1. INTRODUCTION

A high field magnet generally consists of layers of solenoid coils, known as nested magnet, for reliable operation against magnetic stress induced by Lorentz force. Those solenoid coils located in inner layer are generally experiencing higher magnetic field than its outer coils. Therefore, HTS wire with a smaller decrease of critical current according to the external field is used in the insert magnet, while LTS wire is used in the background magnet with a relatively lower magnetic field [1-3].

Unlike the characteristics of previous nested magnets, in the case of a nested magnet consisting of an inner magnet with second-generation HTS wire and an outer magnet with first-generation HTS wire, if there is a gap between the pancake windings of the outer magnet, the critical current of the outer magnet increases, and the central magnetic field of the nested magnet also increases [4]. In HTS magnets consisting of multi-layers, the characteristics of the magnet depend on the attributes of the HTS wire used in each layer of the magnet, and this should be considered when designing a magnet.

This study show the characteristics of a nested magnet consisting of an inner magnet with 12 mm Zr-doped GdBCO tape which has been recently developed, and an outer magnet with general 4.4 mm YBCO tape.

The characteristics of the central magnetic field and critical current according to the changes of gap of the outer magnet were calculated by changing the gap between the pancake windings of the outer magnet from 1 mm to 8 mm in 1 mm steps. In order to find the location of the pancake winding limiting the critical current of the magnet, the electric field of each turn was also calculated.

2. DESIGN AND CALCULATION OF THE NESTED MAGNET

To increase the central magnetic field of a nested magnet, it is easier to increase the contribution of the inner magnet than that of the outer magnet because the inner magnet is closer to the center of the magnet. 12 mm HTS tape, which can conduct a larger current than narrow HTS tape, was used for the inner magnet. For the outer magnet with a relatively low magnetic field, 4.4 mm HTS tape was used.

Table I shows the specifications of the GdBCO and YBCO tapes used in the inner magnet and outer magnet, respectively. GdBCO tape is doped with 7.5% Zr. Fig. 1 shows the Ic-B relation of both wires. The angles of 0° and 90° in Fig. 1 correspond to the parallel and perpendicular direction to the wider surface of the tape, respectively. As shown in Fig. 1, when a parallel magnetic field of 800 mT is applied, the critical current of the 4.4 mm HTS tape is about 20 A, and that of the 12 mm HTS tape is about 90 A.

The structure and specifications of the nested magnet are shown in Fig. 2 and Table II, respectively. OP and IP in Fig. 2 stand for the Pancake winding of Outer magnet and the Pancake winding of Inner magnet. The inner magnet consists of 4 single pancake windings (SP), and 12 mm HTS tape is used with a total length of 12 m per single pancake winding. The outer magnet is made of 8 double pancake windings. Considering the outer radius of the inner magnet and the bobbin of the outer magnet, the inner radius is determined as 47 mm. The total length of the HTS tape per double pancake winding (DP) of the outer magnet is

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TABLE I
SPECIFICATIONS OF THE HTS TAPES.

<table>
<thead>
<tr>
<th>Tape type</th>
<th>GdBCO</th>
<th>YBCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usage</td>
<td>Inner magnet</td>
<td>Outer magnet</td>
</tr>
<tr>
<td>Width</td>
<td>12 mm</td>
<td>4.4 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.1 mm</td>
<td>0.22 mm</td>
</tr>
<tr>
<td>Min. critical current</td>
<td>240 A (at 77 K)</td>
<td>70 A (at 77 K)</td>
</tr>
<tr>
<td>Min. bending radius</td>
<td>11 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>Insulation thickness</td>
<td>0.06 mm</td>
<td>0.06 mm</td>
</tr>
<tr>
<td>Zr doping</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Fig. 1. Ic-B Characteristics of the HTS tapes used for calculation and manufacturing (a) GdBCO HTS tape for the inner magnet, (b) YBCO HTS tape for the outer magnet.

Fig. 2. Structure of the nested magnet.

about 67 m. The inner and the outer magnets are excited individually using two different power supplies. The gap between the pancake windings of the inner magnet and the outer magnet is determined to produce the highest central magnetic field [4].

Critical current is determined using the generated electric field at each turn. The procedure to calculate the electric field can be found in [5] and is summarized as below.

1. After applying a current of 1 A to the inner magnet and outer magnet of the nested magnet, the magnetic fields of the x-components and y-components were calculated for every location of the nested magnet.

2. By increasing the current applied to the inner magnet, its critical current was determined. (In this case, the applied current of the outer magnet was zero).

3. The critical current of the outer magnet was also determined using the same method as described above in step 2. (Here, the critical current of the inner magnet was fixed to the value calculated in step 2).

4. Using the same method as that for step 2, the critical current of the inner magnet was determined. (Here, the critical current of the outer magnet was fixed to the value calculated in step 3).

5. After changing the gap, the calculation of steps 2–4 were repeated, and the critical current of each magnet was determined.

Unlike the nested magnet in which first-generation wire was used for the outer magnet, according to the results of the calculation of this paper, the central magnetic field at the nested magnet (consisting of an inner magnet and outer magnet wound with second-generation wire) always decreased when a gap was inserted between pancake windings of outer magnet.

