Experimental study on temperature distribution measurement of an optical fiber encapsulated coil in liquid nitrogen

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Abstract. Fast quench detection technique is extremely important for high temperature superconducting (HTS) applications, especially HTS magnets. As one of potential candidates, the method based on distributed optical fiber sensors were suggested recently. To keep HTS tape structure intact and reduce thermal propagation time from HTS tape to optical fiber, a method that optical fiber is encapsulated in HTS tape edge along the length direction could be satisfied. In this paper, an optical fiber encapsulated tape (OF-tape) was successfully fabricated. To verify the feasibility of temperature measurement for this tape, a coil wound with OF-tape and a distributed temperature sensor (DTS) system were prepared. The main results show that temperature of the coil can be measured accurately in air and in liquid nitrogen. After suffering impulse currents with peak values of 570 A and durations of 1, 2, and 3 s, temperature rises of the coil are 98.5, 137.8, and 271.0 K, respectively. Moreover, the highest temperature appears from 3.6 m to 21.7 m of the coil when it suffers the impulse current of 460 A/3 s.

1. Introduction

High temperature superconducting (HTS) wire is a key element for many superconducting applications, especially for superconducting magnets. To operate HTS applications in safety, quench detection is extremely necessary. However, traditional means by applying voltage measurement is not efficient enough for long HTS tape quench detection due to the low normal zone propagation velocity (NPZV) [1]. In recent studies, various approaches have been proposed for quench detection such as Fiber Bragg Grating (FBG) sensor [2], acoustic thermometry [3], stray capacitances [4], and distributed optical fiber sensor [5-7]. Due to the thin structure, anti-electromagnetic character, and distributed measurement, the distributed optical fiber sensor can be a practical option for quench detection. In previous researches, the optical fibers were co-wound turn by turn on top or bottom surface of the HTS coil and immobilized by epoxy or Kapton tapes [5-7]. However, this combination method between optical fibers and HTS tapes might cause a temperature measurement time delay because of epoxy and it would be harmful for HTS tape integrity [5]. Therefore, the problem of combining HTS tapes and optical fibers more directly should be solved.

A structure of optical fiber encapsulated HTS tapes (OF-tapes) was proposed by our group in 2014 [8] and Scurti et al. in 2017 [9]. In this structure, optical fibers lie on the both sides of the HTS insert tape, and two lamination layers are placed on the top and bottom of them for protection. After fabricating OF-tapes, the feasibility of temperature measurement for them needs to be verified for further quench detection study.
In this study, considering the cost of HTS tapes, the HTS insert of the OF-tape was replaced by copper insert. It should be mentioned that this change will not affect the structure of the tape and the feasibility of temperature measurement. To verify the feasibility, a coil wound by using OF-tape and a distributed temperature sensing (DTS) system based on Raman-scattering were prepared. Temperature distribution of the coil in air and liquid nitrogen were firstly measured to ensure that the temperature of this structure can be correctly detected by the DTS system. Then, impulse currents with different durations were energized to the coil to generate Joule heat, and the temperature changes of the coil were measured simultaneously. More detailed specifications of the coil and the experimental results are presented and discussed in this paper.

2. Test sample preparation
Figure 1(a) shows the schematic of the OF-tape fabricated by our group. As shown in Figure 1(a), the OF-tape includes three layers, the upper and the lower parts are lamination layers and the middle one is copper tape with two optical fibers along both edges. All of them are fixed together by solder. Figure 1(b) illustrates the picture of the OF-tape, and it can be seen that two optical fibers are successfully encapsulated into the tape.

