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Effects of Air Gap on HTS Magnet Consisting of Double Pancake Windings

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***Abstract*-- An air gap between the pancake windings was provided in this paper to increase the central magnetic field of a high temperature superconducting (HTS) magnet consisting of pancake windings. Unlike the LTS magnet, providing an air gap between the pancake windings increases the central magnetic field of a HTS magnet. Furthermore, the uniformity of the magnetic field near the center of the magnet increased because the pancake windings spread out in wider area. Effects of the air gap on the central magnetic field of an HTS magnet was described in this paper. Calculation of the critical current was carried out by using *E-J* relation of the HTS wire and the optimization technique was adopted to obtain the appropriate critical current which could maximize the central magnetic field. Pancake windings with BSCCO-2223 HTS wire were wound on glass epoxy bobbin. 6 double pancake windings with 200 turns were used to construct a HTS magnet. Characteristics of the HTS magnet including the central magnetic field and the uniformity of the magnetic field were measured and compared with the results of calculation.**

1. INTRODUCTION

Since the development of several km length HTS wires having high critical current, the HTS wires have been widely used for advanced HTS electric machines. Magnets for MRIs and NMRs need to produce high magnetic field [1]. The central magnetic field and the uniformity near the center of a magnet are important factors [2, 3].

The distance between each pancake winding and a magnet center will be getting further in proportion to the gap between the pancake windings. It decreases the central magnetic field of a conventional magnet and a low temperature superconducting (LTS) magnet. On the contrary, an air gap can increase central magnetic field of a HTS magnet. The longer distance between pancake winding and the center of magnet decreases the central magnetic field, but the longer distance increases the critical current of the pancake winding because the magnetic field applied to the pancake winding is weakened.

If the influence of the latter is greater than that of the former, the central magnetic field may increase. Besides, as pancake windings are spread in a wide area, the uniformity of the magnetic field increases near the center of magnet.

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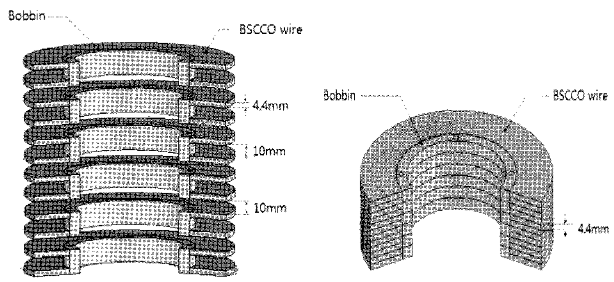
This paper proposed a new method to increase the central magnetic field of a HTS magnet consisting of pancake windings, that is, providing an air gap between pancake windings. When the length of air gap between pancake windings was changed, its influence on the central magnetic field of the HTS magnet was described. Critical current was calculated using the *E-J* relationship of a HTS wire, and optimization method was applied to find the appropriate critical current to maximize the central magnetic field [4].

2. MAGNET WITH AN AIR GAP BETWEEN PANCAKE WINDINGS

Some of magnets used for high magnetic field generation consist of pancake winding. An intentional air gap between pancake windings for increasing the central magnetic field has not yet been attempted.

Fig. 1 shows the magnets with an air gap and without an air gap between pancake windings. When an air gap between pancake winding is provided 1) the distance between pancake windings and the center of the magnet becomes longer 2) and the magnetic field applied to the pancake winding weakens. The first factor (the distance becoming longer) reduces the central magnetic field. That's why air gap isn't provided between pancake windings on conventional copper magnets and LTS magnets.

Regarding HTS magnets, second factor (a weakening of the magnetic field applied to the pancake winding)



(a) with air gap (b) without air gap

Fig. 1. Configuration of the magnet.

increases the critical current of the pancake winding considerably. If the influence of the second factor is greater than that of the first factor, central magnetic field may increase.

When an air gap is provided between pancake windings of a HTS magnet, critical current increases by the second factor. And the central magnetic field on HTS magnet with an air gap increases by the increased critical current. The critical current on the magnet is limited by the outermost pancake windings to which the highest perpendicular magnetic field is applied. Providing an air gap makes the critical current of the outermost pancake winding increases, which ends up an increase of the critical current of the whole magnet.

3. CALCULATION OF CRITICAL CURRENT AND MODEL FOR ANALYSIS

To find out the effect of the air gap installed between pancake windings, the properties of a BSCCO HTS magnet consisted of pancake winding was calculated. The critical current of a BSCCO wire is 126 A at self field, 77K. 1 μV/cm was selected as the criterion of the critical current. The width and thickness of the BSCCO wire were 4.4 mm, 0.285 mm, respectively. Table I shows the specification of the BSCCO wire.

