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Fundamental study on the magnetic field control method using multiple HTS coils for Magnetic Drug Delivery System

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Abstract. The magnetic drug delivery system (MDDS) is a key technology to reduce the side effects in the medical applications, and the magnetic force control is very important issue in MDDS. In this application, the strength of magnetic field and gradient required to MDDS devices are 54 mT and 5.5 T/m, respectively. We proposed the new magnetic force control system that consists of the multiple racetrack HTS magnets. We can control the magnetic field gradient along the longitudinal direction by the arrangement of the multiple racetrack HTS magnets and operating current of each magnet. When the racetrack HTS magnets were used, the critical current was reduced by the self-magnetic field. Therefore, the shape design of HTS magnet to reduce the magnet field into the surface of HTS tapes was required. Therefore, the electromagnetic analysis based on finite element method (FEM) was carried out to design and optimize the shape of multiple racetrack HTS magnet. We were able to suppress the reduction of critical current by placing the magnetic substance at upper and lower side of the HTS magnets. It was confirmed that obtained maximum values of magnetic field strength and field gradient were 33 mT and 0.18 T/m, respectively.

1. Introduction

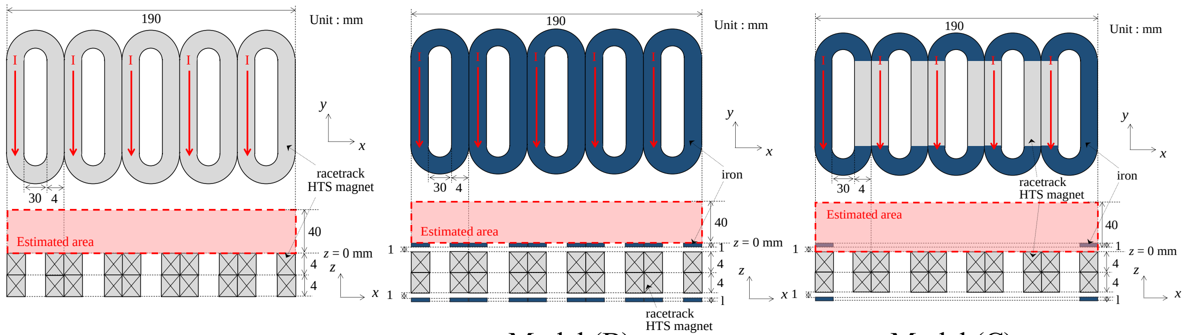
Recently, in the field of regenerative medicine, it is known that magnetic field applied to the human body can control the transplanted cells in the body. The techniques for magnetic field concentration are very important for controlling magnetic nanoparticles, novel electromagnets and trapped HTS bulk magnets were fabricated to apply the cell culture and the magnetic drug delivery system (MDDS) [1-3]. In these applications, we need not only the strength of the magnetic field but also the magnetic field gradient in order to enlarge the medicinal effects. The large magnetic moment is required with increasing the size of the drug particles. However, when the drug particle diameter is 400 nm or less, the magnetic moment is not obtained enough. In that case, we need to increase of the magnetic gradient. In general, the strength of magnetic field and gradient required to MDDS devices are 54 mT and 5.5 T/m, respectively [4]. A neodymium magnet has the highest remnant magnetization in the permanent magnet commercially available. However, the magnetic field generated by neodymium magnet is not sufficiently high for the MDDS. Furthermore, in the electromagnet using a metal wire, a large size coil is required for a high magnetic field generation. On the other hand, it is contemplated that the HTS bulk magnet is used as the source of high magnetic field. However, the HTS bulk magnetic is difficult to control of magnetic field for the MDDS. In this paper, we proposed a new field control method to generate a high magnetic field and field gradient along the longitudinal direction using the multiple racetrack HTS magnets. The multiple racetrack HTS magnets were proposed and designed in order to increase the operating current and generate the high field gradient along the longitudinal direction. We were able to amplify the critical current and high field gradient. In the new MDDS using the multiple racetrack HTS magnets, it is possible to control magnetic field by changing the operating current value.

