Analysis of Eddy-Current Loss and its Reduction in a Conduction-Cooled HTS Magnet

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Analysis of Eddy-Current Loss and its Reduction in a Conduction-Cooled HTS Magnet

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Abstract. Since conduction cooling system is environmental friendly and easy operating, the conduction-cooled method is widely used in cryogenic cooling system of high-temperature superconducting (HTS) magnet. The eddy-current losses are generated in the cooling structures when HTS magnet is charging and discharging or the current in the magnet is alternating. In this paper, a 3D model of analyzing the eddy-current loss was built. The eddy-current losses of a HTS magnet with different cooling structures were calculated. Thermal analysis of the HTS magnet was carried out together with the electromagnetic analysis. The effect of the cooling structures' geometric parameters on the eddy-current losses was discussed. The methods of reducing the eddy-current loss were proposed. The analysis results demonstrate that the optimization of the geometric parameters would greatly benefit the reduction of the eddy-current losses.

1. Introduction

Cryogenic cooling system is an essential part of superconducting devices. Recent advances and development on cry refrigerators have prompted the widely application of conduction-cooled method to cryogenic cooling system of superconducting devices [1-4]. The high thermal conductivity has made copper plates suited to distribute the cooling power to the high-temperature superconducting (HTS) coils [5, 6]. However, eddy current losses would be induced in copper plates when HTS magnet is charging and discharging or operating in AC mode. The losses may cause heat generation in HTS magnet during the operation, and this heat will increase the thermal load of the cryogenic cooling system. Therefore, in order to reduce the eddy current losses and improve the efficiency of heat conduction, the geometric parameters and the configuration of copper plates should be optimized.

In this paper, a three-dimensional model was built to analyze the eddy current losses in the copper plates, heat sinks and cooling rods. The factors which affect the eddy current were studied. Combining the thermal analysis with the electromagnetic analysis, the geometric parameters and the configuration of copper plates were optimized. Finally, the measures which can reduce the eddy current losses were discussed. The analysis results are valuable when designing a cryogenic system for a conduction-cooled HTS magnet.

2. General Structure of a Conduction-cooled HTS Magnet

A condition-cooled HTS magnet is generally cooled by Gifford-McMahon (GM) cryocoolers. The HTS magnet consists of a number of DPCs (double-pancake coil), cooling plates, cooling rods and heat sinks. The heat sinks made of copper (OFHC) are located at the bottom and the top of the magnet. Two cooling plates are attached to the two sides of a DPC, forming a sandwich structure. Inside and outside of the magnet, a number of cooling rods made of copper (OFHC) connect all the cooling plates. Copper braided wires are used to connect the cold head of the cryocooler to the heat sink, providing a flexible connection between the cryocooler and the magnet. Eddy current losses will be induced in the metallic structures by variation of magnetic field. Fig. 1 shows a typical structure of a conduction-cooled HTS magnet.

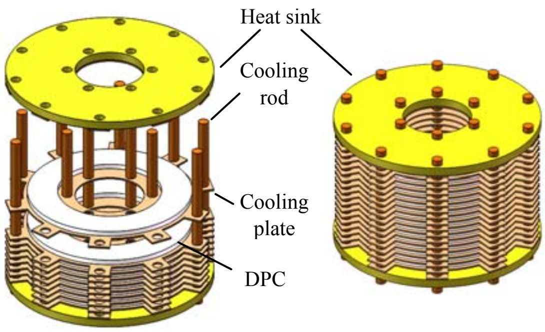

Figure 1. Typical structure of a conduction-cooled HTS Magnet.

3. Eddy current losses

3.1. Factors which affect the eddy current losses

Variation of magnetic flux leads to the generation of eddy current in the cooling plates, heat sinks and other metallic parts, among which, the cooling plates and the heat sinks suffer most of the eddy current losses. Fig. 2 shows the schematic diagram of a metallic disk in sinusoidal magnetic field. Formula (1) can be used to calculate the power of eddy current loss in the metallic disk.

$$P_{\text{eddy}} = \frac{\pi}{16}\rho B_m^2 \omega^2 r^4 d \tag{1}$$

Where Peddy is power of eddy current loss, ρ is the electrical conductivity of the metallic disk. B_m is the magnetic field amplitude. ω is the angular frequency of sinusoidal magnetic field. r and d are the radius and thickness of the disk, respectively.

