Experimental analysis on temperature characteristics of a rectangular bulk YBCO exposed to alternating magnetic field

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Abstract

The motion of magnetic flux will cause temperature rise inside of a bulk high-temperature superconductor (HTS) when exposed to an alternating magnetic field (AMF). In levitation system, like superconducting motors, bearing and vehicle, however, bulk HTSs are always subjected to ripple fields due to mechanical vibration, as well as harmonic field of armature windings, which will cause energy loss inside of bulk HTSs. Part of the heat caused by the energy loss is transferred to liquid nitrogen (LN₂) through the surface of bulk HTSs, and the other part will lead to temperature rise inside bulk HTSs. We experimentally analyzed the temperature characteristics of bulk YBCO under different AMF frequencies in this article. And the effect of AMF on the temperature rise of the bulk HTS under different cooling heights (CHs) and working heights (WHs) was also studied. The results showed that the higher the CH, the greater the temperature rises inside the bulk HTS. Besides, the temperature of the whole bulk HTS increases with the decrease in the WH and the increase in AMF frequency. The results and analyses of this article are useful for the application of bulk HTSs in the high-speed rotating and transportation systems.

Keywords Temperature rise · Alternating magnetic field · High-temperature superconductor · Energy loss · Levitation system

1 Introduction

The high-speed levitation system based on permanent magnets (PMs) and bulk high-temperature superconductors (HTSs) has demonstrated the tremendous potentials in several fascinating applications, such as superconducting maglev vehicles [1–5], linear synchronous motors [6–8], and superconducting flywheel energy storage systems [9–11]. Because of its competitive features like self-stability without energy input, being free from mechanical friction, and no need for active control system, research on levitation force and guiding force of superconducting levitation system has been studied [12, 13], and however, behaviors of bulk HTSs in an alternating magnetic field (AMF) will affect the performance of the superconducting levitation system. Therefore, it

is necessary to study the characteristics of bulk HTSs exposed to an AMF. The current decay characteristics of an HTS coil operated in persistent current mode under AMF are widely studied [14–16], which could be instructive for reduction in current decay of HTS coils. The loss of suspension force of a bulk HTS in the AMF above a PM guide rail has been studied, and results showed that the decrease in the guiding force became more obvious with the increase in the amplitude of the magnetic field [17]. Nevertheless, to the best of our knowledge, studies on temperature effects of bulk HTSs in the case that bulk HTSs are exposed to AMF have not been widely reported and are still only in theory. The heat generated in the bulk HTS will cause temperature rise, which directly reduces the critical current density and increases the penetration area of the external AMF [18, 19]. So it is

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Fig. 1 Cross-sectional view of the HTS bearing (1. copper ring, 2. bulk HTS array, 3. iron ring, 4. PM ring.)

also necessary to study the temperature characteristics of bulk HTSs under a high-gradient AMF.

We are now designing a high-capacity HTS flywheel used for energy storage in a subway station. Cross-sectional view of an HTS bearing used in an HTS flywheel is shown in Fig. 1. Rotor of the HTS bearing is composed of iron rings (3) and PM rings (4), which provides magnetic field. The rotor is mounted on the shaft of the flywheel rotor. Bulk HTSs (2) are fixed in the copper ring (1), which constitute a stator of the HTS bearing. Structure of the HTS flywheel can be referred [20]. Rotor of the flywheel system can be levitated once it is moved up and down due to the flux pinning effect of bulk HTSs. To make the flywheel system and superconducting Maglev-evacuated tube transport system commercially available [21], it was significant to know the working condition of bulk HTSs when they experience an AMF, which would be encountered when the PMs break locally or periodically. Because when the flywheel works in subway station, the vibration of the train, the earthquake or the rupture of the PM rotor would occur, it would cause an AMF. Besides, an AMF also exists in an HTS synchronous motor when the bulk HTS rotor and stator are not synchronized and the rotor will suffer rotating magnetic field, with structure as in [22]. The purpose of this paper is to verify the stability and reliability of the HTS flywheel in such cases and whether the flywheel can reach the purpose of commercial application.

To investigate temperature characteristics of bulk HTSs exposed to an AMF. A testing platform was designed to simulate such a magnetic field. We study the temperature characteristics of the bulk HTS and qualitatively analyze the experimental results.