2. Multiple racetrack HTS coils for MDDS

2.1. Analytical model

The multiple racetrack HTS magnets were proposed and designed in order to generate the high field gradient along the longitudinal direction by controlling the current of HTS magnet. The system consists of the 5 multiple racetrack HTS magnets using GdBCO tape as shown in figure 1, hereinafter referred as to Model (A). The inner curvature diameter of curve section in racetrack coil was 30 mm and the number of turns was 20. Five HTS magnets are individually operated. The critical current is reduced by the self-magnetic field entering HTS magnets. Especially, HTS tape is significantly influenced by the magnetic field in the perpendicular direction to it. Therefore, we studied the way to reduce the magnetic field entering magnets by placing the magnetic substance at upper and lower side of the coil as shown in Figure 1, hereinafter referred as to Model (B). There were air gaps with 1.0 mm between the coils and magnetic substance. Iron (35H210) was used as a magnetic substance. In the Model (C), the magnetic substance located in the center of magnet system (Model (B)), was removed so that the magnetic field reaches to high position from magnet surface.

We performed an electromagnetic analysis based on three-dimensional finite element method (3D FEM) to confirm the critical current and to find the suitable configuration for magnetic control system with high field strength and high field gradient in axial and longitudinal directions.



Model (A) Model (B) Model (C)

Figure 1. Schematic drawing of top view and cross-sectional view of five racetrack HTS magnets analytical model. Model (A), racetrack HTS magnets. Model (B), racetrack HTS magnets +whole iron. Model (C), racetrack HTS magnets + partial iron.

2.2. Analytical result

Figure 2 shows the calculated magnetic field profiles along the longitudinal center line at 0, 10, 20, 30 mm above the racetrack magnet at a transport current of 25 A. The magnetic field is obviously increased in case of the Model (B) and (C).

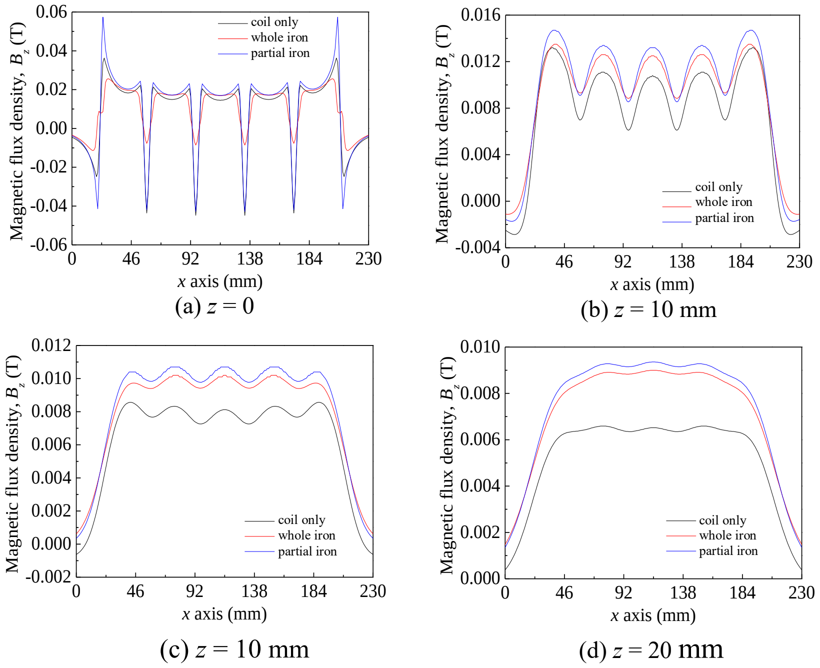


Figure 2. Calculated the magnetic field profiles along the longitudinal direction at (a) z = 0 (b) z = 10 mm (c) z = 20 mm (d) z = 30 mm at 25 A transported in case of Model (A), (B), (C).

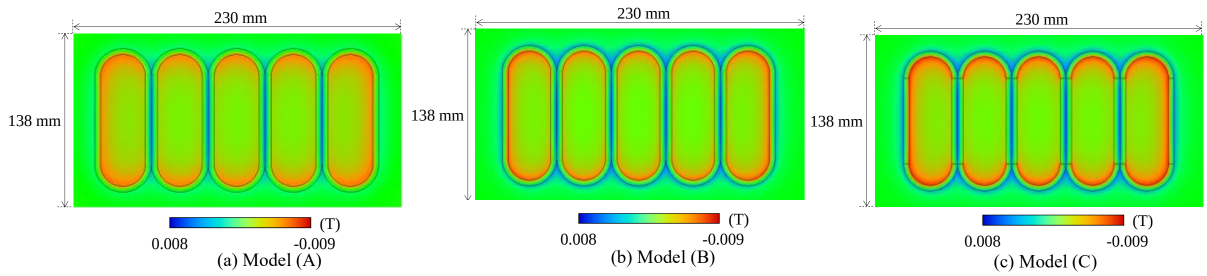


Figure 3. Magnetic field contour maps at top surface of magnet at a transport current of 25 A in case of Model (A), (B), (C).

