ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 22(1), 65-68 (2017) https://doi.org/10.4283/JMAG.2017.22.1.065

Design and Fabrication of 2-T Rotating Halbach Magnet for Magnetic Refrigerator

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(Received 3 January 2017, Received in final form 16 February 2017, Accepted 20 February 2017)

This paper reports simulation and evaluation of the magnetic flux density (MFD) of a rotating Halbach magnet (RHM) composed of a rotating inner Halbach cylinder (HC) and a fixed outer HC. We first chose the dimension of a single HC, then determined the dimensions of an inner and outer HC to get MFD = 2 T. Simulation results were used to guide fabrication of an RHM; its magnetic field in the central axis direction agreed well with simulated values.

Keywords : Rare-earth magnet, Halbach cylinder (HC), Rotating Halbach magnet (RHM), Finite element method (FEM), Magnetic flux density (MFD)

1. Introduction

The magnetocaloric effect determines the efficiency of a magnetic refrigerator. When the refrigerant magnetizes or demagnetizes, the magnetocaloric effect raises or lowers its adiabatic temperature [1]. These refrigeration processes are very similar those that occur in a conventional refrigeration by cyclic compression and expansion of a gas [2]. The entropy change of numerous magnetocaloric materials scales as a power law with an exponent that generally ~ 2/3 [3-5]. As a source of the magnetic field for the magnetic refrigerator, permanent magnets are preferred because they do not require power to generate a magnetic field, so and only mechanical energy is required to move the magnet or the active material [5, 6]. A source with magnetic flux density (MFD) of 1 T or 2 T in an acceptable air-gap volume is suitable for use in compact systems that require a few kilowatts of power [6, 7]. To obtain this MFD, structure configuration must be optimized.

The use of high-energy rare-earth magnets in the conventional technology can improve greatly the efficiency of the devices, and are of central importance for magnetic refrigeration [8]. Rare earths are much more expensive than iron, cobalt and nickel, so a rare-earth magnet array should have the highest magnetic field for a given size and weight of permanent magnet material [9]. The magnetic field strength can be increased by using a Halbach cylinder (HC) made of a rare earth magnet and shielded by soft magnetic materials [10, 11].

In this work, we report the design and fabrication of a rotating Halbach magnet (RHM) that produces MFD = 2 T. We first chose the dimension of a single HC, then determined the dimensions of the inner and outer HCs that yield MFD = 2 T. We used simulation to guide fabrication of an RHM; its measured fields agreed well with simulated values.

2. Design and Fabrication of RHM

The RHM considered (Fig. 1(a), (b)) consists of twelve permanent magnet segments that enclose an air gap (Fig. 1(b)). Access to the magnetic field in the air gap is possible only from the right side of the RHM. The magnetic field in the air gap is greatest when the magnetizations of two HCs are in same direction, but smallest when these directions are opposite.

The electromagnetic field simulation used the finite element method (FEM) on ANSYS Maxwell v15 3D software [12], with Magnetostatic as the solver. The governing equations for these processes are:

$$\nabla \times \frac{1}{\sigma} \nabla \times \vec{H} + \frac{\partial \vec{B}}{\partial t} = 0 \quad (1)$$

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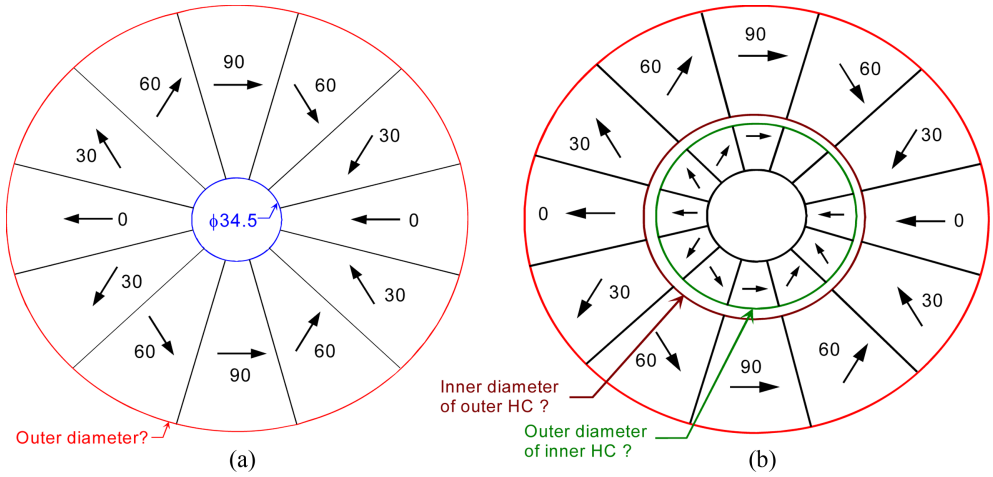