2 Experimental setup

2.1 Experimental details

Figure 2 exhibits the high-speed test device. The device is mainly composed of nine components, which include a base (1) to support the device, a high-speed drive motor coupled with a PM turntable (2) to provide AMF, a cryogenic vessel used for storing liquid nitrogen (LN_2), a wall frame (4) to support the bulk HTS, a horizontal sliding rail (5), and a vertical sliding rail (6) to adjust the position of the bulk HTS. It is worth mentioning that the cryogenic vessel is covered with an aluminum plate-protective cover (3) to protect people and equipment from magnetic particles. In addition, a data transmission line (8) is used to convey the temperature signals of the bulk HTS to the control cabinet (9), where the temperature data can be recorded. It is worth mentioning that the temperature signals can also be manually recorded through a temperature controller. In this experiment, since the temperature in the center of the bulk HTS changes violently and the software cannot record values in time. So the instantaneous temperatures are manually recorded at even intervals of 20 s.

Figure 3 depicts the PM turntable and the cryogenic vessel in detail. PMs are nested in a turntable, which is driven by a high-speed centrifugal motor below. The bottom thickness of the cryogenic vessel is 1 mm. The bulk HTS is fixed above the bottom of the cryogenic vessel. The whole system was mounted on ground so that the system would not be shaken by Lorentz force. Accelerating the turntable from 0 to the target speed, the period is set as

Fig. 2 The experimental system, composed of (1) the base, (2) the high-speed driving motor and PM turntable, (3) the protective cover, (4) the wall frame, (5) the horizontal sliding rail, (6) the vertical sliding rail, (7) the bulk HTS holding and temperature detection device (the detailed structure is shown in Fig. 3), (8) the data transmission line, and (9) the control cabinet

Fig. 3 The PM turntable and the cryogenic vessel

Fig. 4 The YBCO bulk sample

2 s. The PMs are arranged with alternating magnetic poles. To make results more accurate, we choose 15 sampling points on the surface of each PM. Every 5 points located on the inner side, the middle side, and the outer side of the PM. To display the distribution of magnetic flux density (MFD) above the PM turntable, we, respectively, measured the magnitude of MFD at 2, 4, 6, and 8 mm above each PM by Gauss gauge. Then, we plotted the distribution of MFD when the turntable rotates along the inner, the middle, and the outer sides of working surface (every 50 sampling points in a line), respectively.

The bulk HTS sample used in the experiment is a rectangular three-seeded crystal YBCO bulk with 64 mm in length, 32 mm in width, and 12 mm in height, as displayed in Fig. 4. A hole is drilled at the center of the bulk HTS surface to locate the temperature sensor (it is dangerous to punch holes on the bulk HTS. In the practical application of the bulk HTS, it will affect the performance of the bulk HTS). The PT100 temperature sensor is used to measure the temperature inside of the bulk HTS, and temperature variable was converted in terms of standardized output signal. The temperature range of PT100 is $-200\text{ }^{\circ}\text{C}$

Fig. 5 MFD on the surface of 2 mm away from the PM surface

Fig. 6 MFD on the surface of 8 mm away from the PM surface

to $+800\text{ }^{\circ}\text{C}$. It is further noted that the temperature sensor is sealed at the hole to prevent heat leakage.

2.2 Experimental process

Here, we show the distribution of MFD on the surfaces that are 2 mm and 8 mm away from the PM turntable in Figs. 5 and 6, respectively. From Figs. 5 and 6, we can see that the distribution of MFD above the PM turntable is sinusoidal. Besides, the MFD at the middle points is higher than that in both the inner points and the outer points. The purpose of building this kind of MFD distribution is to simulate that the bulk HTS is exposed to the AMF. We used points instead of time as the x-axis because the MFD at the same position at different times is different during the experiment.

Before the flywheel operates, the PM rotor needs to be cooled at a certain height, namely the cooling height (CH) [23]. We firstly tried to study the influence of CH on the temperature characteristics of the bulk HTS under

different rotating speeds of PM turntable. The bulk HTS was first cooled in cryogenic vessel filled with LN_2 for 15 min to the superconducting state at 20 mm and 10 mm away from the surface of PM turntable, respectively. Here, the 10 mm and 20 mm are the CH. Then, the bulk HTS has moved to 2 mm (working height (WH)) away from the PM surface by vertical sliding rail and stayed there for 5 min. After that, we adjusted the speed of PM turntable to 1000 rpm and kept the PM turntable rotating for 5 min. Meanwhile, we recorded the temperature data of the bulk HTS. After measuring, the motor was turned off and the bulk HTS moved away from the PM surface. After the bulk HTS became normal, we repeated the above steps and adjusted the motor speed to 3000 rpm, 5000 rpm, and 9000 rpm. Here, it should be noted that after testing, we will adjust the turntable to the initial position.

