A Cooling Concept for Indirectly Cooled Superconducting Magnets for the Fusion Reactor FFHR[*)]

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(Received 29 October 2014 / Accepted 20 January 2015)

Helical fusion power reactors have competitive advantages for steady-state operation because they use a currentless plasma. This paper presents the cooling concept of the indirectly cooled superconducting helical coil for the helical fusion reactor FFHR-d1. The helical coil consists of continuously wound aluminum-alloy-jacketed Nb_3Sn superconductors and intermediate metal plates that not only cool the conductor indirectly, but also support the electromagnetic force. The copper cooling panels are partially mounted in the stainless steel intermediate plate and cooled by cryogenic supercritical helium. The conductor is cooled by contact with the cooling panels through an insulation material with high thermal conductivity, such as a ceramic. Fundamental calculations show that this cooling concept is technically feasible. Experimental investigations yielded a candidate for the ceramic insulator with high thermal conductivity.

Keywords: heliotron fusion reactor, indirectly cooled superconducting coil, nuclear heat, ceramic insulator, thermal conductivity

DOI: 10.1585/pfr.10.3405011

1. Introduction

Helical fusion power reactors have competitive advantages for steady-state operation, which have been demonstrated by the Large Helical Device (LHD) that uses a superconducting magnet for experiments begun in 1998 [1]. On the basis of outputs from the LHD, design studies of the FFHR-d1 reactors have been performed. The FFHR-d1 has a major radius of 15.6 m, a toroidal field of 4.7 T, and a fusion power of 3.0 GW [2, 3]. Details of the three-dimensional design of the superconducting magnets, consisting of two helical and four poloidal coils, and neutronics analyses have already been published [2]. The up-to-date neutronics analyses show that a maximum nuclear heat of 600 W/m^3 is generated in the helical coil [2]. The cooling scheme for the helical coil must be designed by considering this steady-state nuclear heat, though steady-state operation of helical coils enables AC losses to be neglected, unlike Tokamak reactors. To date, two cooling schemes have been investigated for the helical coil with low-temperature superconductors: forced-flow cooling and indirect cooling. The indirect cooling method was proposed as an alternative to forced-flow cooling, which is commonly used in fusion experimental devices, including the LHD [4]. Forced-flow-cooled conductors require a circulating pump to overcome the pressure drop corresponding to the conductor length. For a large coil, the pressure drop limits the unit conductor length, and a large number of pipes and conductor joints must be installed. Issues of flow obstruction in conductors must also be addressed [5]. On the other hand, the use of indirect cooling enables a simple coil structure to be used because cooling channels are independent of conductor windings [4]. However, no indirectly cooled coils have yet been constructed for experimental fusion devices.

Previous papers have presented a specific design for the indirectly cooled conductor and advances in conductors [6–9]. This paper will investigate whether the indirect cooling method can keep the temperature rise due to nuclear heating sufficiently low. A conceptual design of a coil structure and a cooling scheme will be proposed, and then, the temperature rise due to nuclear heating will be determined. Moreover, advances in ceramic insulators that have played an important role in indirect cooling will be presented.

2. Structure of the Helical Coil and Cooling Concepts

Figure 1 illustrates the alignment of the windings of conductors with a turn number of 360 and intermediate metal plates. The conductor is an aluminum-alloy-jacketed superconductor with a cross section of 100×25 mm, whose operating current is 100 kA. The maximum magnetic field of 11.9 T allows the common Nb_3Sn superconductor to be used. The conductor is wound by a layer winding method. The 35-mm-thick intermediate plates with helium cooling channels are then installed inside the coil. The intermediate plates not only cool the conductors in-

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*) This article is based on the presentation at the 24th International Toki Conference (ITC24).

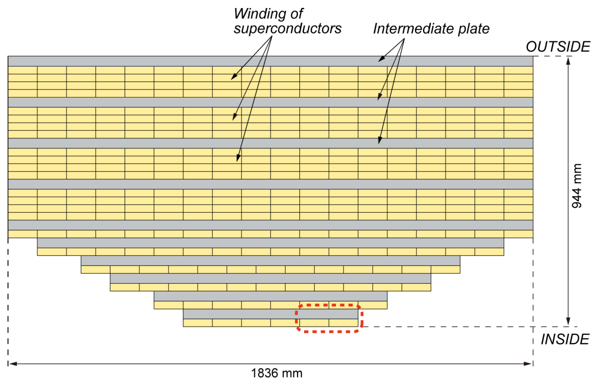

Fig. 1 Structure of the helical coil.