Fig. 1. (Color online) Model for simulating the MFD of the RHM. (a) Model for calculating the outer diameter of the single HC. (b) Model for calculating the inner diameter of the outer HC and the outer diameter of the inner HC. Arrows show magnetization.

$$\nabla \cdot \vec{B} = 0 \tag{2}$$

$$-\nabla \cdot \left(\varepsilon \nabla \frac{\partial \Phi}{\partial t} \right) - \nabla \cdot (\sigma \nabla \Phi) = 0 \tag{3}$$

where σ [S/m] is the conductivity, $\vec{H}$ [A/m] is the magnetic field intensity, $\vec{B}$ [T] is the MFD, ε [F/m] is permittivity, and Φ [Wb] is the magnetic flux.

The 2-T RHM (Fig. 1(b)) is composed an inner HC rotor and an outer HC stator. The permanent magnet was a neodymium magnet N50M with coercivity = 1,042 A/m, and remanence = 1.4 T. To produce MFD = 2 T, the outer diameter of the single HC must be determined first (Fig. 1(a)). The single HC was composed of 12 pieces, each magnetized to a different direction (Fig. 1(a), arrows). Each HC was 200 mm long; the inner diameter in which the refrigerant material is established was chosen to be 34.5 mm. Along the axial direction FEM simulation (Fig. 2(a)) suggest that MFD > 2 T when the outer radius is > 90 mm. The MFD was proportioned to the outer radius r_o [mm] of the single HC (Fig. 2(b)), as

$$B = 1.01 + 0.012 \times r_o \tag{4}$$

We set $r_o = 97$ mm because the MFD may leak through at air gap between the inner and outer HC. At this time, MFD was ~ 2.15 T.

When determining the outer diameter of the inner HC, the RHM must have maximum MFD > 2 T and minimum MFD ≈ 0 T (Fig. 3, 4). The MFD was > 2 T when the inner HC had $r_o > 30.62$ mm (Fig. 3). The profiles of minimum MFD are more complex (Fig. 4(a)) than those of maximum MFD. The peaks of the maximum MFD do not only appear at center, but also at both ends of HC. The MFD at the axial core decreased as r_o of the inner HC increased, until $r_o = 38.62$ mm, then increased as r_o