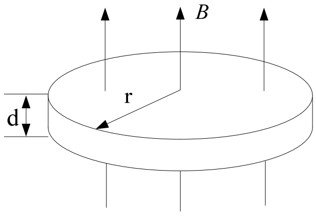

Figure 2. Schematic diagram of a metallic disk in sinusoidal magnetic field.

Although formula (1) is not suited to calculate the power of eddy current loss in all situations, it still highlights some factors which affect the eddy current losses. It shows that the eddy current loss is connected with the angular frequency and amplitude of the magnetic field and the geometric parameters of the metallic structure. For a HTS magnet, the angular frequency and amplitude of the magnetic field are determined by the amplitude and frequency of the current in the magnet. This paper focuses on studying the suitable geometric parameters of the cooling plate to achieve low losses and high heat conduction efficiency.

3.2. Eddy current losses in the metallic structures

A three-dimensional HTS magnet model was built to analyze the eddy current losses in the metallic structures. We need to calculate the eddy current losses with different geometric parameters of the cooling plate, the computations are time-consuming, and so a small scale HTS magnet model is employed. The magnet consists of 4 DPCs, three cooling plates, two heat sinks and 22 cooling rods. The specifications of the HTS Magnet is shown in Table 1 respectively. Fig. 3 shows the HTS magnet model. The model was developed with the commercial software ANSYS.

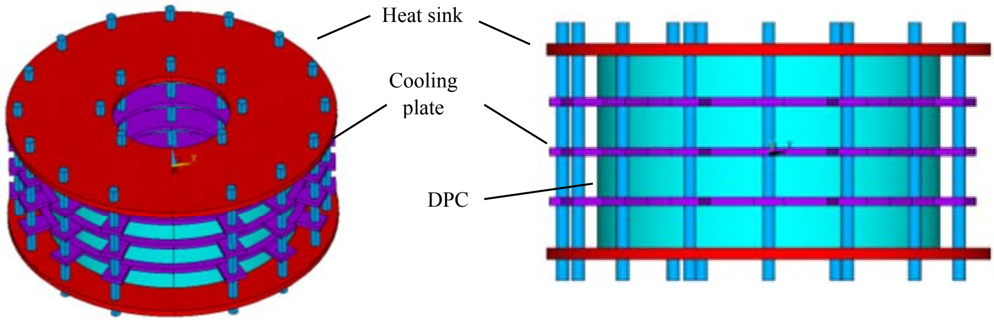

Figure 3. A three-dimensional HTS magnet model.

Table 1. Specifications of the HTS Magnet.

Type of the magnet	solenoid
Number of DPCs	4
Number of turns (one double-pancake)	80
Operating current	190 A
Operating temperature	20 K
Thickness of the heat sink	3 mm
Thickness of the cooling plate	0.5~3 mm
Number of cooling rods	22

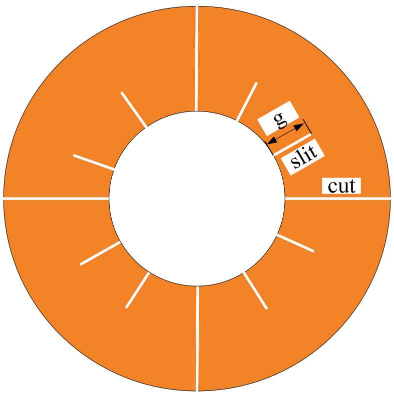

Figure 4. Top view of the cooling plate.

Fig. 4 shows the top view of the cooling plate. The cooling plate contains four cuts which make the plate into four divisions. Each division comes with two slits, which are so short that none of them would create complete division of the plate. The length of the slit is “g”. In order to study the effect of the number of the cuts, the length of the slit and the thickness of the cooling plate on the eddy current losses, we calculated the eddy current losses when the cooling plate is with different geometric parameters. Fig. 5 shows the eddy current loss of the metallic structures when the cooling plate is with different thicknesses, cuts and slit lengths. The amplitude and frequency of the current in the magnet is 190A and 50Hz, respectively.

