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Magnetic Shielding Effect on Halbach Cylinder used in Magnetic Refrigerators

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The system for producing magnetic field constitutes an important component of magnetic refrigerator. Many researchers have directed significant effort to increase the magnetic field intensity, because the magnetocaloric effect at the Curie temperature increases with the power of 2/3 of the magnetic field. In this study, we report the simulation of the magnetic field intensity at polar axis of a Halbach cylinder (HC) by i) changing the length and thickness of the HC, ii) having with or without gap of the HC, and iii) surrounding the HC with a soft magnet shell, acting as a shielding. We simulated the field distribution of a HC with a finite size. Furthermore, the detailed numerical results of the magnetic field distribution and its dependence on shielding are presented in this study.

Keywords : magnetic refrigerator, Finite element method (FEM), Halbach cylinder (HC), magnetic shielding

Introduction

The efficiency of a magnetic refrigerator system depends on the magnetocaloric effect of the magnetic refrigerant. In magnetocaloric effect, the adiabatic temperature of a magnetic refrigerant increases or decreases when the refrigerant magnetizes or demagnetizes [1]. The magnetic refrigeration is theoretically analogous to the conventional refrigeration ones and are usually accomplished by the means of the cyclic compression and expansion of the gaseous system [2]. A high magnetic field is necessary for the success of a magnetic refrigerator system, because the magnetocaloric effect at the Curie temperature increases with the power of 2/3 of the magnetic field [3].

One magnetic source used for the magnetic refrigerator is the permanent magnet, which produces a magnetic field without electricity consumption, and only mechanical energy is required to move the magnet or the active material [4]. The optimization of the structural configuration can lead to the magnetic field with 1 T or 2 T with an acceptable air-gap volume. Such a source is suitable for a few kilowatt power and compact systems [4]. Rare earth magnet such as $Nd_2Fe_{14}B$ and $SmCo_5$ are widely used for the strong magnetic field application. Rare earth metals are much more expensive than iron and nickel; therefore, it is important to design a magnet array with the highest magnetic field for a given size and weight of permanent magnet material [5]. The magnetic refrigerator will liquefy the gaseous hydrogen if the high magnetic field will be produced, and the high effective magnetocaloric material at temperature domain for liquefying the hydrogen will be developed.

In this study, we report the simulations for the magnetic flux density at the polar axis of the HCs by changing their length and thickness, having with or without gaps, and surrounding them with a soft magnetic shell, acting as a shielding.

2. The Model for Magnetic Field Calculations

Finite element methods are widely used in the electromagnetic field simulation. Two types of systems for simulating the magnetic field were considered. One system was a closed circuit, and the other was an open circuit as shown in Fig. 1, displaying a sketch of an unshielded closed circuit watched from the top of the cylinder. The z-axis is the direction of the length of the cylinder, and the

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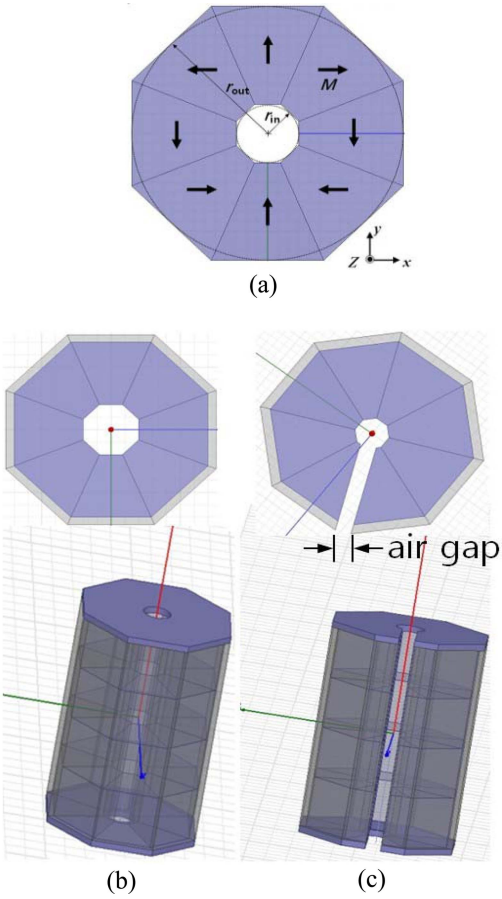