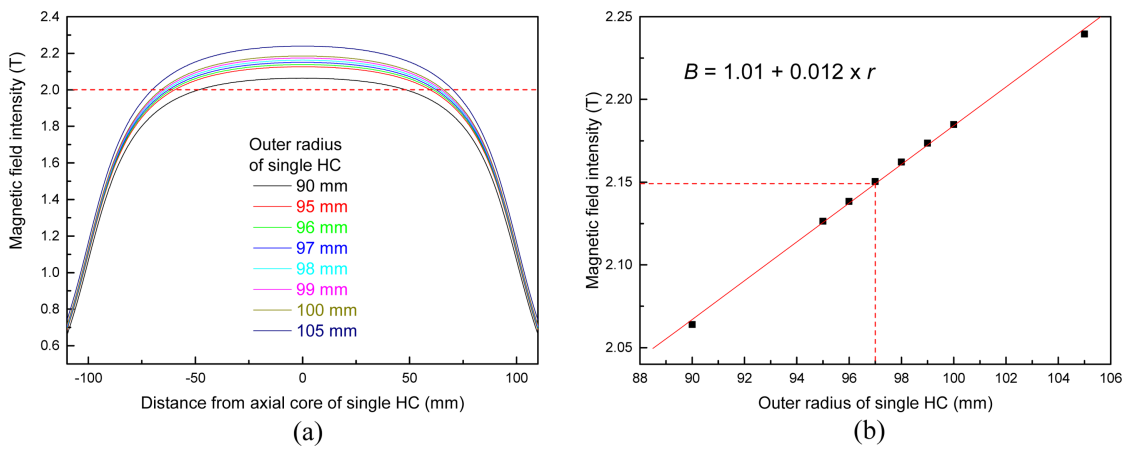
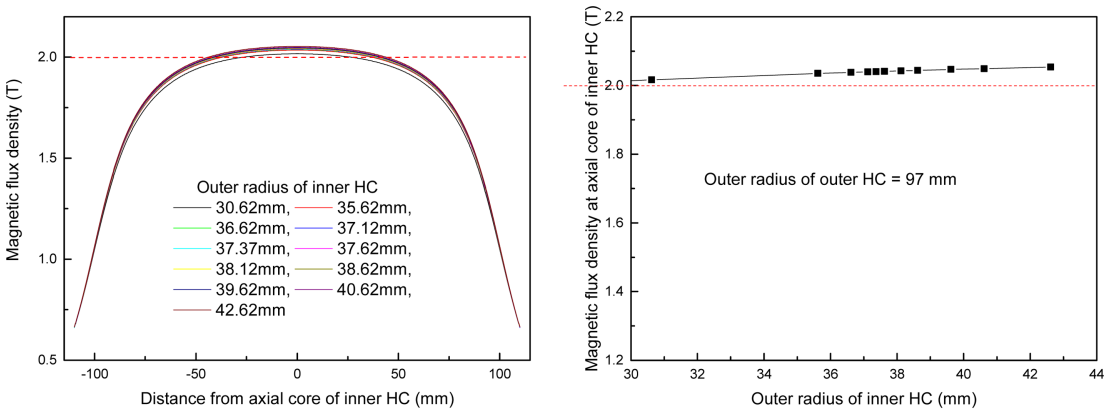
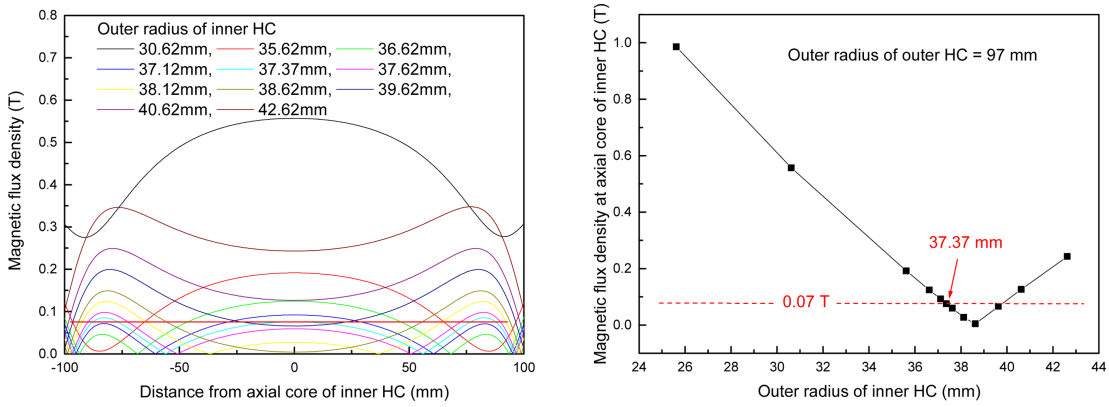


Fig. 2. (Color online) (a) Profiles for simulating magnetic field of axial direction according to the outer radius of the single HC. (b) Result of the least square fitting at the axial core of single HC.



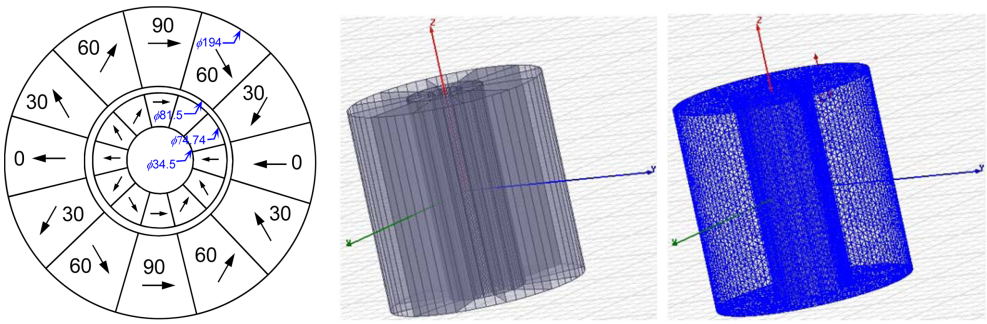
(a) (b)

Fig. 3. (Color online) (a) Profiles for simulating magnetic field of axial direction of HM according to the outer radius of the inner HC when that the magnetizations of the inner and outer HC are same direction. (b) Result of the least square fitting at the axial core of the HM.



