Journal of Magnetism and Magnetic Materials 405 (2016) 231–237

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Numerical simulation and performance improvement of a multi-polar concentric Halbach cylindrical magnet for magnetic refrigeration

Yonghua You [a,b,*], Yue Guo [a], Shuifang Xiao [a], Shen Yu [a], Hu Ji [c], Xiaobing Luo [d]

[a] State Key Lab. of Refractory and Metallurgy, Wuhan University of Science and Technology, Wuhan 430081, China
[b] Key Laboratory for Ferrous Metallurgy and Resources Utilization of Ministry of Education, Wuhan University of Science and Technology, Wuhan 430081, China
[c] China Electric Power Research Institute, Wuhan 430074, China
[d] School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

ARTICLE INFO

Article history:
Received 14 December 2015
Received in revised form
18 December 2015
Accepted 22 December 2015
Available online 23 December 2015

Keywords:
Numerical simulation
Performance improvement
Concentric Halbach cylinder
Permanent magnet
Rotary magnetic refrigerator

ABSTRACT

Multi-polar concentric Halbach cylinders of magnets could generate the magnetic field varying considerably in the annular gaps, thus were applied in the rotary magnetic refrigerators. In the current investigation, a six-polar concentric Halbach cylinder is developed based on the ideal concentric one by the numerical simulation with COMSOL Multiphysics. Cylinder radii are optimized and magnet material profiles are adjusted for a better overall performance (Λ_{cool}). Moreover, the segmentation on the concentric cylinder is conducted for an easy fabrication, and the edge effect of finite-length device is studied. With the present investigation, it is found that a larger external radius of external cylinder facilitates a larger flux density in the high field region ($|\overline{B}|_{high}$), while Λ_{cool} could be worse. Meanwhile, with the removal of magnet materials enclosed by the equipotential lines of magnetic vector potential, the magnetic flux density in low field region ($|\overline{B}|_{low}$) drops from 0.271 to 0.0136 T, and Λ_{cool} rises from 1.36 to 1.85 $T^{0.7}$. Moreover, a proper segmentation would not degrade the difference between $|\overline{B}|_{high}$ and $|\overline{B}|_{low}$, on the contrary, Λ_{cool} rises by about 20.2% due to magnet materials lack for efficiency replaced by soft irons. Finally, current 3D simulation indicates the edge effect on Λ_{cool} could be trivial.

1. Introduction

Magnetic refrigeration is based on the magneto-caloric effect, or the temperature change when exposed to a varied magnetic field, of magneto-caloric materials (MCMs). This new type of refrigeration technique has several obvious advantages over the conventional vapor compression one, such as more energy efficient, no enhancing greenhouse effect or depleting Ozone layer, etc., and thus has a great potential for the prospective commercial and civil applications [1]. Since Ames Laboratory and Astronautics Corporation of America presented the demonstration unit of magnetic refrigeration near room temperature [2,3], and the discovery of giant magneto-caloric materials was reported in 1997 [4], the research interest in the new cooling technique has been greatly aroused, resulting in a variety of magnetic refrigeration prototypes being constructed all over the world [5–10].

It is well known to all that the performance of a magnetic refrigerator strongly depends on the adiabatic temperature change (ΔT_{ad}) of the adopted refrigerant, which is greatly related to the exposed magnetic fields. Despite that both superconducting [3] and electrical [5] magnets could generate powerful magnetic fields for magnetic refrigeration, the majority of prototypes built in recent years have adopted permanent magnets due to the advantages of low cost, small volume and no power consumption [6,8]. On the other hand, the magnetic field generated by a permanent magnet is usually limited, and the temperature change of MCMs is not that large near room temperature, for example, about 3.2 K when Gd inserted in a magnetic field of 1 T [11]. Therefore, the efficient design of permanent magnet is highlighted for an economical magnetic refrigerator [12]. Bjørk et al. believed that the magnetic flux densities in the high and low field regions should both be considered for the optimal design of a permanent magnet of magnetic refrigerator, and proposed a combination parameter to characterize such magnets [13]. With the parameter combination, 12 magnet designs were compared, and some guidelines of optimal design were presented [12].

A Halbach array is a special arrangement of permanent magnets that augments the magnetic field on one side of the array while canceling the field of the other side to near zero [14]. A two-polar Halbach cylinder was investigated to generate an intense and homogenous magnetic field in the bore, and some geometrical

* Corresponding author at: State Key Lab. of Refractory and Metallurgy, Wuhan University of Science and Technology, 947 Heping Road, Wuhan 430081, China.
E-mail address: hust_yyh@163.com (Y. You).

http://dx.doi.org/10.1016/j.jmmm.2015.12.077
0304-8853/

parameters were optimized with the numerical simulations [13]. To generate the magnetic field varied considerably for the application of a rotary refrigerator, which has the advantages of high efficiency and compact configuration, etc. [9], a multi-polar concentric Halbach cylinder was proposed [15]. Such a magnet assembly consists of two cylinders with opposite wave numbers, and could generate the high and low field regions in the annular gap with considerably different flux densities. Bjørk et al. found that a concentric Halbach cylinders is more efficient for the magnetic refrigeration by comparing it with the two half Halbach cylinder and the two linear Halbach array, etc. [16]. They made use of commercial software COMSOL Multiphysics to design a four-polar concentric Halbach cylinder, including the cylinder segmentation for an easy manufacture [17,18]. The magnet assembly with four poles was applied in the high-speed magnetic refrigeration prototype at Risø DTU [19], and both experimental and numerical investigations were conducted. These researches demonstrated that the prototype had a good refrigeration performance, meanwhile, it was also found that the friction loss considerably degraded the cooling performance under the condition of high revolution rate [20].