Fig. 1. (Color online) Model of HC for simulating the magnetic field. (a) unshielding closed circuit. Arrows show magnetization. The shielding (b) closed and (c) open circuit.

arrows show magnetization. Figs. 1(b) and 1(c) are the models of the closed and open HC, respectively, shielded by magnetic shielding material, S1008 steel. The side-opening is for the access of magnetic refrigerant materials to the center of the air gap.

The permanent magnetic material used for simulating was rare earth magnet N50M with a coercivity (H_c) and retentivity (B_r) of 1,042 kA/m and 1.4 T, respectively.

3. Results and Discussion

Fig. 2(a) shows the mesh configuration for simulating the magnet field, and Fig. 2(b) shows the simulated magnetic field distribution of the HC. The magnetic field was solved by the Ansys Maxwell v15 3D software [6], and the Magnetostatic Solver was used. The total number of mesh was 230,450 tetrahedra. The governing equations for solving with the Magnetostatic solver of Maxwell 3D software are as follows:

$$\nabla \times \vec{H} = \vec{J} \tag{1}$$

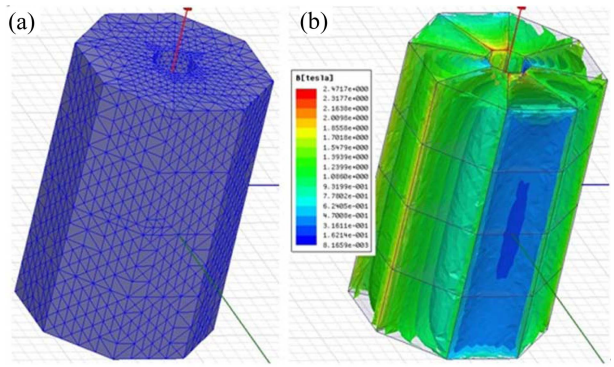

Fig. 2. (Color online) (a) Mesh configuration for simulating magnetic field and (b) simulated magnetic field distribution of HC.

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

$$\vec{B} = \mu_0(\vec{H} + \vec{M}) = \mu_0 \cdot \mu_r \cdot \vec{H} + \mu_0 \cdot \vec{M}_p \tag{3}$$