![Figure 1](image1.png)

**Figure 1.** Schematic (a) and photo (b) of the optical fiber encapsulated tape.

![Figure 2](image2.png)

**Figure 2.** Photo of the optical fiber encapsulated coil.

| Table 1. Specifications of the OF-tape and the coil. |
|-----------------------------------------------------|
| OF-tape Width and thickness of the OF-tape 12.0 mm×0.3 mm |
| Material of the insert tape Copper |
| The coil Inner diameter of the coil 15.0 cm |
| Outer diameter of the coil 20.8 cm |
| Total length of the coil 29.2 m |
| Turns of the coil 52 |

Here, the materials of optical fiber coating and two lamination layers are acrylate and stainless steel, respectively. As shown in Figure 2, the OF-tape was wound into a pancake coil. The total length of the OF-tape used for this coil is 29.2 m and the tensile force is 28 N during the winding process. Besides, the turn-by-turn insulation material is Kapton tape. More detailed specifications of the OF-tape and coil are shown in Table 1.
3. **Experiment**

3.1 **Principle of temperature measurement based on Raman-scattering**

Generally, due to the interaction between incident light pulses and optical fiber material, scattering light will occur [10]. There are three types of scattering light, which can be classified as Rayleigh-, Brillouin-, and Raman-scattering. Among them, Raman scattering light has two spectral components: Stokes component and Anti-stokes component. Compared with the wavelength of the incident light, Stokes light is higher and Anti-stokes one is lower. The intensity of Anti-stokes light is strongly sensitive to temperature while that of Stokes light has a small dependence on temperature. Ratio of Anti-stokes and Stokes intensities is commonly used to calculate temperature, and the equation can be written as [11]:

\[ \frac{I_a}{I_s} = \left( \frac{\lambda_s}{\lambda_a} \right)^4 \times e^{\frac{\hbar c v_0}{k T}} \]  

(1)

Where \( R \) is the ratio of Anti-stokes and Stokes intensities; \( I_a, I_s \) are the intensities of Anti-stokes light and Stokes light; \( \lambda_s, \lambda_a \) are the wavelengths of Stokes light and Anti-stokes light; \( \hbar \) is Planck constant; \( k \) is Boltzman constant; \( c \) is the velocity of light; \( v_0 \) is the frequency of incident light and \( T \) is the absolute temperature.

In addition, optical time domain reflectometry (OTDR) techniques were applied to acquire the position information of temperature changes [11].

3.2 **Experimental setup**

![Experimental setup](image)

**Figure 3.** Experimental setup of the temperature measuring system.

As depicted in Figure 3, the experimental setup of the temperature measurement system consists of a DTS device, a PC, the coil, an oscilloscope and a voltage source. The DTS device can send short light pulses to optical fibers and detect the intensities of Stokes light and Anti-stokes light. And then it can demodulate light signals into electrical signals. It is worth to mention that only one optical fiber was connected to the DTS device at a time in this study. The PC not only can receive data from DTS device but can send control signal to the DTS device. The voltage source is used to energize impulse currents to the coil, and in these processes, the current and voltage signals of the coil will be recorded by the oscilloscope. Moreover, the coil was in the liquid nitrogen bath when it suffered impulse currents.

4. **Results and discussion**

In order to check the accuracy of temperature measurement for the DTS system, temperature of the coil in air and liquid nitrogen was firstly measured. Figure 4 shows the test results. The distance in the
horizontal axis begins from the point where the optical fiber is connected to the DTS device. As shown in Figure 4, at the first few meters of the optical fiber, there is an obvious drop of the temperature curve. The reason is that when the optical fiber is connected to DTS device, it is actually connected with the reference fibers inside the DTS device. The temperature of the reference fibers is room temperature and that of the coil is 77 K, therefore, a temperature transition definitely exists in the calculation results. In order to obtain correct test results of the coil, two sections of optical fiber with the length of 18 m were added at two ends of the encapsulated optical fiber. As a result, length range of the coil is from 18 m to 47.2 m. It can be found that in air, the temperature of the coil is 295 K, and in liquid nitrogen, the temperature is 77 K, which exactly corresponds to the liquid nitrogen boiling temperature at one standard atmosphere pressure.

![Figure 4. Temperature distribution of the coil in air and liquid nitrogen measured by DTS device.](image)

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![Figure 5. Typical V-t and I-t curves of the coil during the temperature measuring experiment.](image)

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Since the reliability of temperature measurement for the DTS system has been demonstrated, the DTS device could be applied to test the temperature changes of the coil.