Fig. 3(a) shows the magnitude of the central magnetic field produced by the inner and outer magnet. The gap of the outer magnet was increased from 1 mm to 8 mm and the gap of the insert magnet was fixed to 1 mm in Fig. 3(a). As shown in Fig. 3(b), the gap between pancake windings of the outer magnet increased from 1 mm to 8 mm, the critical current of the outer magnet increased by 38%, from 31.3 A to 43.1 A. However, as the magnetic constant of the outer magnet decreased by 37%, from 12.3 mT/A to 7.7 mT/A, the central magnetic field of the outer magnet decreased by 12.8%, from 385.2 mT to 335.7 mT.

The electric fields of each turn of both the inner magnet and the outer magnet in Fig. 4 support the above explanation. The currents of the inner magnet and outer magnet were 75.5 A and 31.3 A, respectively.

In general, in the mid-turn part of the outermost pancake winding, the perpendicular magnetic field is applied. However, in the case of the magnet with second-generation wire, the critical electric field is generated in the innermost turn, where the maximum magnetic field is applied but the maximum perpendicular magnetic field is not applied.
3. MANUFACTURING OF THE NESTED MAGNET AND ITS EXPERIMENT

In order to verify the calculated results, a nested magnet was manufactured based on the calculated results. Fig. 5(a) shows the single pancake winding used for the inner magnet and Fig. 5(b) shows the double pancake winding used for the outer magnet. Fig. 5(c) shows the complete assembled nested magnet. To measure the voltage of the first turn, where the highest electric field is generated in each pancake winding of the inner and outer magnet, voltage taps were installed in the inner and outer magnet. The distance between voltage tap of the inner and outer magnet were 4 cm and 15 cm, respectively. When the double pancake windings are used for the outer magnet, the connection between pancake windings in the bore is unnecessary. Therefore, more space in the bore of the outer magnet is available. A gap of 1 mm, which generated the maximum central magnetic field, was inserted between the pancake windings.

The experiment was conducted in liquid nitrogen. In order to compare the measured results with the calculated results, the critical current of each magnet, the generated voltage of each pancake winding, and the central magnetic field of the nested magnet were measured. The results of the critical current and the central magnetic field of the nested magnet are shown in Fig. 6. 

The measured critical currents of the inner magnet and outer magnet were 80.8 A and 32.6 A, respectively, which was 4% ~ 7% higher than the calculated critical currents, 75.5 A and 31.3 A. The central magnetic field of the nested magnet was 920.4 mT, which was 5% higher than the calculated magnetic field, 876.3 mT.

The critical current refers to the current that flows when the voltage generated in the first turn located in the innermost part of the pancake winding is the same as the voltage criterion, 1 μV/cm. Because the distance between taps were 4 cm and 15 cm, 4 μV and 15 μV would be generated in the first turn located in the innermost part of the pancake winding.
Fig. 6. Comparison of the characteristics of the nested magnet. Left: critical current of the inner and outer magnet, right: central magnetic field.

Fig. 7. Generated voltage of first turn (a) inner magnet, and (b) outer magnet.

When the critical current is applied, the voltage generated in the first turn of each pancake winding, as shown in Fig. 7. The characteristics of voltage generated in each pancake winding showed similarities in both the measured and calculated results. In the case of the inner magnet, 4 μV was generated in the outermost pancake winding (IP1 and IP4), and in the case of the outer magnet, 15 μV was generated in the No. 7 (13, 14) pancake winding.

Fig. 8 shows the measured central magnetic field of the location, with a distance of 10 mm from the center of the nested magnet. As explained before, due to the difference between the calculated and measured critical currents, there is some difference at the central magnetic field generated by both currents. The decreasing patterns of the central magnetic field along the magnet axis showed almost the same pattern in the calculated and measured value. Both the calculated and measured central magnetic fields decreased to 96% at 10 mm from the center.

4. CONCLUSION

This paper presented the characteristics of a nested magnet consisting of an inner magnet with 12 mm GdBCO HTS tape and an outer magnet with 4.4 mm YBCO HTS tape. By calculating the characteristics of the nested magnet, the inner magnet and outer magnet were designed. In addition, in order to verify both designed and calculated results, a nested magnet was manufactured, and its characteristics were measured.

Unlike the outer magnet using first-generation HTS tape, in the nested magnet using second-generation HTS tape for both the inner magnet and outer magnet, no increasing effect of the central magnetic field due to the gap of the outer magnet was observed. As a result of calculation and experiment, the critical current of the inner magnet was limited by the first turn, which was located in the innermost part of the outermost pancake winding. The critical current of the outer magnet was limited by the first turn of the innermost part in the No. 2 and No. 7 pancake windings, but was not limited in the outermost pancake winding. The critical currents measured in both the inner magnet and outer magnet were 80.8 A and 32.6 A, respectively, which were almost the same as the calculated critical currents of 75.5 A and 31.3 A, respectively.

REFERENCES