Fig. 3 shows the simulation results depending on the

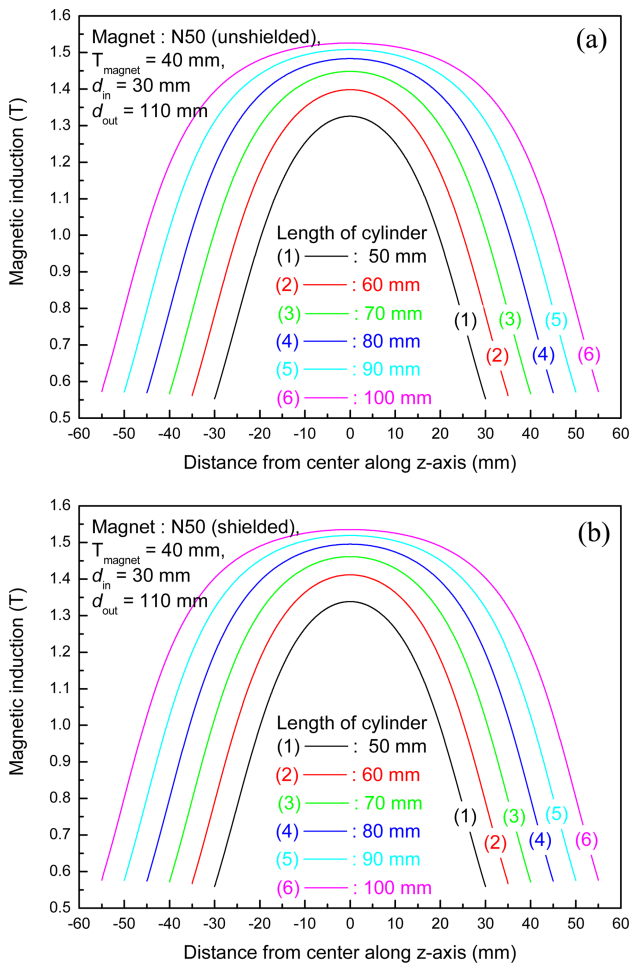

Fig. 3. (Color online) Magnetic field profiles along z-axis of the closed HC with the lengths of 50, 60, 70, 80, 90, and 100 mm at (a) without and (b) with shielding by S1008 steel.

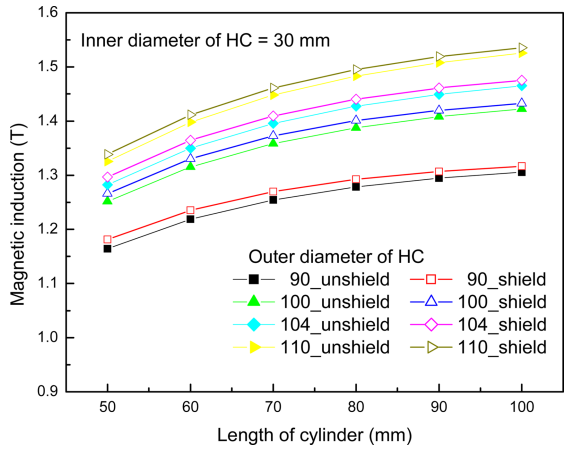

Fig. 4. (Color online) Change in magnetic field strength at the center of the HC with varying length without or with a shielding thickness of 6 mm. d_{outs} of the shielded HC were not included the shielding thickness.

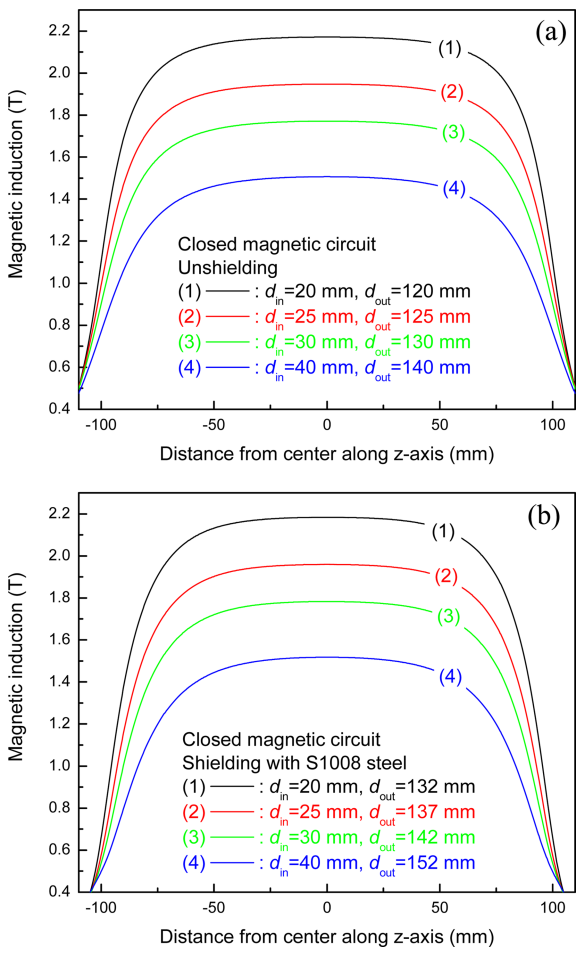

Fig. 5. (Color online) Magnetic field profiles along z-axis of the closed HC with the d_{ins} of 20, 25, 30, and 40 mm at (a) without or (b) with the shielding by S1008 steel. The length of the HC was 200 mm, and the thickness of magnet segment was 50 mm. d_{outs} of the unshielded HC were 120, 125, 130, and 140 mm. d_{outs} of the shielded HC were 132, 137, 142, and 152 mm.