The typical V-t and I-t curves of the coil during the temperature measuring experiment are shown in Figure 5. In this case, the duration of the impulse current is 300 ms and peak values of the current and voltage are 468.0 A and 117.0 V, respectively. Additionally, the frequency of the impulse current is 50 Hz.
Figure 6. Temperature changes of 20 m-point of the coil when the coil suffers impulse currents with different durations.

Positions of two ends of the encapsulated optical fiber in the outermost and innermost turn are defined as 0 m-point and 29.2 m-point, respectively. Figure 6 shows temperature changes for 20 m-point of the coil during the experiment. In particular, temperature of the coil is normalized by the measured one at $T_0=77$ K. Peak values of impulse currents for the two cases in Figure 6(a) are approximately 470 A, and the durations are 300 ms and 500 ms in sequence. The values of temperature rise and total time of temperature changes for the two cases are almost the same, which are 1.12 $T_0$ and 8 s, respectively.

To observe a greater temperature rise, more Joule heat should be generated by the coil. Thus, on one hand, we enhanced the peak values of the impulse currents; and on the other hand, we increased the durations of the impulse currents.

As shown in Figure 6(b), impulse currents with peak value of 570 A, and durations of 1 s, 2 s, and 3 s were loaded to the coil. Enough time was kept between every two tests to make sure that the coil was fully cooled down. Temperature rises for the three cases are 98.5, 137.8 K, and 271.0 K, which are 1.28, 1.79, and 3.52 times of 77 K, respectively. Besides, total durations of temperature changes are 11.5, 15.0 and 32.0 s, respectively.

Figure 7 presents the temperature distribution of the coil after suffering impulse current with the peak value of 460 A and the duration of 3 s. In terms of time, the temperature rise of the coil can be observed at $t_1=3$ s and the maximum temperature occurs at 6 s. Then, at $t_2=16$ s, temperature of the coil drops to 77 K. In addition, the impulse current was loaded to the coil at 2.7 s. Therefore, a time delay of 0.3 s exists between overcurrent and temperature rise. In the position point of view, maximum temperature rise appears from $d_1=3.6$ m to $d_2=21.7$ m of the coil, and from 5 s to 10 s, temperature in this length range is approximately the same. Comparing with this area, temperature of the rest parts of the coil is smaller. Additionally, the value of the maximum temperature of the coil in this test is 192.5 K, which is 2.5 times of the initial temperature of 77 K.
Figure 7. Temperature distribution of the coil sensed by optical fiber.

Figure 8 shows the positions of the measured points for the coil. The 0 m-point is at the outermost turn and 29 m-point is at the innermost turn, and they are defined as the first turn and the 52th turn, respectively. Positions of 3.6 m-point and 21.7 m-point are at the 5.7th turn and 37th turn and the area from 3.6 m to 21.7 m is filled with gird in Figure 8. It can be seen that the contact area between the OF-tape and liquid nitrogen in these positions is smaller than the outer and the inner turns. Therefore, the heat transfer rate is smaller and the temperature would be higher in these positions when the coil suffers impulse currents.

According to the results, the reliability of the DTS system was demonstrated. Furthermore, temperature changes of the coil can also be measured successfully under overcurrent. Therefore, it is confirmed that the structure is practical for temperature measurement.

5. Conclusion
In this study, a structure of OF-tape was presented and fabricated. A DTS system based on Raman-scattering technology and a coil wound with the OF-tapes were prepared. Then impulse currents with different peak values and durations were energized to the coil to generate Joule heat. During the process, the temperature changes of the coil were monitored by the DTS device.

The results show that temperature values of the coil in air and in liquid nitrogen are 295 K and 77 K, respectively. For the cases of impulse currents with peak values of 570 A and the durations of 1, 2, and
3 s, temperature rises of the coil are 98.5, 137.8, and 271.0 K, respectively. Furthermore, temperature distribution of the coil is presented when it suffers the impulse current of 460 A/3 s, and the highest temperature rise is found from 3.6 m to 21.7 m. It’s reasonable because the heat transfer rate is smaller at this area.

The feasibility of temperature distribution measurement using DTS system for the OF-tape has been demonstrated in this paper. Thus, OF-tapes with HTS inserts can be fabricated for further study on quench detection.

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