As described in Fig. 5 (1), the thickness and the number of cuts of the cooling plate have a tremendous impact on the eddy current losses. When the cooling plate is a whole ring with no cut, as the thickness of plate increases, the eddy current losses of the plate is decreasing. The length of the slit only changes the value of the losses, and it doesn’t change the variation trend of the losses. When the cooling plate is with one cut, the losses of the plate decrease with the increasing of the thickness. When the cooling plate is with four cut, the losses of the plate rise at first and go down latter with the increasing of the thickness.

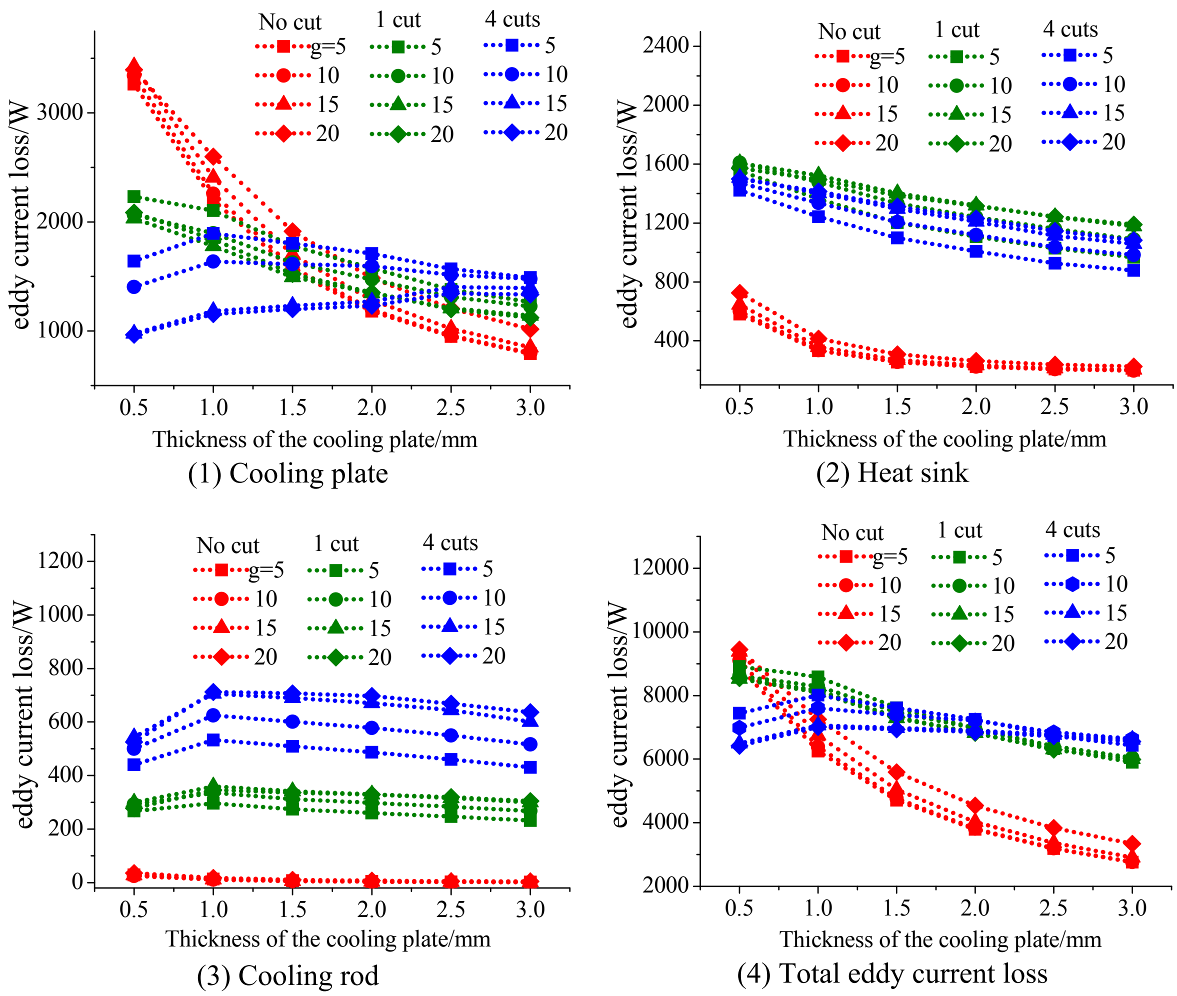

Figure 5. Eddy current loss of the metallic structures.

Fig. 5 (2) shows the eddy current losses of the heat sink. The number of cuts in the heat sink is the same as that of the plate. But no slits are existed in the heat sink. Whether the heat sinks has cuts or not, the losses in the heat sink are decreasing with the increasing of the thickness of the cooling plate. The losses of the heat sink with no cut are much lower than the losses of the heat sink with cuts.

Fig. 5 (3) shows the eddy current losses of the cooling rod. With the number of cuts increases, the losses of the cooling rod are increasing. As there is no cut in the plate, most of the induced currents circulate along the plate, and few induced currents flow through the rod. However, if the plate has a cut blocking the induced currents from circulating along the plate, current loop is failed to form, and the induced currents will be forced to flow through the rods near the cut. So the eddy current losses of the rods increase. The more cuts, the more induced currents in the rods and the more losses. The total eddy current losses of the metallic structures are shows in Fig. 5 (4). When the thickness of the plate is 3mm and there is no cut in the plate, the total loss is the lowest.

3.3. The induced current in the cooling plates

Fig. 6 shows the induced currents in the cooling plates with no cut, 1 cut and 4 cuts. It is obvious that the slits can block the induced current from flowing in the inner side of the plate. The induced currents circulate along the outer side of the plate with no cut. Few induced currents flow through the rods. The cuts change the flowing path of the induced currents. In Fig. 6 (3), far away from the cut, the induced currents still flow along the outer side of the plate, while around the cuts, slight eddy current circuits are formed on each side of the cut and find their way out from the rods near the cut. And this is also the reason for the increase of the eddy current losses in the rods. In Fig. 6 (5), since the plate has four cuts, eddy current circuits only can be formed in the quarter area of plate. More induced currents flow through the rods, so the eddy current losses in the rods are the most.