As is well known, the more poles the concentric Halbach cylinder has in a rotary magnetic refrigerator, the more times the refrigerants are magnetized and demagnetized in one revolution, and thus the larger refrigeration capacity the refrigerator generates, or the smaller revolution rate the refrigerator runs with for a constant refrigeration capacity. Therefore, in the current investigation, the concentric Halbach cylinders with six poles is investigated with the numerical method. Some geometry parameters are optimized based on the balance between the magnetic field performance and magnet material consumption. Besides, in consideration of the magnetic flux liable to leak from the high to low field regions in a concentric Halbach cylinder, an extra work is conducted to minimize the magnetic flux density in the low field region. In addition, the concentric cylinder segmentation is conducted for an easy manufacture, and the corresponding three-dimensional simulation is constructed for the finite length device as well.

2. Numerical model and validation

2.1. Physical model

The current concentric Halbach cylinder is based on the ideal six-polar concentric one, where the internal and external radii of internal cylinder are expressed by r_{in}, r_{ext}, while R_{in} and R_{ext} represent the counterparts of the external cylinder, respectively, as is shown in Fig. 1. The ideal concentric cylinder has an uniform norm of remanent magnetic flux density, and the radial and circumferential components are calculated by Eqs. (1) and (2), respectively [13,14]. It is noted that the wave numbers of external and internal cylinders are equal to 3 and −3, respectively, thus six poles are generated in the concentric cylinder, in accordance with the arrows in Fig. 1.

$$B_{rem,r} = |B_{rem}|\cos(k\theta) \tag{1}$$

$$B_{rem,\theta} = |B_{rem}|\sin(k\theta) \tag{2}$$

where B_{rem} represents the remanent magnetic flux densities of materials, while | and | stand for the norm of vector. k and θ refer to the wave number and peripheral angle, respectively, while the subscripts r and θ stand for the radial and circumferential components, respectively.

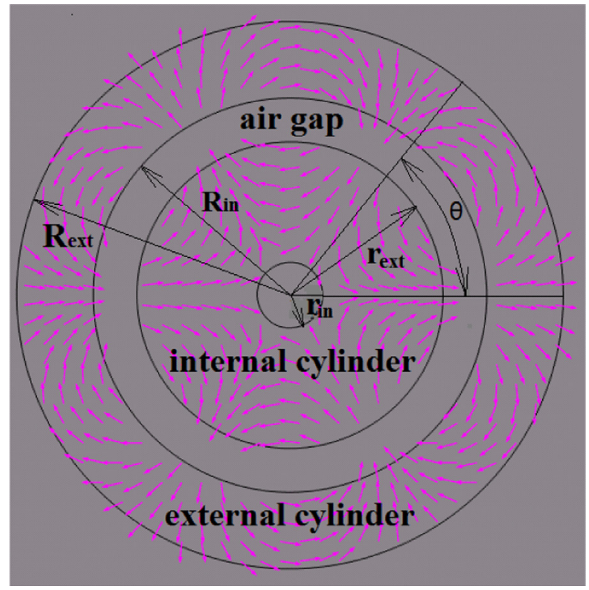

Fig. 1. The cross section of ideal concentric Halbach cylinder with six poles. The red arrows represent the remanent magnetic flux density vector. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The magnets of neodymium–iron–boron (NdFeB), adopted to manufacture the current concentric Halbach cylinder, have the remanent magnetic flux density and relative permeability of 1.4 T and 1.05, respectively [21].

It is noted that the radii of r_{ext} and R_{in} are equal to 70 and 90 mm, respectively, resulting in a gap size of 20 mm, while the values of r_{in} and R_{ext} are to be determined based on the balance of maximal magnetic flux density difference and minimal magnet material consumption in the current investigation. Besides, the magnet profile is optimized for a minimal flux density in the low field region and segmentation is conducted on the concentric cylinder for a simple manufacture process.

2.2. Governing equations and boundary conditions

In the current investigation on the Halbach array of permanent magnets, no conduction current is applied. With the stationary assumption, the Ampere's law could be expressed by

$$\nabla \times H = 0 \tag{3}$$

where ▿ and × refer to the differential operator and cross product, respectively, while H represents the magnetic field.

For the convenience of the analysis and improvement on the concentric Halbach cylinder performance, the magnetic vector potential expressed by A, rather than the magnetic scalar potential, is adopted, with which the magnetic flux density(B) is calculated by

$$B = \nabla \times A \tag{4}$$

The constitutive relation from the magnetic field to magnetization field is presented by

$$B = \mu_0\mu_r H + B_{rem} \tag{5}$$

where μ_0 and μ_r refer to the vacuum and relative permeabilities, respectively. It is noted that B_{rem} is equal to 0 T for the soft irons and air.

The continuity of magnetic vector potential, together with those of normal magnetic flux density and tangential magnetic field, is applied at the interfaces between different materials in the