Measurement of temperature dependent AC losses in HTS bulk by electric and calorimetric methods

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Abstract. HTS bulk can trap higher magnetic field than a permanent magnet and electric motor and actuators are promising applications. The HTS bulks in those electric machines are exposed to AC magnetic field perturbations, which cause AC losses in the bulks. Therefore, it is important to understand the AC loss characteristics. In the previous works, we measured the AC losses by an electric method using the double pick-up coil method. This time, we measured the AC losses by a calorimetric method using a cryo-cooler and heater at different temperature. In this paper, the AC losses measured by the electric and calorimetric methods are compared with each other to investigate the validity of the measurement methods.

1. Introduction

HTS bulks can trap higher magnetic fields than permanent magnets. Therefore, more compact and higher-performance electric motors and actuators can be realized by using HTS bulks. The HTS bulks in these electric machines are exposed to AC magnetic field perturbations, which causes AC losses in the bulks. The AC losses affect the efficiency of the machines and, moreover, decrease the trapped magnetic fields of the bulks by raising the temperature [1-3]. Therefore, it is important to know the AC loss characteristics to design the machines.

In previous work, we measured the AC losses by an electric method using the double pick-up coil method [1,4]. This time, we measured the AC losses at different temperatures by a calorimetric method using a cryo-cooler and heater. The electric method has high sensitivity and resolution. However, the method may give wrong results if the electro-magnetic environment around the sample bulk is not well defined. Therefore, it is necessary to prove the validity of the measurement method. On the other hand, a calorimetric method is less sensitive and has lower resolution but give actual losses regardless of the electro-magnetic environment around the sample, provided that the calibration is done correctly. We compare the AC losses measured by the electric and calorimetric methods simultaneously with each other to investigate the validity of the measurement methods.

2. Experimental set-up and measurement methods

Specifications of a disk shaped YBCO bulk used in the experiment are shown in Table 1. The experimental set-up is illustrated in Figure 1 (a) and (b). The bulk was connected to a cold head of a GM type cryo-cooler by a carbon fiber reinforced plastic (CFRP) rod of φ 22 mm and 400mm long and cooled by conduction cooling. The nominal cooling power of the cryo-cooler is 10W at 80K. AC external magnetic fields are applied to the bulk parallel to the bulk axis by a copper coil (Figure 1. (a))
immersed in liquid nitrogen bath. The details of the arrangement around the bulk are illustrated in Figure 1. (b). The whole arrangement was placed in the vacuum in the inner cryostat. A pair of pick-up coils surrounding the bulk, the inner and outer, are for the electric measurement of AC losses. Number of turns of the inner and outer pick-up coils are \( n_i \) and \( n_o \) and wound on co-centric cylindrical surfaces of radii \( r_i \) and \( r_o \), respectively. The turns and radii of the inner and outer pick-up coils are so adjusted that
\[
\pi n_i r_i^2 = \pi n_o r_o^2
\]
and the pick-up coils are connected to each other differentially to cancel inductive voltage induced in the pick-up coils. Heights of the pick-up coils are the same \( h_0 \). A flux sensing coil is placed apart from the bulk to detect the phase of the AC external magnetic field to measure the resistive voltage component of the signal from the pair of the pick-up coils by a lock-in amplifier. The AC loss per cycle per unit volume \( Q[J/m^3/cycle] \) is given by the following equations.

\[
Q = \frac{1}{2} \frac{KV_0 B_0 h_0}{(n_i - n_o)\mu_0 v_b f}, \quad (1)
\]

where \( B_0 \) and \( f \) are the amplitude and frequency of the external AC magnetic field, respectively. \( V_0 \) is the amplitude of the resistive component of the voltage signal from the pair of the pick-up coils and \( v_b \) is the volume of the bulk. \( K \) is the correction factor and given by the following equation.

\[
K = \frac{n_i - n_o}{n_i K_i' - n_o K_o'}.
\]

where \( K_i' \) and \( K_o' \) are given by the following equation by putting \( r = r_i \) and \( r_o \), respectively.