Moreover, we adjusted the WH of the bulk HTS as 4 mm and 6 mm, respectively, to study the influence of WH on the temperature characteristics of the bulk HTS and obtained the temperature data in the cases that the speed changes from 1000 rpm to 9000 rpm.

When the CH and WH of the bulk HTS are determined, we further studied the influence of rotating speed (1000 rpm, 3000 rpm, 5000 rpm, and 9000 rpm) on the temperature characteristics of the bulk HTS.

Note that the copper-made temperature sensor would induce eddy current in the AMF, and its own temperature will increase. So, we considered the effect of the temperature rise of the sensor itself and rectified the data by contrast experiments in the data processing.

Fig. 7 Variation of temperature with time under different rotating speeds of PM turntable in the case that the CH is 10 mm and the WH is 4 mm

3 Results and discussion

3.1 Influence of CH on temperature characteristics

Figures 7 and 8 plot the temperature curves under different rotating speeds of PM turntable in the cases that the WH is 4 mm and the CH is 10 mm and 20 mm.

By comparing Figs. 7 and 8, we found the temperature rise in the case that CH is 10 mm is lower than that of 20 mm under the same rotating speed of PM turntable. Table 1 also lists the temperature values at different times at 5000 rpm. We can see that the temperature during the 10–4-mm process is lower than that during the 20–4-mm process. This is because less magnetic flux was captured due to the shorter travel distance at 10–4 mm. As analyzed above, the lower the CH, the less internal loss of the bulk HTS at the same WH. The “10–4 mm” and

Fig. 8 Variation of temperature with time under different rotating speeds of PM turntable in the case that the CH is 20 mm and the WH is 4 mm

Table 1 Temperature values at different times at 5000 rpm

Time (s)	Temperature under 10–4 mm (K)	Temperature under 20–4 mm (K)
0	77	77
20	88	116
40	100	125
60	101	125
80	101	125
100	101	125
200	103	126
300	106	126

“20–4 mm” are used here: The first number represents CH, and the second number indicates WH.

Moreover, we noticed that temperature curves are almost coincident under the rotating speed of 1000 rpm and 3000 rpm of PM turntable in Fig. 7. However, the temperature values under the rotating speed 1000 rpm and 3000 rpm of PM turntable in Fig. 8 are very different. This is because the heat loss caused by AMF is basically unchanged at the low rotating speed of PM turntable (less than 3000 rpm) during the 10–4-mm process. And only when the speed is over 3000 rpm, can the temperature rise be obviously caused inside the bulk HTS, which is verified by the temperature curves under rotating speed from 3000 rpm to 5000 rpm. By contrast, the temperature rise of the bulk HTS is relatively high even at low speed during the 20–4-mm process due to the violent flux motion. And at 9000 rpm, the internal temperature rise of the bulk HTS reaches 160 K.

According to the above analysis, higher CH means more flux captured at the same WH and also means greater loss in the bulk HTS.

3.2 Influence of WH on temperature characteristics

We choose the CH of 20 mm to study the maximum loss of the bulk HTS, in which case it is easier to find the effect of WH on the internal temperature rise of the bulk HTS. Figures 9, 10, and 11 show the variation of temperature with time under the different rotating speeds of the PM turntable in the cases that CH is 20 mm and the WH is 2, 4, 6, and 8 mm, respectively.

From Figs. 9, 10, and 11, we can see that the lower the WH, the higher the temperature. This can be explained as follows:

Fig. 9 Variation of temperature with time under rotating speed of the turntable 1000 rpm in the cases that the CH is 20 mm and the WH is 2, 4, 6, and 8 mm, respectively

Fig. 10 Variation of temperature with time under rotating speed of the turntable 5000 rpm in the cases that the CH is 20 mm and the WH is 2, 4, 6, and 8 mm, respectively

The amplitude of the external MFD affects the induced current of bulk HTS, which affects the penetration depth of bulk HTS. The penetration depth of bulk HTS under the AMF can be expressed as

$$r_{ac} = \frac{H_{AC}}{\mu_0 J_C}, \quad (1)$$

where μ_0 is the vacuum permeability, J_C is the critical current density, and H_{AC} is the amplitude of the external MFD. The hysteresis loss caused by the external MFD in the unit cycle of the bulk penetration can be expressed as

Fig. 11 Variation of temperature with time under rotating speed of the turntable 9000 rpm in the cases that the CH is 20 mm and the WH is 2, 4, 6, and 8 mm, respectively

$$w = \frac{2\mu_0 H_{AC}^3}{3J_c r_{ac}} \quad (2)$$

According to (2), we know that the hysteresis loss has a three-power relationship with H_{AC} and increases with H_{AC} . In Figs. 5 and 6, we can see that the lower the WH, the higher the MFD. Therefore, the temperature of the bulk HTS is higher under the lower WH due to the more hysteresis loss under the higher MFD.