Figure 3 shows the contour map of magnetic field in the x-y plane at z = 0 mm. Figure 4 shows the magnetic field dependence of critical current and the load line for the magnetic field applied perpendicular or parallel to the wide face of the GdBCO tape. The magnetic field in the perpendicular direction to the HTS tape was reduced by placing iron. From figure 4 (b), the critical current is 88 A, 103 A and 102 A in the case of Model (A), (B) and (C), respectively. The critical current for Model (B) and (C) were almost the same, but improved compared with the Model (A). Therefore, we would like to discuss the magnet design based on Model (C) with possible to generate more effective magnetic field.

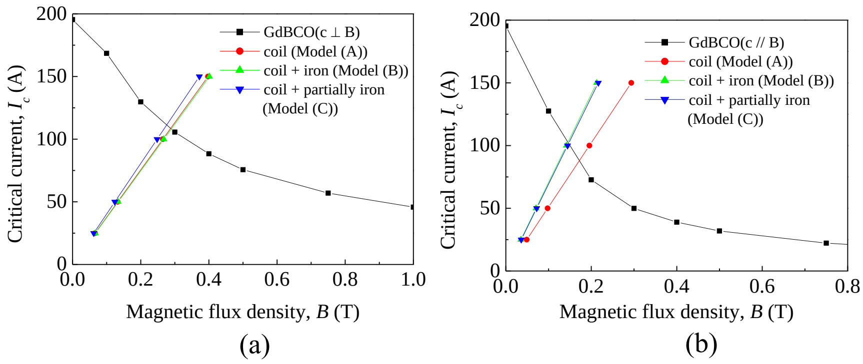


Figure 4. The magnetic field dependence of critical current of GdBCO tape and the load line for the magnetic field applied (a) parallel and (b) perpendicular to the face of the HTS tape in case of Model (A), (B), (C).

3. Improvement of magnet design to obtain the high critical current

To increase the critical current, we placed iron at inner side of HTS racetrack magnets as shown in figure 5 (a). In addition, we inserted iron cores into the racetrack HTS magnets as shown in figure 5 (b). Figure 6 shows the magnetic field dependence of the critical current and load line. The critical current of the racetrack HTS magnets was increased. Table 1 shows the critical current of each model.

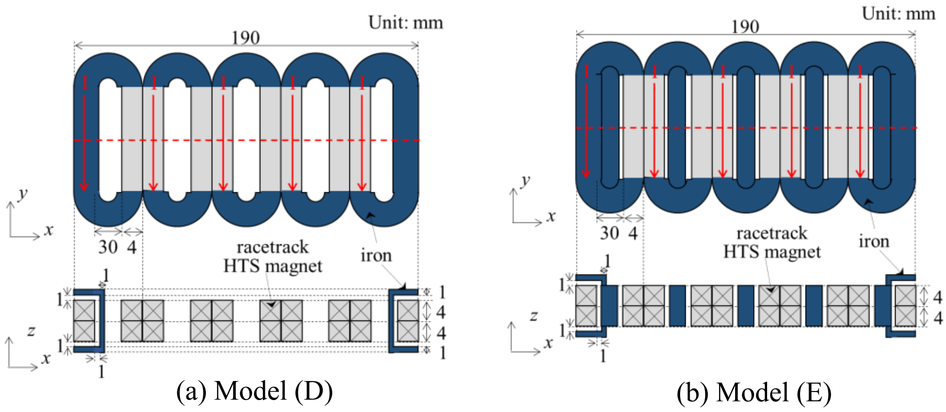


Figure 5. Schematic drawing of top view and side view of five racetrack HTS magnets. Model (D), with inner side iron. Model (E), with inner and iron cores model.