length of the cylinder with an inner diameter (d_{in}) and outer diameter (d_{out}) of 30 and 110 mm, respectively, and the magnetic segment thickness of 40 mm. Figs. 3(a) and 3(b) show the magnetic field profiles of the cylinder without and with shielding by the S1008 steel. The magnetic field intensity increased, and the uniform area broadened with increasing length of the HC.

Fig. 4 shows the change in magnetic field strength at the center of the cylinder for the length and the d_{out} alteration without and with a shielding thickness of 6 mm. The magnetic field strength increased with increasing the cylinder length and thickness of the magnet. The magnetic field strength produced was >1.5 T for the length of >90 mm and d_{out} of >104 mm. The field strength of the shielded cylinder was 0.6% larger than that of the

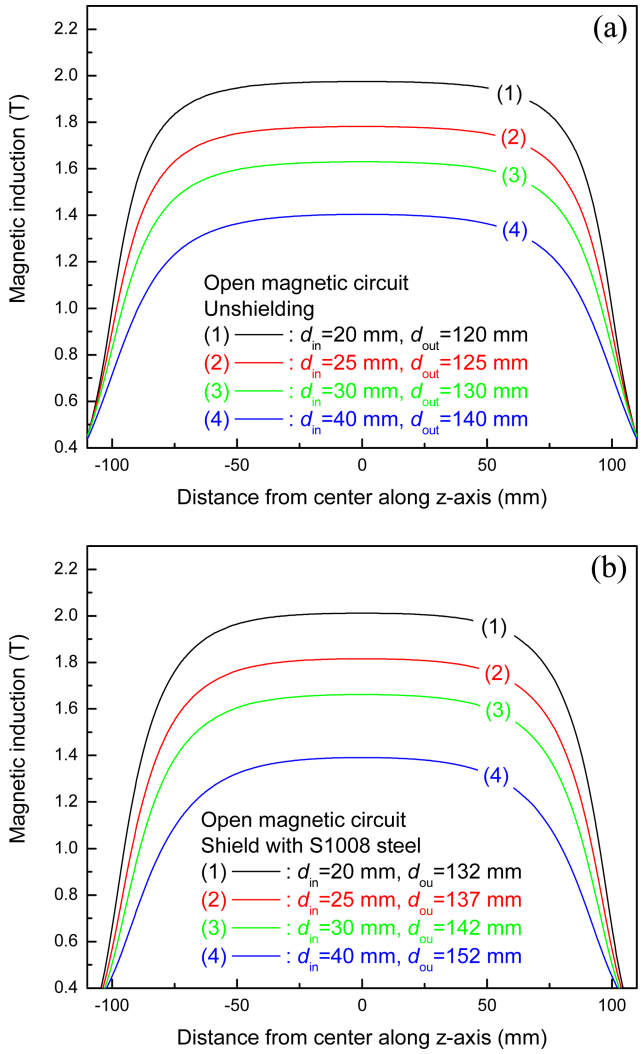

Fig. 6. (Color online) Magnetic field profiles along z-axis of the open HC with the thicknesses of 20, 25, 30, and 40 mm at (a) without and (b) with the shielding by S1008 steel. d_{outs} of the unshielded HC are 120, 125, 130, and 140 mm. d_{out} of the shielded HC are 132, 137, 142, and 152 mm.

