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Design of nested Halbach cylinder arrays for magnetic refrigeration applications

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ABSTRACT

We present an experimentally validated analytical procedure to design nested Halbach cylinder arrays for magnetic cooling applications. The procedure aims at maximizing the magnetic flux density variation in the core of the array for a given set of design parameters, namely the inner diameter of the internal magnet, the air gap between the magnet cylinders, the number of segments of each magnet and the remanent flux density of the $Nd_2Fe_{14}B$ magnet grade. The design procedure was assisted and verified by 3-D numerical modeling using a commercial software package. An important aspect of the optimal design is to maintain an uniform axial distribution of the magnetic flux density in the region of the inner gap occupied by the active magnetocaloric regenerator. An optimal nested Halbach cylinder array was manufactured and experimentally evaluated for the magnetic flux density in the inner gap. The analytically calculated magnetic flux density variation agreed to within 5.6% with the experimental value for the center point of the magnet gap.

1. Introduction

Magnetic refrigeration at room temperature is an emerging technology with numerous developments in magnetocaloric working materials [1,2], magnetic circuits [3] and active magnetic regenerator (AMR) design [4]. Different types of magnetic field sources have been used in magnetic cooling prototypes throughout the years [5,6]. The pioneering prototypes of Brown [7] and Zimm et al. [8] used superconducting coils to generate the magnetic field. Permanent magnets, which are more frequent in recent prototypes, have been considered more advantageous due to the relatively small energy cost to generate an average-to-high magnetic flux density (generally >1.0 T). From a thermodynamic cycle perspective, permanent magnet arrangements allow for a recovery of the work needed to magnetize the solid refrigerant, which increases the theoretical potential for large efficiency of magnetic refrigeration. Additionally, permanent magnet circuits require little maintenance to confine the magnetic flux lines into a volume region without generating electromagnetic perturbations in the surroundings. These characteristics make this class of magnetic circuits more attractive for small scale AMRs.

Different designs of permanent magnet circuits have been developed for AMR coolers, such as the C-shaped Halbach [9,10], Halbach cylinder [11], nested Halbach cylinders [12,13], rotor–stator [14], and the coaxial permanent magnet circuit [15]. A review of magnet designs for magnetic refrigeration was carried out by Bjørk et al. [3].

The performance of AMR systems depends on a synergistic coupling between the designs of the regenerator and the magnetic circuit. Parameters such as the regenerator aspect ratio and bed geometry, mass of magnetocaloric material, number of regenerators, magnetic field volume, magnetic field waveform and magnetic field intensity have to be considered simultaneously to achieve an optimum compromise between size, cost and efficiency. With this in mind, Bjørk et al. [15] proposed the following figure of merit to characterize permanent magnet designs for magnetic refrigeration:

$$\Lambda_{\mathrm{cool}} = \left(\langle B_{\mathrm{high}} \rangle^{2/3} - \langle B_{\mathrm{low}} \rangle^{2/3} \right) \frac{\vartheta_{\mathrm{Field}}}{\vartheta_{\mathrm{Magnet}}} \tau^{*} \tag{1}$$

where $\langle B_{\mathrm{high}} \rangle$ is the volumetric average high magnetic flux density, $\langle B_{\mathrm{low}} \rangle$ is the volumetric average low magnetic flux density, $\vartheta_{\mathrm{Field}}$ is the total volume where the magnetic field is applied, $\vartheta_{\mathrm{Magnet}}$ is the volume of permanent magnet raw material, for instance, $Nd_2Fe_{14}B$, and τ^{*} is the fraction of the cycle period during which the magnet is used. Λ_{cool} quantifies the potential of a magnetic circuit for magnetic refrigeration applications. An ideal magnet for an AMR prototype should guarantee a high magnetic field variation (higher magnetocaloric effect), a large volume of generated magnetic field

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(larger density of magnetocaloric material), must be used during most of the cycle time (ideally in a continuous cycle) and, equally important, use a small amount of permanent magnet (to reduce cost).

Building on previous developments [12,16–19], the present work proposes an analytical model and a design procedure to determine the dimensions of nested Halbach cylinders that maximize Λ_{cool} and the magnetic flux density variation. The input parameters of the design procedure are the inner diameter of the internal magnet, the air gap between the magnet cylinders, the number of segments of each magnet and the remanent flux density of the $Nd_2Fe_{14}B$ magnet grade. The procedure was refined and verified using 3-D computational modeling [20]. An optimal system configuration prototype was manufactured and the design procedure was validated through a comparison with experimental results for the magnetic flux density in the magnetic gap. Experimental data for the magnetic flux density and torque are presented and discussed.

2. Nested Halbach cylinders

Nested Halbach cylinders (NHC) were used recently in AMR apparatuses [12,13]. The NHC configuration shown in Fig. 1 consists of two concentric Halbach cylinders so that each magnet array generates a magnetic field in its core. If the magnetic field contributions of each magnet are added, then the maximum magnetic flux density, $\vec{B}_{max}$, of the NHC is observed at the core of the inner magnet, as shown in Fig. 1(a). Conversely, when the magnetic field contributions are subtracted, the minimum magnetic flux density, $\vec{B}_{min}$, is obtained, as seen in Fig. 1(b). Thus, it follows that the NHC configuration is an alternating magnetic field source. By creating a relative motion between the cylinders, the magnetic field changes continuously between the maximum and the minimum flux density positions [21,17,12].