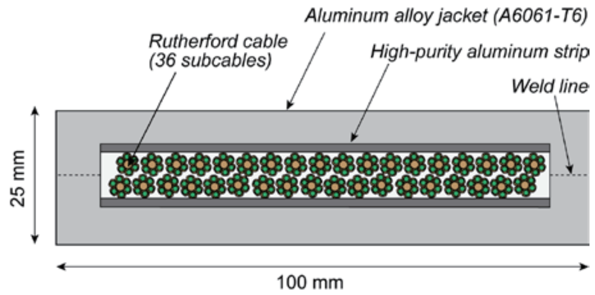

Fig. 2 Schematic of the conductor.

directly, but also support the electromagnetic force. The alignment of the intermediate plates depends on the distribution of nuclear heat. The plates thus contact all of the conductors because nuclear heating generates the most heat on the inside.

Figure 2 illustrates the cross section of a superconductor optimized for FFHR-d1. The Rutherford cable consists of 216 (6×36) Nb_3Sn wires, along with 36 copper wires. The heat-treated cable and low-melting-point metal fillers are embedded in an aluminum alloy jacket with a high filling factor. Two 2-mm-thick high-purity aluminum strips reduce the hotspot temperature during quenching. The two jacket halves are bonded by friction-stir welding (FSW), which does not damage the cable.

Figure 3 illustrates the conceptual structure of two rows of conductors and the intermediate plate (encircled by a red dotted line in Fig. 1). The copper panels, with a helium flow channel, are mounted in the stainless steel intermediate plate at regular spacings to cool the conductor conductively. The conductors are covered with a 2-mm-thick insulator. The insulator is mainly made of an organic material, such as epoxy resin, which is commonly used as an insulator for superconducting magnets. A ceramic is also used as an insulator locally where the copper cooling panel comes into contact with the conductor because ceramic materials typically have higher thermal conductivity than organic materials. Supercritical helium, whose inlet temperature is 4.5 K and whose pressure might, for example, be 0.4 MPa, flows in the cooling channels. The helium

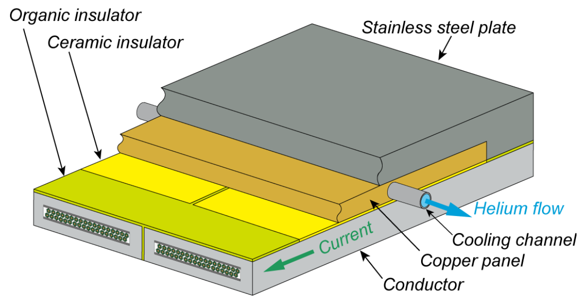

Fig. 3 Method of cooling the windings.

flow is independent of the current flow, unlike in forced-flow-cooled conductors. The intermediate plates support the conductor subjected to an electromagnetic force.

3. Estimate of the Temperature Rise Due to Nuclear Heating

The temperature rise from the initial helium temperature of 4.5 K is expected to be less than 1 K because it causes the critical current of the superconductors to decrease. A temperature rise of 1 K reduces the critical current by about 20%. In this section, the temperature rise due to nuclear heating is estimated by considering three contributing factors: the temperature rise in the helium, ΔT_{He} ($= T_2 - T_1$), the temperature gradient in the thickness direction of the ceramic insulator, ΔT_{ins} ($= T_3 - T_2$), and the temperature gradient in the longitudinal direction along the conductor, ΔT_{con} ($= T_4 - T_3$), as shown in Fig. 4. The temperature reaches a maximum at the midpoint of the conductor between the copper cooling panels (T_4 in Fig. 4). A nuclear heat of 600 W/m^3 is assumed to be generated not only in the conductor but also in the intermediate plate. The total temperature rise is thus:

$$\Delta T_{\mathrm{total}} = \Delta T_{\mathrm{He}} + \Delta T_{\mathrm{ins}} + \Delta T_{\mathrm{con}}. \tag{1}$$

First, ΔT_{He} is estimated by

$$m\left(H_{T=T_1+\Delta T_{\mathrm{He}}} - H_{T=T_1}\right) = Q\, L_1\, d_2\, w, \tag{2}$$

where m is the mass flow rate of helium, H is the enthalpy of helium, T_1 is the initial temperature of helium, Q is the heat generation per unit volume, L_1 is the spacing of the cooling panels, d_2 is the total thickness of the conductor and intermediate plate (as shown in Fig. 5), and w is the width of the windings, which corresponds to the product of the turn number per layer and the width of the conductor. Since the helium is assumed to cool not only the conductors but also the intermediate plate, d_2 is used. The heat exchange effectiveness of the cooling panel is assumed to be almost unity, which can be achieved by designing the cooling channel properly.