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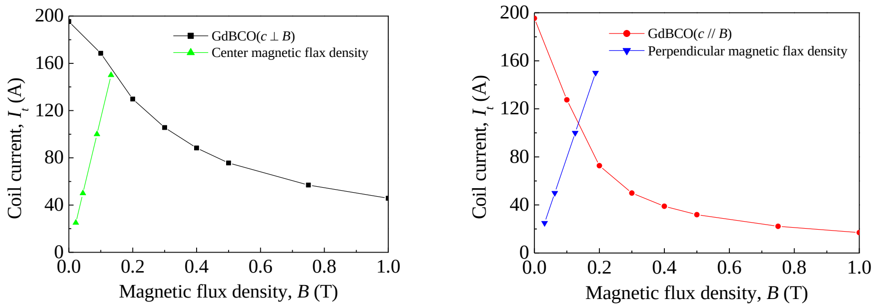
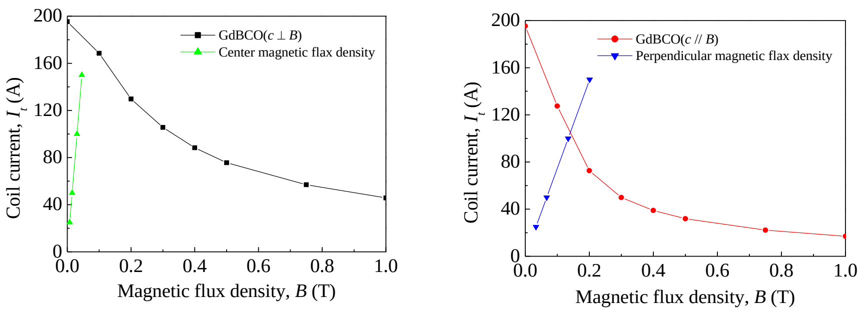


(a) Model (D)



(b) Model (E)

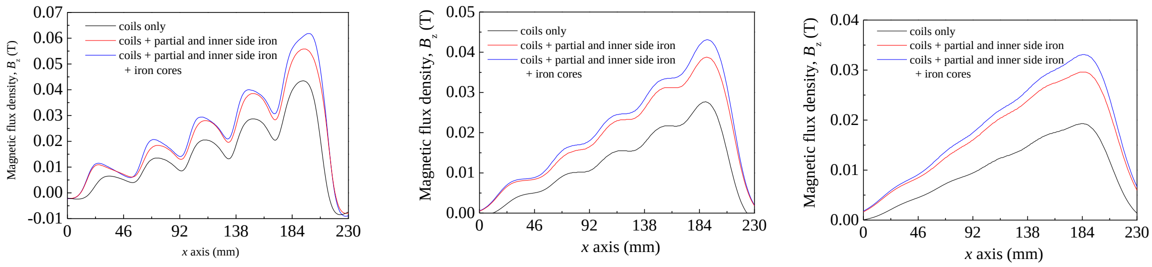
Figure 6. The magnetic field dependence of critical current of GdBCO tape and the load line in case of Model (D), (E).

Table 1. Critical current of each model

model	racetrack HTS magnets(**Model (A)**)	With inner side and partial iron (**Model (D)**)	With inner side and partial iron + iron cores **(Model (E))**
I_c (A)	88	108	105

4. magnetic field generating for MDDS

We evaluated the magnetic field and magnetic field gradient in control of operating current of coils in Model (A), (D), and (E). The operating current of each racetrack coil in the magnet system was individually controlled then, for generation of the magnetic field gradient, operating current was set to be linearly large value in order from the left-end coil under the condition the maximum value of operating current was 90% of critical current. Figure 9 shows the calculated magnetic field profiles of the racetrack HTS magnets at z = 10, 20 and 30 mm. Table 2 shows maximum magnetic field density and magnetic gradient at z = 30 mm. The gradient was maximum in Model (E). Therefore, in this study, Model (E) was the most effective for MDDS.



(a) z = 10 mm (b) z = 20 mm (c) z = 30 mm

Figure 7. The calculated magnetic field profiles at each height.

Table 2. Magnetic flux density and magnetic field gradient at z = 30 mm of each model.

Analysis model	Magnetic flux density (mT)	Magnetic field gradient (T/m)
HTS racetrack Magnets(**Model (A)**)	19	0.103
With inner side and partial iron(**Model (B)**)	30	0.158
Coils + inner side and partial iron + iron cores (**Model(E)**)	33	0.179

5. Conclusion

In this study, we proposed the multiple racetrack HTS magnets for MDDS, it was possible to control magnetic field by changing the current value. We investigated and developed the magnetic field source for the MDDS by the multiple racetrack HTS magnets using the electromagnetic field analysis. The results in this study were summarized as below,

- The critical current of the racetrack HTS magnets was increased 17A and the magnetic field gradient was improved by placing the iron plate and core compared with only HTS racetrack coils.
- The magnetic field of 33 mT and field gradient of 0.179 T/m were obtained above 30 mm from the magnets surface , but they were still not enough to apply for the MDDS devices.

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