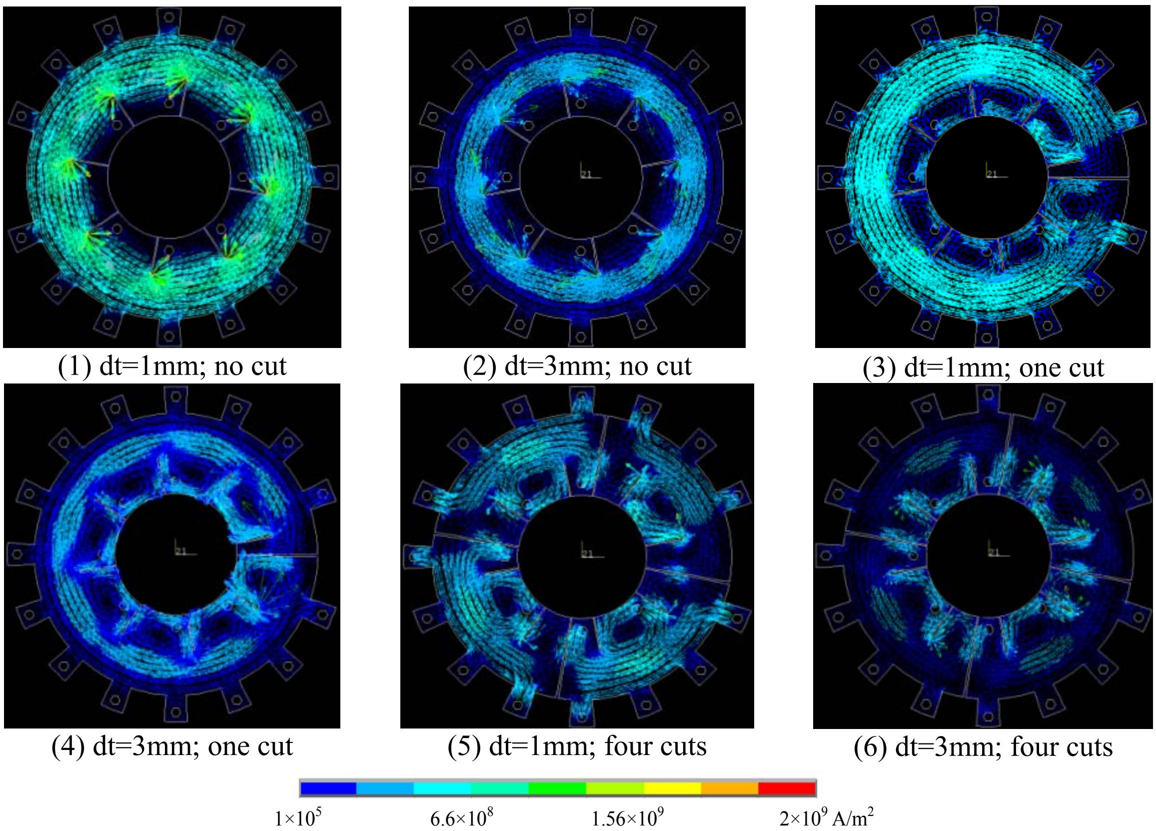

Figure 6. Induced currents in the cooling plates (dt is the thickness of the plate).

The thickness of the cooling plate is equal to the distance between the adjacent DPCs. With the increase of the plate's thickness, the distance between the DPCs increases. The magnetic field distribution in the metallic structures is different, so the eddy current loss changes correspondingly. Comparing Fig. 6 (2) with Fig. 6 (1), the value of the induced currents in Fig. 6 (2) is much smaller than that in Fig. 6 (1) and correspondingly the losses are much lower.

4. Thermal analysis of the HTS magnet

The design of the cooling plate should consider both the low eddy current losses and the cooling efficiency. Thermal analysis of the HTS magnet is carried out together with the electromagnetic analysis. A FEM thermal model of the HTS magnet was built. In order to compare the cooling efficiency of cooling plate with different geometric parameters, a temperature-dependent load map of the cryocooler is always adopted in the thermal analysis. Firstly, the HTS magnet is cooled to 20 K. Then, the calculated AC losses of the HTS DPCs and the eddy current losses of the metallic structures are transferred to the thermal analysis model as heat sources. Thirdly, the temperature of the magnet is calculated. The maximum temperature rise of the HTS DPSs is used as an indicator to evaluate the cooling efficiency. And the lower of the maximum temperature rise, the better. The duration of AC current is 0.05 s. The calculated AC losses of the DPCs are shown in Table 2 [7, 8]. Fig. 7 shows the calculated results of maximum temperature rise.

Table 2. The calculated AC losses of the HTS DPC.

#DPC1	171.57 W
#DPC2	45.41 W
#DPC3	45.41 W
#DPC4	171.57 W

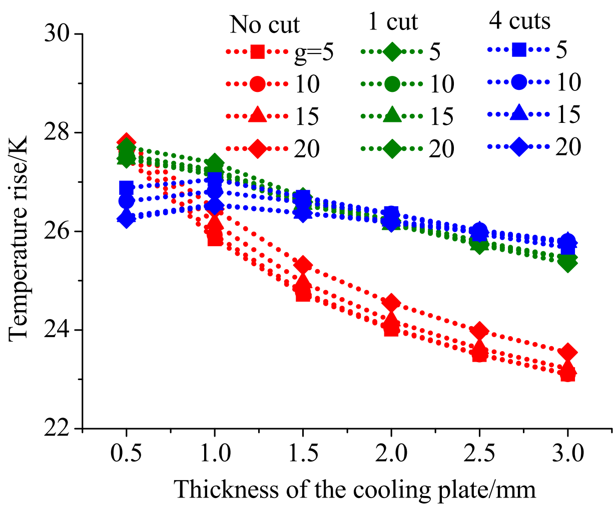

Figure 7. Maximum temperature rise of the HTS magnet.

