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Abstract

Recent research into the development of magnetic refrigeration (MR) operating at room temperature has shown that it can provide a reliable, energy-efficient cooling system. To enhance the cooling power of the magnetic refrigerator, it is required to use a magnetic refrigerant material with large magnetocaloric effect (MCE) at the appropriate temperature. Most advanced magnetic refrigerant materials show largest MCE at high applied magnetic fields generated by a superconducting magnet. For application of MCE to air conditioners or household refrigerators, it is essential to develop a permanent magnet array to form a compact, strong, and energy-efficient magnetic field generator. Generating a magnetic field well above the remanence of a permanent magnetmaterial is hard to achieve through conventional designs. A permanent magnet array based on a hollow cylindrical flux source is found to provide an appropriate geometry and magnetic field strength for MR applications.

Keywords
Magnetic fields, Permanent magnets, Magnetic materials, Refrigerators, Magnetoresistance

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Permanent magnet array for the magnetic refrigerator

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Recent research into the development of magnetic refrigeration (MR) operating at room temperature has shown that it can provide a reliable, energy-efficient cooling system. To enhance the cooling power of the magnetic refrigerator, it is required to use a magnetic refrigerant material with large magnetocaloric effect (MCE) at the appropriate temperature. Most advanced magnetic refrigerant materials show largest MCE at high applied magnetic fields generated by a superconducting magnet. For application of MCE to air conditioners or household refrigerators, it is essential to develop a permanent magnet array to form a compact, strong, and energy-efficient magnetic field generator. Generating a magnetic field well above the remanence of a permanent magnet material is hard to achieve through conventional designs. A permanent magnet array based on a hollow cylindrical flux source is found to provide an appropriate geometry and magnetic field strength for MR applications.
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INTRODUCTION

The magnetocaloric effect (MCE) is the heating or the cooling of magnetic solids in a varying dc magnetic field. When an externally applied magnetic field increases, the spin entropy in the ferromagnetic material is reduced due to the alignment of magnetic moments with the direction of the magnetic field. The conservation of total entropy in an adiabatic process leads to the enhancement of lattice entropy, thus raising the temperature of the material. The MCE can be determined from the direct, magnetization or heat capacity measurements. The temperature change ΔT_{ad} is obtained from the measured data.[1] Usually the maximum MCE occurs for ferromagnetic materials at their Curie temperatures T_c because the spin entropy change is maximum at T_c. The search for magnetic materials showing large MCE has increased because they can be used as solid magnetic refrigerant materials for magnetic refrigerators (MRs).[2–5] A MR can be used to replace the standard gas-compression refrigerator because it offers an energy-efficient and environmentally clean operation.

Zimm *et al.*[6] have demonstrated a reciprocating magnetic refrigerator working near room temperature using Gd($T_c = 294$ K) in a magnetic field between 1.5 and 5 T. In the MR system, two beds containing a spherical powder of Gd move in and out of high magnetic field volume at low frequency. The magnetic field has been provided by a liquid He-immersed superconducting magnet. In this system water was employed as the heat transfer fluid. The temperature changes due to MCE were 4.5 and 11 K when the magnetic field changes were 1.5 and 5 T, respectively. Using superconducting magnets for household MR is unrealistic and the conventional permanent magnet arrangements do not provide the necessary field strengths for MR. Therefore it is important to develop a permanent magnet array which can provide magnetic fields typically above 1.5 T for advanced magnetic refrigerant materials such as $\mathrm{Gd_5(Si_xGe_{1-x})_4}$ alloys.[3,4] Bohigas *et al.*[7] employed permanent magnets arranged in a conventional design to generate a magnetic field in a rotary MR. Two NdFeB permanent magnets (50 mm×50 mm×25 mm) displaced parallel to each other produced a uniform magnetic field of 0.3 T in the region between the two permanent magnets. ΔT_{ad} was 1.6 K for Gd ribbon attached on a disk and rotating in a magnetic field of 0.3 T.

MAGNETIC FIELD SOURCE

Usually the magnetic refrigerant materials are either packed in a magnetocaloric bed as small spheres[6] attached around a disk as a ribbon[7] or separated in a pile of thin, equally spaced sheets.[8] Along with a large MCE magnitude, a strong applied magnetic field is critical to the efficiency of MR. The simplest permanent magnet design would be to place two rectangular-shaped permanent magnets parallel to each other separated by a certain distance, but this does not provide the necessary field strength for MR.[7] To enhance the magnetic flux density, soft magnetic material with a high permeability can be attached to both ends of the permanent magnets, therefore becoming a yoke-shaped permanent magnet.[8] These are easily fabricated but the generation of magnetic fields well above the remanence of the permanent magnet material is difficult.

However it has been shown that a magnetic field beyond the remanence of a permanent magnet material can be achieved by arranging permanent magnet segments in the form of hollow cylindrical shells.[9,10] The basis for the design of a hollow cylindrical permanent magnet array (HCPMA) originates from the rotation theorem of Halbach.[11] Using the rotation theorem, the magnetization vectors of each permanent magnet segment can be positioned to produce a coherent magnetic flux density in the center of the HCPMA. The analytical formula for the maximum magnetic flux density in the center of the ideal permanent magnet arrays is given by

$$B = B_R \ln(r_o/r_i), \tag{1}$$

where r_i and r_o are the inner and outer radii, respectively. In practical applications, the continuous structure is divided