TABLE I
THE SPECIFICATIONS OF A BSCCO HTS WIRE.

Type of wire	BSCCO reinforced wire
Width	4.4 mm
Thickness	0.285 mm
Critical Current	126 A, 77 K, 0 T
Min. Bend Diameter	38 mm
Thickness of Insulation	0.06 mm

Fig. 2 shows the I_c-B relation of the BSCCO wire at various angle of a magnetic field. In Fig. 2, 0° and 90° indicate a parallel and a perpendicular magnetic field, respectively. As is shown in Fig. 2, when the angle of a magnetic field angle is high, critical current reduces greatly. A magnet with an air gap between pancake windings may produce magnetic field higher than that of a magnet without an air gap because the magnetic field applied to the pancake winding with air gap is reduced.

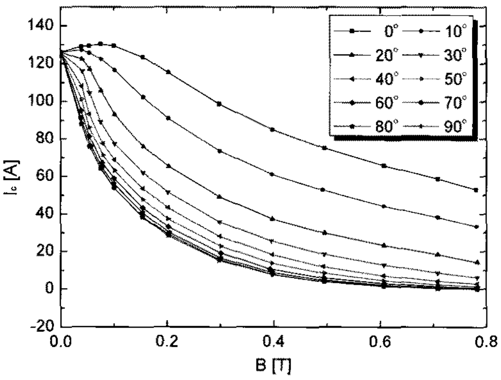


Fig. 2. I_c-B relation of the BSCCO wire.

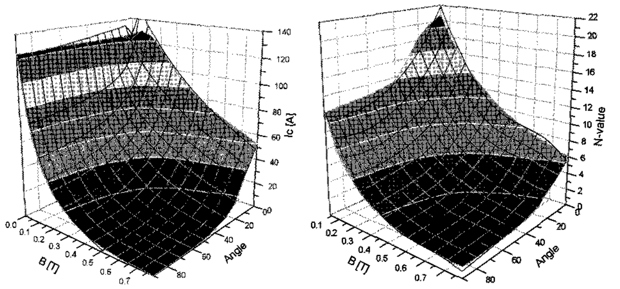
In order to estimate the magnetic field applied to the HTS wire precisely, the HTS wire was divided into 10 elements because the magnitude and the direction of the magnetic field are not identical even within the HTS wire [5]. Detailed procedure for the calculation of the magnetic field applied to the HTS wire is presented in Ref. 5. The electric field of nth turn of a pancake winding was calculated by using the angle and the magnetic field dependent power-law shown below.

$$E_n = E_c \left(\frac{I}{I_c(B_n,\theta)}\right)^{n(B_n,\theta)} \quad (1)$$

where B_n is the magnitude of a magnetic field, E_c is 1 μV/cm. I and I_c are the applied and the critical current of the HTS wire, respectively. n is the index number used for the power-law calculation. θ is the direction of magnetic field applied to the HTS wire [6].

Fig. 3.(a) and (b) show the measured angle-dependent I_c-B relation and n-value of the BSCCO wire, respectively. The surfaces in Fig. 3 indicate the measured I_c-B relation and n-value and the lines indicate interpolated ones. The largest n value is about 21 at self field. The critical current of pancake winding was calculated by using E-J relation and evolution strategy. Evolution strategy is one of the non-deterministic optimization methods and the procedure for the calculation of the critical current [5].

The HTS magnet with six double pancake coils was fabricated to prove the effect of the gap between the pancake windings. A double pancake winding had 200 turns, so total number of turns of 6 double pancake windings was 1200 turns. The total length of BSCCO wire that was used for HTS magnet winding was 564 m. The inner diameter of the HTS magnet was 115 mm, and outer diameter was 184 mm. Fig. 4 shows the structure of



(a) I_c-B curve (b) n-value curve

Fig. 3. Interpolated I_c-B curve and n-value curve of BSCCO wire.

TABLE II
THE SPECIFICATIONS OF THE MAGNET.

