field of outer low-temperature superconducting (LTS) coils is currently under development. The AC loss of the insert coil during field ramping is approximately 8.8 W, which is difficult to dissipate at the operating temperature of the LTS coils (4 K). However, since a ReBCO coil can operate at a temperature above 4 K, the ReBCO insert coil is cooled to about 10 K by two GM cryocoolers, and the LTS coils are independently cooled by two GM/JT cryocoolers. Two GM cryocoolers cool a circulating helium gas through heat exchangers, and the gas is transported over a long distance to the cold stage located on the ReBCO insert coil, in order to protect the cryocoolers from the leakage field of high magnetic fields. The temperature difference of the 2nd cold stage of the GM cryocoolers and the insert coil can be reduced by increasing the gas flow rate. However, at the same time, the heat loss of the heat exchangers increases, and the temperature of the second cold stage is raised. Therefore, the gas flow rate is optimized to minimize the operating temperature of the ReBCO insert coil by using a flow controller and a bypass circuit connected to a buffer tank.

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1. Introduction

The generation of high magnetic fields is important in research for deriving a variety of new physical properties. Recently, there has been an increasing need for high-field magnets [1-5] for materials research. The critical current density of ReBCO coated conductors has shown remarkable improvements in recent years, and their mechanical strength is also high, allowing the generation of high magnetic fields of more than 20 T [3-5], which is difficult to achieve with NbTi and Nb$_3$Sn conductors alone. Moreover, ReBCO-coated conductors can operate for practical use at 10–40 K. This means that a coil wound with a ReBCO-coated conductor is suitable for operation using a conduction cooling system, which does not need liquid helium.

A new 25 T cryogen-free magnet using a ReBCO insert coil in the inner coil of outer low-temperature superconducting (LTS) coils wound with NbTi and Nb$_3$Sn is currently under development at Tohoku University [6]. Until now, 18 T cryogen-free magnets, and an upgraded magnet generating 20 T, both having Bi2223 insert coils, have been developed at Tohoku University [7,8]. Compared with the 20 T cryogen-free magnet, in a 25 T cryogen-free magnet, the magnetic field contribution of the insert coil will be 2.5 times higher, and the total conductor length will increase drastically. As a result, the AC loss of the ReBCO insert coil during the specified field ramping time of 60 min will produce a heat load of approximately 8.8 W. Meanwhile, to provide protection from the leakage field of high magnetic fields, the cryocoolers must be arranged at positions away from the coils, so that a long-distance cooling technique is required.

In this paper, we discuss the concept of a cryogenic system for a 25 T cryogen-free magnet, in which the cooling systems of the LTS coils and the ReBCO coil are separated. They are independently cooled to different operating temperatures of 4 K and 10 K.

2. Concept of the cryogenic system

The specifications of the 25 T cryogen-free magnet are shown in Table 1. The magnet uses a ReBCO insert coil that generates 11.5 T in a 14 T background field of outer LTS coils [6]. In the case of the previous 20 T conduction cooling magnet, both the LTS and HTS coils were cooled by a single GM/JT cryocooler with a 4.3 W-class cooling capacity at 4.2 K. In the 25 T conduction cooling magnet, the heat load of the LTS coil cooling system is currently estimated to be about 5.5 W, and if we add this to the ac-loss of the ReBCO insert coil (8.8 W), the total will be 14.3 W. To dissipate this heat load with 4.2 W-class GM/JT cryocoolers with a cooling capacity of 4.3 K [9], at least four sets will be required, and complicated pipe lines must be arranged in a limited space. However, a ReBCO coil has a high critical current density in practical use at 10–40 K, and it does not necessarily need to be cooled at 4 K. In a temperature range of about 10–40 K, a GM cryocooler has a higher cooling capacity of 10 W at 8 K (1.5 W at 4.2 K) [10] than that of a GM/JT cryocooler at 4 K and is cheaper. Thus, the cooling systems of the LTS coils and the cooling system of the ReBCO coil were separated, and the coils were independently cooled to different operating temperatures of 4 K and 10 K.