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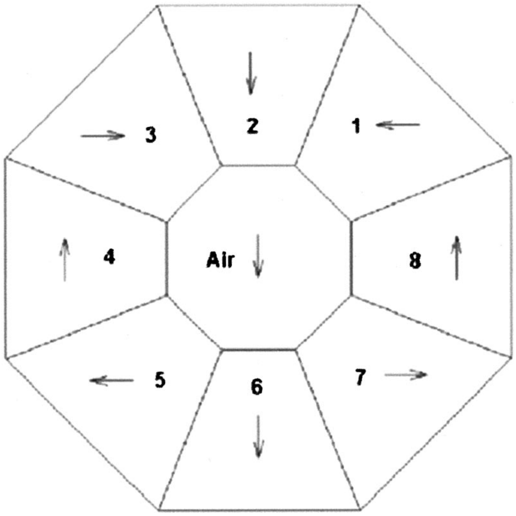

FIG. 1. Permanent magnet array with eight segments. Arrows indicate the directions of magnetization vectors of each segment.

into a smaller number of segments that are joined together. A HCPMA with eight segments for MR applications may be favorable over a larger number of segments because it is easy to fabricate while losing only 10% of the magnitude of B compared with the value expected on the basis of Eq. (1). Figure 1 shows the cross section of a HCPMA with eight permanent magnet segments. The directions of magnetization vectors are indicated as arrows. As shown in Fig. 1, the air gap is enclosed by eight permanent magnet segments. Access to the magnetic field in the air gap is possible only through the top of the HCPMA.

MODIFIED HCPMA FOR A ROTARY MR SYSTEM

For a reciprocating MR system, refrigerant materials are moved alternately in and out of the bore of the magnet using an air cylinder drive.[6] The temperature of the refrigerants increases when the refrigerant materials enter the magnetic field and decreases as they exit the magnetic field. In this scheme, a modified HCPMA without a slot may be used.[12] But for a rotary MR system where the refrigerant materials in the beds rotate in a circular path,[7] a slot is required to access the air gap where the magnetic field is the strongest. If the slot height is too large, then the magnetic flux lines will be distorted significantly in the air gap. Slot widths smaller than the size of the refrigerant material would prevent its access to the magnetic field. Figure 2 shows the geometry for the modified HCPMA with a slot and the arrows indicate the direction of magnetization vectors of each segment. Soft magnetic materials (indicated by SM in the center) were used for focusing and enhancing the magnetic field. The thin bar-shaped SM materials attached to the left were used for reducing the magnet flux leakage. This geometry looks like a C-shaped yoke and provides easier access for the magnetocaloric beds. The cross sectional dimensions of the array are 114×128 mm^2 and the air gap height is 12.7 mm. NdFeB($B_R=1.2$ T) was used as a permanent magnet and FeVCo was used as a soft magnetic material for the finite element calculations. The magnetic field at the center of the air gap was about 1.9 T and was homogeneous.

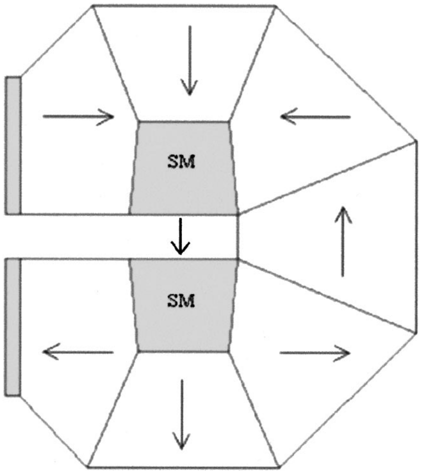

FIG. 2. A modified permanent magnet array with seven permanent magnet segments and soft magnetic materials. The direction of magnetization vectors of permanent magnets is indicated by arrows. The direction of magnetic field in the pole gap of the modified permanent magnet array points downward. The shaded areas represent soft magnetic materials. The cross sectional dimensions of the array are 114×128 mm^2 and the air gap height is 12.7 mm.

The magnetic flux lines when Gd is located in the air gap are shown in Fig. 3. The cross sectional dimensions of Gd are 15.2×10 mm^2. The magnetic field is also homogeneous, and the magnitude of magnetic flux density within the Gd sample increased from that without a sample. The measured magnetization curves ($M-H$) of Gd at 290 and 310 K were incorporated into the finite element calculation for the magnetic flux density. The magnitudes of the magnetic flux densities within the Gd sample were 2.5 and 2.25 T for 290 and 310 K, respectively. The magnitude of B at 310 K was less than that at 290 K because the magnetic moments of Gd become weak above T_c which is at 294 K.

SUMMARY AND CONCLUSION

For the application of MCE to magnetic refrigerators, a strong magnetic field is required because MCE increases as

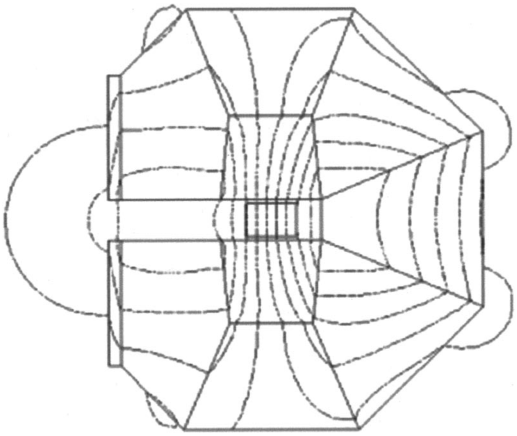

FIG. 3. The magnetic flux lines in the modified permanent magnet array where Gd is located at the center of the array.

the magnitude of applied field increases. Permanent magnets are ideal for MR applications due to their compact size, large remanence, and zero power consumption requirements, but conventional permanent magnet designs cannot produce a sufficiently high magnetic field so that the magnetic induction is well above the remanence of the permanent magnet materials. Therefore a modified permanent magnet array with a slot for refrigerants was designed based on the rotation theorem of Halbach. The magnetic field at the air gap was 1.9 T. This design is appropriate for a rotary magnetic refrigerator and provides a larger magnetic field than conventional permanent magnet designs.

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