The NHC configuration was chosen as the magnetic field source for an AMR test apparatus developed at the Federal University of Santa Catarina for the following reasons: (i) it can generate high magnetic flux densities of the order of 1.5 T; (ii) it is compact, so a reasonable mass of magnetocaloric material can be contained in the high magnetic field change region; (iii) it can be easily assembled with a simple structure; and (iv) it creates a variable field simply by rotating the cylinders, thus enabling operating frequencies as high as 4 Hz [12]. Nevertheless, the main disadvantage of NHCs is that they house a single regenerator per core, so for continuous cyclic operation at least two NHCs are required. Other drawbacks of NHCs are: (i) oscillating torque due to segmented magnets [13,16]; (ii) asymmetric magnetic field waveforms that reduce the AMR performance by making the low field period shorter than the high field period [12,13,22]; and (iii) the use of a significant amount of permanent magnet raw material ($Nd_2Fe_{14}B$).

Typically, NHC arrays have low values of Λ_{cool} when compared with other magnetic circuits [3]. However, the ability to change the magnetic field at high frequencies with low inertial effects makes this configuration next to ideal for testing and optimizing AMRs [10,11]. One of the main challenges of using NHC arrays as the variable magnetic field source in AMR test devices is the design of the motion system. Appropriate selection of components, such as gear boxes, pulleys, belts, driver and shaft couplings, is crucial for achieving frequencies of the order of 1–4 Hz with low noise and small mechanical losses.

Rotating a single magnet or counter rotating the two magnets dictates how the magnetic field will change in the core of the NHC array, as illustrated in Fig. 2. Rotating the internal magnet (I) with a static external magnet (E), Fig. 2(a), results in the simplest and most compact magnet motion configuration, since the external magnet is usually the heaviest piece [12]. As illustrated in Fig. 2(a), rotating the inner array causes both the magnitude (modulus) and the orientation (direction) of the magnetic flux density vector to change continuously. At position [(E) at 0°; (I) at 0°], $\vec{B}$ is maximum with a downward direction, while at position [(E) at 0°; (I) at 45° or 135°], the modulus of $\vec{B}$ is smaller with the orientation always in phase with the angle of the inner array. The minimum field is observed at position [(E) at 0°; (I) at 180°]. The change in direction of $\vec{B}$ gives rise to a external magnetic force acting on the magnetocaloric regenerator positioned in the magnet core. This magnetic force tends to rotate the regenerator with the magnet, generating structural problems which are more serious when the regenerator matrix is composed by thin parallel-plates or pins. Additionally, a rotating magnetic field direction in the magnetic gap increases the complexity of evaluating demagnetizing losses in AMRs [23,24].

Counter rotating the internal and external magnets, Fig. 2(b), requires a more complex magnet motion system. However, as the Halbach cylinders counter rotate, the modulus of $\vec{B}$ changes continuously, but the orientation is kept fixed. In Fig. 2(b), at position [(E) at 0°; (I) at 0°], $\vec{B}$ is maximum and points downward, while at position [(E) at $-45°$; (I) at 45°], the magnitude of $\vec{B}$ has decreased, maintaining the same direction. At position [(E) at $-90°$;

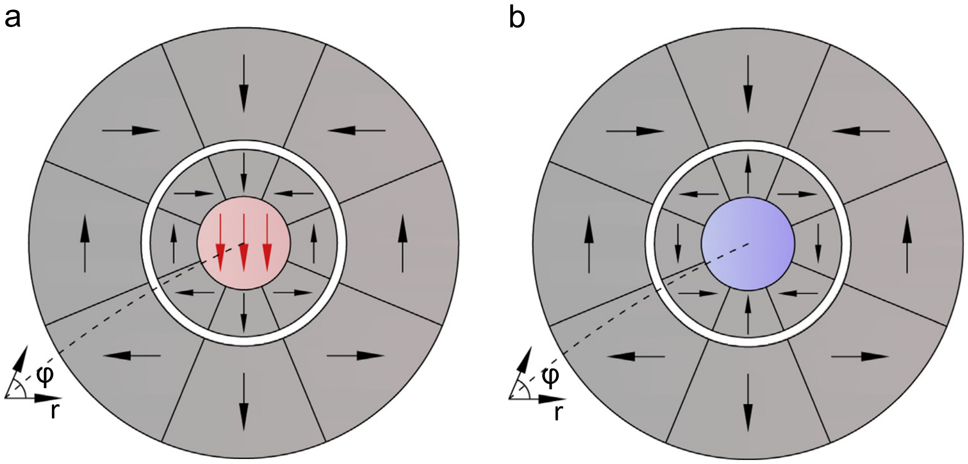

Fig. 1. Nested Halbach cylinders: (a) at the maximum magnetic field position and (b) at the minimum magnetic field position. The black arrows indicate the remanent flux density of the permanent magnet segments, while the red arrows indicate $\vec{B}$ in the magnetic gap. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)