For long-distance cooling, the LTS coils were cooled by GM/JT cryocoolers in which a cooling pipe is extended to the LTS coils, based on the design of the cooling system for the previously developed 18 T and 20 T cryogen-free magnets. On the other hand, the ReBCO coil was cooled by circulating helium gas by using GM cryocoolers and a helium compressor. In both cases, the temperature difference of the heat transfer is independent of the distance over which the helium mist and gas circulate. By optimizing the gas flow rate, the temperature of the cold stage of the coil was minimized to 8.5 K when operating at 0.5 g/s, even when a heat load of about 10 W was generated.

| Parameter                      | HTS | LTS1 | LTS2 | LTS3 | LTS4 | LTS5 |
|-------------------------------|-----|------|------|------|------|------|
| Conductor                     | ReBCO | Nb$_3$Sn | Nb$_3$Sn | Nb$_3$Sn | NbTi | NbTi |
| Inner diameter (mm)           | 102 | 300  | 372  | 458  | 545  | 628  |
| Outer diameter (mm)           | 276 | 366  | 452  | 539  | 622  | 712  |
| Coil height (mm)              | 408 | 540  | 628  | 628  | 628  | 628  |
| Magnetic field contribution (T)| 11.5| 2.43 | 2.91 | 2.73 | 2.69 | 3.24 |
3. Cooling system of the LTS coils

3.1. Initial cooling circuit

Since the LTS coils have a large heat capacity compared with the ReBCO coil, a large cooling capacity is required for the initial cooling. Although the cooling capacity of the GM/JT cryocooler is large at 4 K, it is small from room temperature to about 4 K. The cooling pipes of the JT system are branched, and this bypass piping is used in the three modes.

The cooling circuit for the initial cooling is shown in Fig. 1 (a). Table 2 shows opening and closing of the bypass piping in the three modes.

In mode 1 (300–50 K), the LTS coils are cooled by the gas which comes from the first bypass piping of GM/JT-#1 through two single-stage GM cryocoolers. These two single-stage GM cryocoolers also cool a thermal radiation shield.

Next, in mode 2 (50–20 K), the LTS coils are cooled by the gas which comes from the second bypass piping of GM/JT-#2 through the 2nd cold stage of GM/JT-#2.

Finally, in mode 3 (20–4 K), the 1st and 2nd bypass valves are closed, and coolant gas is sent to the LTS coils through the two JT valves of GM/JT-#1 and GM/JT-#2. The calculated result of the LTS coil temperature at initial cooling is shown in Fig. 1 (b). The result demonstrates that the initial cooling time is estimated at about 312 hours (13.0 days).

3.2. Heat invasion from the support of the ReBCO coil

By separating the cooling systems of the LTS coils and the ReBCO coil, the heat invasion from the support of the ReBCO coil to the LTS coils is increased. The heat loads to the two GM/JT cryocoolers at 4 K is listed in Table 3. The heat invasion from the support of the ReBCO coil is 37 mW, which is small enough compared with the total heat load of 5.6 W. The heat loads can be cooled by the two GM/JT cryocoolers with 4.2 W-class cooling capacities at 4.3 K [9].

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Table 2. Opening and closing of the bypass piping in the three modes.

| Valve         | Mode 1  | Mode 2  | Mode 3  |
|---------------|---------|---------|---------|
|               | (300–50 K) | (50–20 K) | (20–4 K) |
| Bypass-#1     | Open    | Close   | Close   |
| Bypass-#2     | Open    | Open    | Close   |

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Fig. 1 (a) Cooling circuit of the LTS coils; (b) Calculated result of the time variation of the LTS coil temperature at initial cooling.
Table 3. Heat loads to the GM/JT cryocoolers at 4 K.

| Heat load                                         | Value  |
|--------------------------------------------------|--------|
| AC-loss of the LTS coils (W)                     | 2.63   |
| Joule loss of the junctions (W)                  | 0.869  |
| Heat invasion from the support (W)               | 0.189  |
| Heat invasion from the support of the ReBCO coil (W) | 0.037  |
| Thermal radiation (W)                            | 0.151  |
| Heat load from the cold stage of the power lead (W) | 1.70   |
| Total (W)                                        | 5.58   |