By comparing Figs. 9, 10, and 11, we further noticed that when the rotating speed is low (for instance, 1000 rpm), the temperature rise curves under 2 mm and 4 mm almost coincide, as shown in Fig. 9. However, when the speed is 5000 rpm and 9000 rpm, as shown in Figs. 10 and 11, respectively, the temperature rise at 2 mm is largest, and the temperature rise under WHs of 4 mm and 6 mm is almost same. In the future application of bulk HTS in an AMF, we do not suggest choosing the WH of 2 mm because the internal loss of the bulk HTS is too high under this case.

3.3 Influence of rotating speed of PM turntable on temperature characteristics

Figure 12 shows the temperature rise curves of the rotating speeds under 1000 rpm, 3000 rpm, 5000 rpm, 7000 rpm, and 9000 rpm at 20–2 mm. It can be seen that the temperature rises gradually with the increase in rotating speed. The highest temperature reaches 185 K when the rotating speed is 9000 rpm.

Moreover, it can be seen that the temperature rises higher as the speed increases, which can also be concluded from Figs. 7 and 8. We also found that under

Fig. 12 Variation of temperature with time under rotating speed of PM turntable 1000 rpm, 3000 rpm, 5000 rpm, 7000 rpm, and 9000 rpm in the case that the CH is 20 mm and the WH is 2 mm

rotating speed of 1000 rpm and 3000 rpm, the temperature rise of the bulk HTS reaches the saturation point at the time of 50 s and there is little change after that. But at the speed of 9000 rpm, the temperature rise does not reach a stable value even at the end of 300 s, which is caused by the AMF at high speed.

The analysis shows that at the condition of 20–2 mm the temperature rise under 1000 rpm is similar to that under 3000 rpm. The maximum value of temperature rise under 5000 rpm is 36 K higher than that under 3000 rpm (about 33.1% increased), and the maximum value of temperature rise under 7000 rpm is 7.7 K higher than that under 5000 rpm (about 5.3% increased). However, the temperature rise under 9000 rpm is extremely intense, reaching 185 K, which is 33.1 K higher than the maximum value under 7000 rpm (about 30.2% increased). In the range of 0–7000 rpm, the temperature rise tends to be saturated, but after more than 7000 rpm, there will be an obvious temperature rise.

Here, I would like to explain a common phenomenon in Figs. 7, 8, 9, 10, 11, and 12. When the temperature of the bulk HTS increases above 92 K (the critical temperature of the bulk HTS), the temperature will continue to rise. Because the MFD under the bottom of the bulk HTS is different when the bulk HTS decreases from CH to WH, the magnetic flux captured by each part of the bulk is different. We can see from Figs. 5 and 6 that the MFD of every point above the surface of the PMs is different. When exposed to AMF, the part with more magnetic flux captured becomes normal, while the part with less magnetic flux captured is still in superconducting state and the temperature still keeps rising. The sensor only measures the temperature of a certain position in the bulk HTS, not the temperature of the whole bulk HTS. The loss of each part of the bulk depends on the magnitude of the magnetic field. On the other hand, because of the poor thermal conductivity of the bulk, the heat cannot be emitted well. This is why after the numerical value of the temperature sensor increases above 92 K, there are still loss and temperature rise.

4 Conclusion

The temperature characteristics of bulk HTS exposed to AMF have been studied, and results have been discussed. Firstly, at the same CH, lower WH means greater loss. The loss of WH 2 mm is significantly higher than that of 4 mm, 6 mm and 8 mm. Secondly, temperature inside the bulk HTS tends to be saturated with the increase in rotating speed. However, when it reaches 9000 rpm and there will still be a distinct temperature rise, which should be paid attention to in the practical application of bulk HTS. At the next stage, we will use slitting to reduce the eddy current

of the bulk HTS and establish a simulation model to analyze temperature rise inside the bulk HTS exposed to AMF. Besides, we will optimize the system structure to test the effect of temperature on the thermal stress of the system.

Contributions of this paper include:

- A high-speed test device is designed and manufactured to generate a high-frequency and high-gradient MFD, which would be useful in research on rotating HTS levitation system (bearing) when the PMs break locally or periodically.
- These data provide theoretical references to future superconducting Maglev-evacuated tube transport system under extremely harsh conditions, which are also useful for the HTS synchronous motor. There is a very high reference value to analyze the loss of the bulk HTS.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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