ΔT_{ins} can be estimated from the one-dimensional heat conduction equation:

$$\Delta T_{\mathrm{ins}} = \frac{Q\, L_1\, d_1\, t_{\mathrm{ins}}}{L_2\, \lambda_{\mathrm{ins}}}, \tag{3}$$

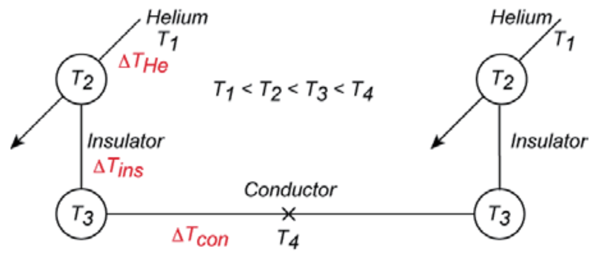

Fig. 4 Temperature distribution and definition of symbols T.

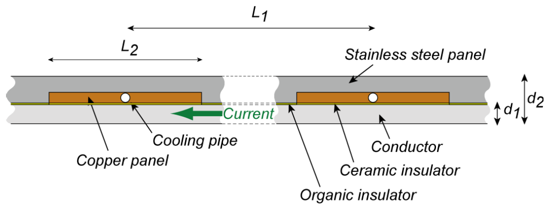

Fig. 5 Definition of symbols, L and d.

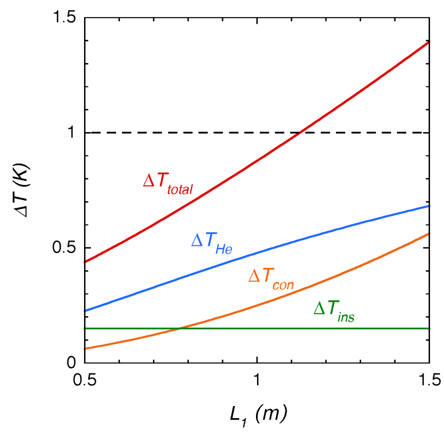

Fig. 6 Calculated temperature rise as a function of the spacing of the cooling panels, L_1.

where d_1 is the thickness of the conductor, t_{ins} is the thickness of the insulator, L_2 is the length of the cooling panel (as shown in Fig. 5), and λ_{ins} is the thermal conductivity of the ceramic insulator.

Finally, the temperature gradient in the longitudinal direction along the conductor, ΔT_{con}, can be calculated via

$$\Delta T_{con} = \frac{Q L_1^2}{8 \lambda_{con}}, \quad (4)$$

where λ_{con} is the effective thermal conductivity in the longitudinal direction of the conductor. The effective thermal conductivity of a composite can be calculated by a mixture law [10]. The heat exchange between the conductor and the stainless steel intermediate plate is negligible because the organic insulator has a relatively low thermal conductivity.

Inserting appropriate values for the parameters in the above equations, we can obtain a numerical solution for the temperature rise, as shown in Fig. 6. The parameters used are listed in Table 1. The assumed position is the innermost layer of the coil, which is subjected to the maximum nuclear heat. The turn number is therefore set to 6. In the calculations, the ratio L_2/L_1 is assumed to be fixed at 0.2, and L_1 is varied. The calculations show conclusively that the total temperature rise can be controlled to be less than 1 K when $L_1 < 1.1$ m. Mounting the cooling panels at a spacing of 1 m is technically feasible. L_2 corresponds to 0.2 m, which is also a reasonable size. These results suggest that the indirect cooling concept can be applied to the helical fusion reactor.

Table 1 Parameters used for the calculations.