4. Cooling system of the ReBCO insert coil

4.1. He gas circulating system

A schematic view of the cooling system of the ReBCO coil is shown in Fig. 2(a). For the long-distance heat transfer of about 1.5 m from the cooling head of the GM cryocoolers to the ReBCO coil, the circulating helium gas is cooled by the 1st and 2nd cold stages of the GM cryocoolers through the 1st and 2nd heat exchangers. The gas is circulated by a compressor located in a room-temperature area.

It is first cooled by about 50 K in the 1st cold stage of the GM cryocoolers through the 1st heat exchanger, and is then cooled through the 2nd heat exchanger down to about 10 K by the 2nd cold stage of the GM cryocoolers. Furthermore, another cold stage with wound gas piping is arranged at the upper and lower sides of the ReBCO coil, and the coil is conduction-cooled with a high-purity aluminium cold plate inserted into the coil. The rise of the gas temperature can be reduced to half by going to the upper and lower cold stages of the ReBCO coil and returning to the 2nd cold stage of the GM cryocoolers. These components are stored in the same radiation shield, which is cooled by the single-stage GM cryocoolers.

Moreover, since the density of low-temperature helium gas rises as it cools from room temperature down to the operating temperature of 10 K, it is expected that the capacity of the helium gas will run short. Therefore, a buffer tank is connected in parallel to the compressor at the room-temperature area. Also, the gas flow rate is adjusted with a flow controller.

4.2. Optimization of the gas flow rate at the operating temperature

The temperature difference of the second cold stage of the GM cryocoolers and the cold stage of the ReBCO coil depends on the gas flow rate and can be suppressed by increasing it. At the same time, however, the thermal loss of the first and second heat exchangers will increase, and the temperature of the first and second cold stages of the GM cryocoolers will rise in accordance with this situation.

The temperatures when the cooling capacity of the GM cryocoolers coincides with the heat loads of 10.3 W listed in Table 4 were calculated at various gas flow rates. The cooling capacity of the two GM cryocoolers is assumed to be 10 W at 8 K (1.5 W at 4.2 K) per unit [10]. Fig. 2(b) shows the calculation results of the temperature of the cold stage of the coil and the first and second cold stages of the GM cryocoolers. The results show that the temperature of the cold stage of the coil can be minimized to 8.5 K at a gas flow rate of 0.5 g/s.

Table 4. Heat loads to the GM cryocoolers at 10 K.

| Heat load                                         | Value  |
|--------------------------------------------------|--------|
| AC-loss of the ReBCO coil (W)                     | 8.8    |
| Joule loss of the junctions (W)                  | 1.33   |
| Heat invasion from the support (W)               | -0.037 |
| Thermal radiation (W)                            | 0.006  |
| Heat load from the cold stage of the power lead (W) | 0.18   |
| Total (W)                                        | 10.3   |
5. Conclusion

We have discussed the concept of a cryogenic system for a 25 T cryogen-free magnet. The results are summarized below.

- The cooling system of the LTS coils and the cooling system of the ReBCO coil were separated, and they were independently cooled to different operating temperatures of 4 K and 10 K, so that the high cooling capacity of the GM cryocoolers could be used for cooling the ReBCO coil.
- The LTS coils were cooled by GM/JT cryocoolers using bypass piping, and the initial cooling time was estimated to be about 312 hours (13.0 days). The heat invasion from the support of the ReBCO coil was 37 mW, which was small enough compared with the total heat load of 5.6 W. The heat loads of the LTS coils at 4 K can be cooled by the two GM/JT cryocoolers with 4.2 W-class cooling capacities at 4.3 K.
- For the ReBCO coils, we developed a cooling system in which helium gas cooled by the GM cryocoolers is circulated. It was shown that the temperature of the coil cold stage can be minimized to 8.5 K at a gas flow rate of 0.5 g/s by optimizing the gas mass flow.

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