If the cooling plate is a whole ring with no cut, the maximum temperature is decreasing with the increase of the plate's thickness. The temperature can be reduced for about 5 K when the plate's thickness changes from 0.5 mm to 3 mm. If the plate has one cut, the maximum temperature is also decreasing with the increase of the plate's thickness with the temperature only reduced for about 2 K when the plate's thickness changes from 0.5 mm to 3 mm. If the plate has four cuts, the maximum temperature of the magnet doesn't change much with the increase of the plate's thickness. Compared to the thickness of the plate and the number of cuts, the length of the slit has little effect on the maximum temperature of the magnet.

From the above analysis, increasing of the plate thickness is a method to reduce the temperature rise of the magnet. However, the effect on suppressing the temperature rise of the magnet is getting weak with the increase of the plate's thickness. So it is unwise to use a very thick cooling plate, which would increase the cost and weight of the magnet. For the HTS magnet operates with a 50 Hz current, the suitable thickness of the cooling plate is 3 mm, and the plate is a whole ring. The length of the slit is 5mm or 10mm.

The above analysis results are based on the assumption that frequency of the current in the magnet is 50 Hz. If not, the optimal results of the cooling plate might be totally different. Fig. 8 shows the eddy current loss of the cooling plate when the frequency of the current is 5Hz. In Fig. 8, the eddy current loss is growing with the increase of the plate's thickness. This is completely different from the eddy current loss shown in Fig. 5 (1), so the suitable parameters of the cooling plate are also different. The result shows that it is very essential to design the cooling structures considering the current parameters. The losses of the plate with cuts are much lower than the losses of the plate without cuts. The more cuts the plate has, the lower the eddy current losses are [9]. Although making cuts and slits can reduce the losses in this situation, the cuts and slits will weaken the thermal performances. Both the losses and the thermal performances should be considered.

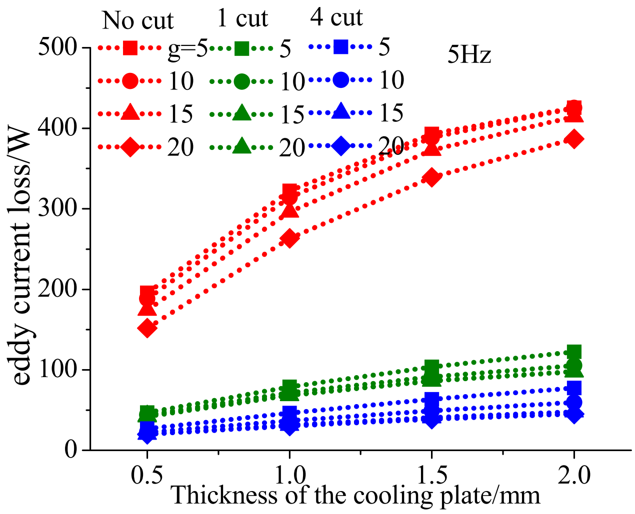

Figure 8. Eddy current losses of the cooling plate.

5. Conclusion

This paper analyzes the eddy current losses and the induced current of a HTS magnet. The thermal analysis was carried out to optimize the parameters of the cooling plate. The conclusions of this paper are as follows:

1) When the frequency of the current is 50Hz, the eddy current losses of the plate decrease with the increase of the plate's thickness. However, if the frequency of the current is 5Hz, the eddy current losses of the plate increase with the increase of the plate's thickness. In the design of the cooling plate, the current parameters should be seriously considered.

2) The thickness of the plate, number of cuts and slits can change the induced currents, but whether these measures can reduce the losses or not, it still depend on the current characteristics of the magnet.

3) In this paper, the frequency of the current in the magnet is 50Hz. To reduce the temperature rise of the magnet, it is better to design the cooling plate to be a thick and complete circular ring shape.

As a next step in this work, the effect of the current frequency on the eddy current losses will be carried out.

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