Q (W/m^3)	600
L_1 (m)	Variable
L_2/L_1	0.2
d_1 (mm)	25
d_2 (mm)	60
t_{ins} (mm)	2
W (m)	0.612
λ_{con} (W/m-K)	300
λ_{ins} (W/m-K)	1
T_1 (K)	4.5
Helium pressure (MPa)	0.4
m (g/s)	10

An alternative method to reduce the temperature rise is to use a two-phase flow of helium, which would keep the temperature constant. ΔT_{He} is expected to be negligible. However, the gas phase may inhibit the heat transfer between the helium flow and the copper cooling panel. Future studies will need to evaluate the heat transfer.

4. Candidate for Ceramic Insulator

Although the thermal conductivity of the ceramic insulator is set to 1 W/m·K in the previous section, such a highly conductive insulator has not yet been developed for use at cryogenic temperatures. Therefore, we measured the thermal conductivity of a candidate material at cryogenic temperatures. The candidate material is a composite laminate consisting of aluminum nitride (AlN) and pyrolytic graphite. The fabricated sample has a 2-mm-thick three-layer structure (AlN 0.32 mm/graphite 1.36 mm/AlN 0.32 mm). The AlN and graphite have a thermal conductivity of 170 and 1700 W/m·K at room temperature, respectively [11]. The laminate is expected to have a thermal conductivity of 440 W/m·K at room temperature, which is comparable to that of copper. While graphite is electrically conductive, AlN is a perfect insulator. The diamagnetism of graphite will probably not influence the accuracy of magnetic fields and the stability of superconductors because the absolute value of the magnetic susceptibility of graphite (-6×10^{-4}) is much less than that of stainless steel 316 ($\sim10^{-2}$ at 4.2 K) [12, 13].

Figure 7 shows the measured thermal conductivity at low temperature. A unidirectional steady-state method was

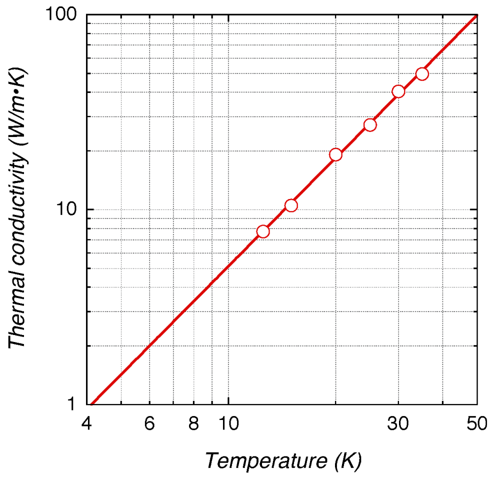

Fig. 7 Measured thermal conductivity of the AlN/graphite laminate sample.

used to measure the thermal conductivity [10]. The thermal conductivity decreased with decreasing temperature below 50 K. Although the thermal conductivity was measured down to only 12 K, extrapolation of the measured data reveals that the thermal conductivity at 4.5 K is approximately 1 W/m·K. This confirms that a ceramic insulator with high thermal conductivity can be developed using a proper selection and optimal combination of materials.

Further investigation will be required to optimize the material. Mechanical strength need to be addressed as well. For example, thermal stress becomes a problem during cool-down because ceramic materials have much lower thermal contraction than copper, stainless steel and a conductor. Interlayer materials, such as a thin layer of soft metals, might be necessary to reduce thermal stress. Bending stress is also problematic because insulators should be bent along conductors during the fabrication of coils. Bending stress may cause a crack and degradation of dielectric strength. An alternative way to bend insulators is to form the final shape of insulators with curvature by machine processing.

5. Conclusion

Cooling concepts for the indirectly cooled superconducting helical coils of the fusion reactor FFHR have been investigated by focusing on the temperature rise due to nuclear heating. Bring the cooling panels into contact at a regular spacing of, for example, 1 m can cool the conductor windings and limit the temperature rise of the conductor to less than 1 K. The insulator between the conductor and cooling panel should have a high thermal conductivity above 1 W/m·K at cryogenic temperatures. Such an insulator can be developed by using ceramic materials. One candidate, namely an AlN/graphite laminated material, was explored in this study. Further experimental investigation is necessary to find the optimal insulation material.

Acknowledgements

This work was funded by grant number NIFS14UFAA003 from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan. The authors express their gratitude to Thermo Graphics Co., Ltd. for manufacturing the insulator sample.

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