Type of wire	BSCCO reinforced wire
Inner diameter	115 mm
Outer diameter	184 mm
Height	202 mm
No. of double pancake windings	6
Total number of turns	1200
total length of wires	564 m
Air gap	0mm or 10mm

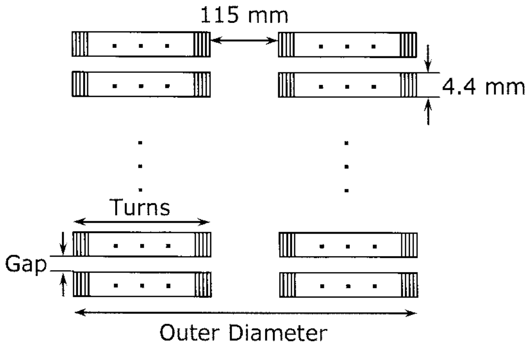


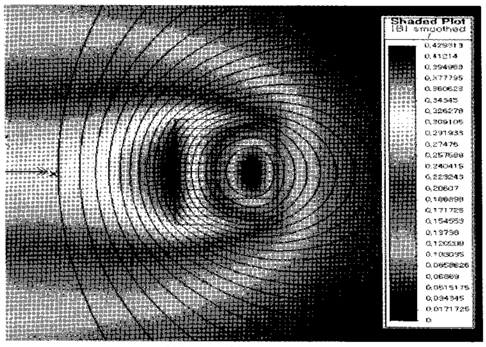
Fig. 4. Structure of HTS magnet consisting of pancake windings.

the HTS magnet consisting of pancake windings. The insulation of 60 μm in its thickness was put between each turn. Table II shows the specification of the HTS magnet consisting of double pancake windings.

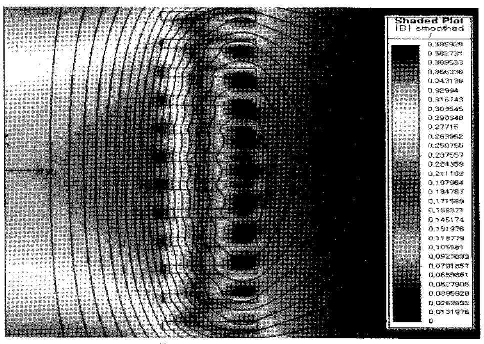
4. CALCULATION RESULTS

The effect of an air gap on the central magnetic field was calculated at a different air gap between pancake windings. The number of turns of one pancake winding was 200 turns and the number of double pancakes winding was 6 and the air gap was 0 mm or 10 mm.

Fig. 5 shows the magnetic field of the HTS magnet, where critical current was conducting at both cases. In case of the gap of 10 mm, the magnetic flux density in the outermost pancake windings of the HTS magnet was lower than the case of no gap.



(a) Air Gap : 0 mm



(b) Air Gap : 10 mm

Fig. 5. Magnetic flux density of HTS magnet.

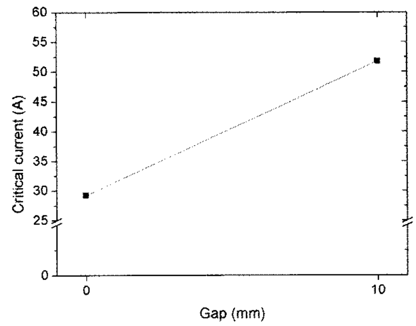


Fig. 6. Critical current versus air gap.

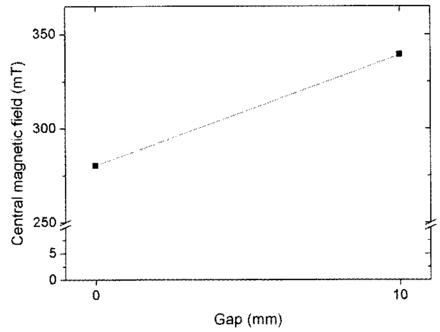


Fig. 7. Central magnetic field versus air gap.

Fig. 6 shows the critical current of the HTS magnet versus air gap. When there is an air gap between pancake windings, the magnetic field applied to pancake windings decreases. The decreased magnetic field causes critical current of the pancake winding increase. When air gap changed from 0 mm to 10 mm, critical current increases from 29.23 A to 51.74 A, the 77% increase.

Fig. 7 shows the central magnetic field of the HTS magnet versus air gap. Installing an air gap between the pancake windings shows clearly the central magnetic field getting increased. When the air gap changed from 0 mm to 10 mm, central magnetic field increased from 0.280 T to 0.339 T, the 21.07% increase.

Fig. 8 shows the non-uniformity of the central magnetic field near the center of the magnet versus air gap. The difference of the magnetic field from the center of the magnet to 10 mm away from the center of the magnet along and axis was defined as the non-uniformity. When the air gap increased, the non-uniformity decreased because the pancake windings were distributed widely.