\[
K_i' = \frac{1}{2} \left( \frac{d + h_0}{\sqrt{(d + h_0)^2 + r_i^2}} - \frac{d - h_0}{\sqrt{(d - h_0)^2 + r_i^2}} \right),
\]

\[
K_o' = \frac{1}{2} \left( \frac{d + h_0}{\sqrt{(d + h_0)^2 + r_o^2}} - \frac{d - h_0}{\sqrt{(d - h_0)^2 + r_o^2}} \right),
\]

Figure 1. Experimental set-up and Sample arrangement

| Table 1. Specifications of sample bulk |
|--------------------------------------|
| Diameter                             | 31.0mm |
| Height                               | 15.0mm |
| Composition                          | YBa2Cu3O7-y (Metal impregnated) |
| Critical temperature                 | ~85K   |
| Maximum trapped magnetic field       | 0.71T at 77.3K |

Table 1. Specifications of sample bulk
where $2d$ is the thickness of the bulk. If $h_0$ is long enough compared with the thickness of the bulk, $K=1$. In our experiment $K=1.10$ for $h_0=80$mm and $2d=15$mm. Equation (3) is obtained by applying an analytical method in the reference [5].

A heater of a Manganin wire was placed on the peripheral area of the bottom of the bulk and a semiconductor temperature sensor at the center for the calorimetric measurement. The bulk sample was thermally insulated by stylus-form as show in Figure 1(b). The calorimetric method used in this experiment is explained in the following. The most of the heat was conducted through the CFRP rod between the bulk and cold head of the cryo-cooler. Therefore, the thermal equilibrium equation of the bulk is,

$$C_p \cdot \frac{dT_b}{dt} + \kappa(T_b - T_{cd}) = Q,$$

where $C_p$ and $\kappa$ are the heat capacity of the bulk and the coefficient of the thermal conduction between the bulk and the cold head, respectively. $T_b$ and $T_{cd}$ are the temperatures of the bulk and cold head, respectively. $Q$ is the heat input by the heater or the AC loss. The thermal time constant $\tau = C_p/\kappa$ was in the range of hours in this experiment and, therefore, the second term in the right side of Eq. (4) is small compared with the first term in the time range of tens of minutes. Therefore, the value of $dT_b/dt$ is almost constant for a stepwise heating. Examples of time evolutions of $T_b$ are shown for constant values of the heater input and for the AC losses generated by AC magnetic fields of constant amplitudes in Figure 2 (a) and (b), respectively, where $T_b$ increases almost linearly.

The procedure of the calorimetric method is as follows.

1) Putting the heater current zero until $T_b$ becomes steady state at given temperature $T_{b0}$. $T_{b0}$ is controlled by controlling $T_{cd}$.
2) Applying a given value of stepwise current to the heater, the time evolution of $T_b$ for a given heater input $Q_h$ is recorded.
3) Repeating the steps 1) and 2) changing $Q_h$, a calibration curve $Q_h$ vs. $dT_b/dt$ at a given value of $\Delta T = T_b - T_{b0}$ for a given $T_{b0}$ is obtained.
4) Applying external AC magnetic field of a given amplitude $B_m$ to the bulk of the temperature $T_{b0}$, the time evolution of $T_b$ is recorded.
5) From the values of $dT_b/dt$ at a given value of $\Delta T$ and the calibration curve, the AC loss $Q_{ac}$ is obtained.

During the measurement, $T_{cd}$ was kept constant $T_{cd}$ was feed-back controlled by a heater attached to the cold head sensing $T_{cd}$ by a thermometer.

### 3. Measurement results
Following the procedure described above, the AC losses were measured calorimetrically changing $B_m$ at different $T_{bo}$. The AC losses also were measured simultaneously by the electrical method. The AC losses measured by the both methods are plotted in Figure 3 (a), (b) and (c) for $T_{bo}=60K, 70K$ and $77K$, respectively. Both of the AC loss data agree well with each other. These results are the proof that both of the electric and calorimetric methods are valid and that the measured data were valid.

4. Concluding remarks
AC losses in a bulk HTS subjected to AC external field were simultaneously measured by calorimetric and electric methods which we developed. The data measured by the both methods agreed well with each other. Thus, the validity of the both methods and also the measured data was proven. Generally a calorimetric method is time consuming. On the other hand, an electric method is much less time consuming. Therefore, once an electric method whose validity is proven is developed, we can measure the losses efficiently with high sensitivity and resolution.

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