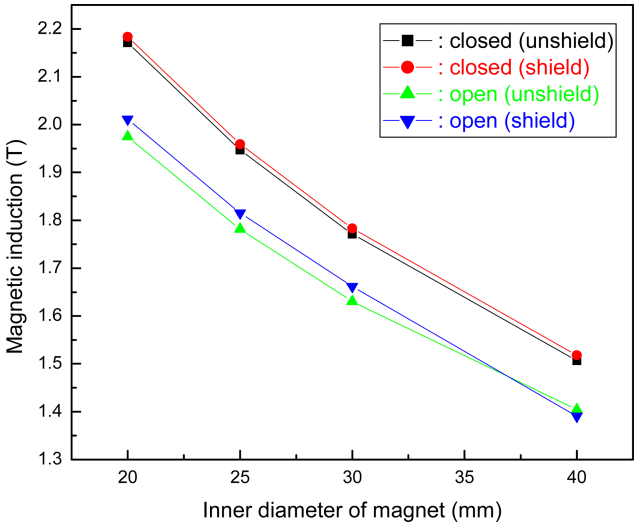

Fig. 7. (Color online) Change in magnetic field strength at the center of the closed and open HC for d_{in} without and with shielding by S1008 steel.

unshielded one.

Figs. 5 and 6 show the magnetic field profiles along z-axis of the closed and open HC with the d_{in} of 20, 25, 30, and 40 mm at (a) without and (b) with shielding by S1008 steel. The outer diameters of the HC including shielding thickness were 132, 137, 142, and 152 mm. The length of the cylinder was 200 mm, and the thickness of the magnet was 50 mm. The magnetic field strength decreased with increasing the d_{in}.

Fig. 7 shows the change in the magnetic field strength at the center of the closed and open HC for the d_{in} without and with shielding by S1008 steel. The magnetic field strength at the center of the closed cylinder was >2.1 T at an d_{in} of 20 mm. The magnetic field strength at the center of the cylinder decreased with increasing d_{in}. The magnetic field strength of the shielded and closed cylinder was 0.6% larger than the unshielded one. The magnetic field strength of the shielded and open cylinder was 1.8% larger than the unshielded one. The shielding effect was larger in the open cylinder case than the closed one, because the flux leakage was smaller than the closed cylinder than the open one.

In the case of the unshielded cylinder, the field intensities of the cylinders with the d_{ins} of 20, 25, 30, and 40 mm were 9.9%, 9.3%, 8.6% and 7.3% higher than the field intensities of the open cylinder having the same d_{ins}. The d_{outs} of the HC including shielding thickness were 132, 137, 142, and 152 mm.

4. Conclusion

(1) The magnetic field was simulated at the polar axis of the HC by varying its length and thickness, having with or without gap, and surrounding the cylinder with a soft magnet shell, acting as a shielding.

(2) The magnetic field intensity increased, and the uniform area broadened with increasing length of the HC.

(3) The magnetic field intensity increased with increasing length of the cylinder and increasing the magnet.

(4) The magnetic field strength decreased with increasing d_{in}.

(5) The magnetic field strength of the shielded open cylinder was 1.8% larger than the unshielded one.

(6) The shielding effect was more effective for the open HC than the closed one.

Acknowledgements

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References

[1] X.N.Xu, D. W. Lu, G. Q. Yuan, Y. S. Han, and X. Jin, J. Appl. Phys. **95**, 6302 (2004).
[2] X. Bohigas, E. Molins, A. Roig, J. Tejada, and X. X. Zhang, IEEE Trans. Magn. **36**, 538 (2000).
[3] R. Bjφrk, C. R. H. Bahl, A. Smith, and N. Pryds, Intl. J. Refrigeration **33**, 437 (2010).
[4] F. Allab, A. Kedous-Lebouc, J. P. Yonnet, and J. M. Fourier, Intl. J. Refrigeration **29**, 1340 (2006).
[5] S. J. Lee and D. C. Jiles, IEEE Trans. Magn. **38**, 2991 (2002).
[6] Ansys inc., http://www.ansys.com.