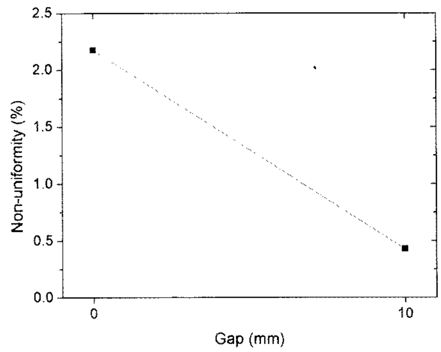


Fig. 8. Non-uniformity of the magnetic field near the center of the magnet versus air gap.

When air gap changed from 0 mm to 10 mm, non-uniformity decreased from 2.2% (without air gap) to 0.4% (10 mm air gap). Installing air gap between pancake windings not only increased the central magnetic field but also reduced non-uniformity of the magnetic field near the center of the magnet.

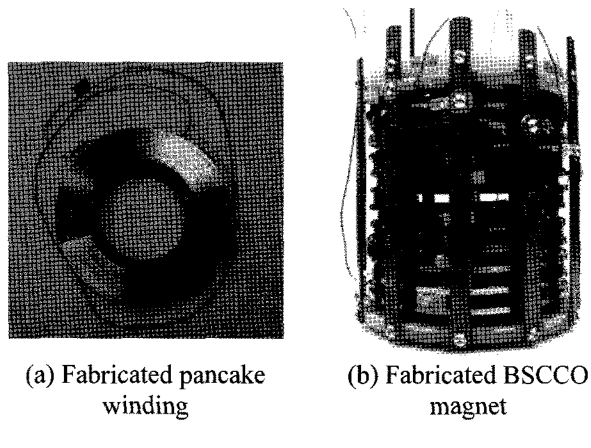
5. MEASUREMENT OF HTS MAGNET CHARACTERISTICS

The pancake windings with BSCCO-2223 HTS wire were wound on glass epoxy bobbins. 10 mm of air gap was provided between pancake windings of a double pancake winding. A Hall sensor was used to measure the central magnetic field and the magnetic field along the axis. The Resistive connections of winding terminals were made by using copper bars. 15 mm × 2 mm copper bars were mounted at the outside of the double pancake windings and then connected the terminal of each double pancake winding. Fig. 9 shows the fabricated HTS magnet. Fig. 9.(a) shows a double pancake winding and six double pancake windings were assembled to make a magnet as shown in Fig. 9.(b).

Direct current power source was used to excite the HTS magnet consisting of 6 double pancake windings.

The current of the HTS magnet is determined by the critical current of outermost pancake windings, the critical current of which is the lowest. The calculated critical current of the HTS magnet with 10 mm air gap was 51.74 A and measured critical current was 51.7 A. Both currents agreed very well.

The measured central magnetic field with 10 mm air gap was 344 mT and the calculated central magnetic field was 339 mT. Fig. 10 shows the magnetic flux density measured by a Hall sensor along the axis of the fabricated HTS magnet. It was moved from 0 mm (center of the magnet) to 30 mm along the axis. The decrement ratios of the magnetic flux density without an air gap (from 344.5 mT to 335 mT) was 12.6%.



(a) Fabricated pancake winding (b) Fabricated BSCCO magnet

Fig. 9. Pancake winding and the BSCCO magnet.

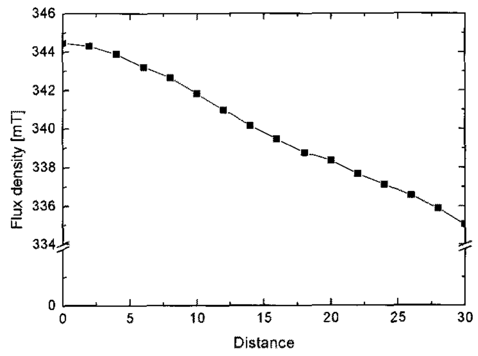


Fig. 10. Variations of magnetic flux density along axis.

6. CONCLUSION

In this paper, the effect of the air gap between the pancake windings of a HTS magnet on central magnetic field was analyzed and then verified that through test. Air gap increased the central magnetic field of a HTS magnet unlike a conventional magnet. The critical current of the pancake windings increased when an air gap increases, which ends up an increase of the central magnetic field. Besides, air gap reduced the non-uniformity of the magnetic field near the center of a HTS magnet.

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