(a) (b)

Fig. 4. (Color online) (a) Profiles for simulating magnetic field of axial direction of HM according to the outer radius of the inner HC when that the magnetizations of the inner and outer HC are opposite direction. (b) Result of the least square fitting at the axial core of the HM.



(a) (b) (c)

Fig. 5. (Color online) (a) Determined dimension, (b) the estimated model for simulating the magnetic field, and (c) the mesh configuration of RHM.

increased further. We chose $r_o = 37.37$ mm (Fig. 5(a)) by considering the three peaks, so RHM had minimum MFD = 0.07 T.

The chosen dimensions of RHM are as follows. The HC had outer diameter = 194 mm and inner diameter = 81.5 mm. The inner HC had outer diameter = 74.74 mm and inner diameter = 34.5 mm. The air gap between the inner HC and outer HC was 3.38 mm. The RHM was

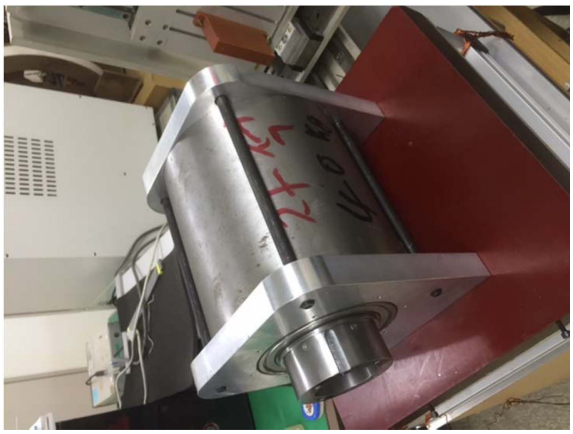


Fig. 6. (Color online) Photograph of the fabricated RHM.

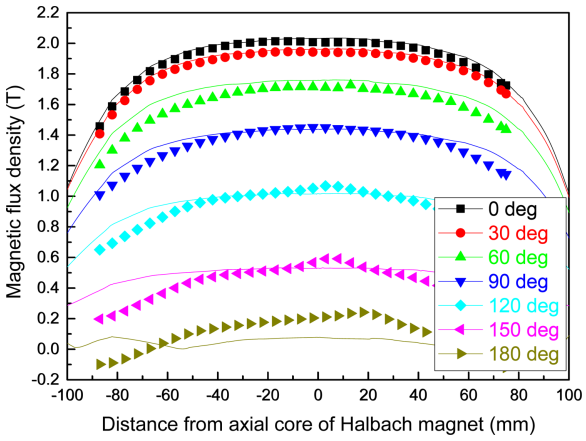


Fig. 7. (Color online) MFD profiles of the RHM. The lines are simulated MFD, and symbols are measured one.

simulated using a mesh composed of ~1,252,800 tetrahedra (Fig. 5(c)). The RHM was manufactured at the Baotou Research Institute of Rare Earth in China on the basis of the simulation [13].

3. Results and Discussion

The RHM (Fig. 6) was fabricated in accordance with simulation results, and the MFD of the central axis was measured using a Gaussmeter (F.W. Bell 8030) with flat-type Hall probe (STF81-0404-10) by rotating the inner HC in increments of 30°. The measured results were compared to the simulated results. When the magnetizations of inner and outer HC are in the same direction, the MFD should be greatest; the maximum values MFD were of 2.03 T in the simulation and 2.01 T in measurement. The simulated and measured MFDs of the RHM agreed well at 0° and 30°, but less well at 150° and 180° (Fig. 7).

4. Conclusion

A strong magnetic field is important in a magnetic refrigerator, because the magnetocaloric effect at the Curie temperature increases as $MFD^{2/3}$. A rotating Halbach magnet (RHM) is composed of an inner Halbach cylinder (HC) rotor and an outer HC stator. We first used FEM to simulate the size of a single HC, then determined the dimensions of the inner HC to produce MFD = 2 T. We determined the outer diameter of the single HC to be 194 mm. The inner HC had inner = 34.5 mm and outer diameter = 74.74 mm. We used simulation results to guide fabrication of the RHM. The measured MFD agreed well with simulated values.

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