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Prospects of Development of Magnetizing Systems with Strong Stray Field for Refrigerators Based on Giant Magnetocaloric Effect

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The systems of magnets for magnetizing devices in the refrigerators based on materials with a giant magnetocaloric effect are analysed. Permanent magnets in these systems are magnets made of materials with giant anisotropy, which generate strong stray fields whose strength exceeds the saturation induction B_S of the magnet material ($H > B_S \approx 4\pi M_S$, where M_S is saturation magnetization of this material). Taking into account the volume of such magnets, a new parameter (specific field H_{SP}) is introduced for description of the magnetic systems. The highest values of the specific field ($H_{SP} \approx 5.2M_S$) are achieved in the system consisting of monolithic cylindrical disks with radial and axial components of magnetization. As shown, the quasi-nonuniform system, in which disks are made of uniformly magnetized sectors, can also generate stray fields with high values of specific field, which are close to H_{SP} generated by the systems of monolithic disks.

Проаналізовано системи магнетів для магнетувальних пристроїв у рефрижераторах на основі матеріялів з гігантським магнетокальоричним ефектом. Сталі магнети в цих системах мають бути виготовлені з матеріялів з гігантською анізотропією, що забезпечує одержання сильних полів розсіяння, тобто таких полів, напруженість яких перевищує індукцію насичення матеріялу магнету B_S ($H > B_S \approx 4\pi M_S$, де M_S — магнетованість насичення). Для характеристики таких систем з урахуванням об'єму магнетів уведено новий параметер — питоме поле H_{SP}. Встановлено, що найвищі значення питомого поля ($H_{SP} \approx 5{,}2M_S$) досягаються у системі, яка складається з монолітних циліндричних дисків із радіяльною та осьовою компонентами магнетованости. Крім того, показано, що так звана квазинеоднорідна система, в якій диски складено з однорідно намагнетованих секторів, також має ґенерувати поля розсіяння з великим рівнем питомого поля, що є близьким до відповідних значень H_{SP} для систем із монолітних дисків.

Проанализированы системы магнитов для намагничивающих устройств в рефрижераторах на основе материалов с гигантским магнитокалорическим эффектом. Постоянные магниты в этих системах должны быть изготовлены из магнетиков с гигантской анизотропией, что обеспечивает получение сильных полей рассеяния, т.е. таких полей, напряженность которых превышает индукцию насыщения материала магнита B_S ($H > B_S \approx \approx 4\pi M_S$, где M_S — намагниченность насыщения). Для характеристики таких систем с учетом объема магнитов введен новый параметр — удельное поле H_{SP}. Установлено, что наиболее высокие значения удельного поля ($H_{SP} \approx 5{,}2M_S$) достигаются в системе, состоящей из монолитных цилиндрических дисков с радиальной и осевой компонентами намагниченности. Показано также, что так называемая квазинеоднородная система, в которой диски составлены из однородно намагниченных секторов, также должна создавать поля рассеяния с высокими величинами удельного поля, близкими к соответствующим значениям H_{SP} для систем из монолитных дисков.

Key words: magnetocaloric effects, magnetizing system, specific field, average field, monolithic disk, quasi-nonuniform system.

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1. INTRODUCTION

At present, a number of leading countries provide investigations of refrigerators based on giant magnetocaloric effect (MCE) [1–5]. MCE consists in a change of magnetic material temperature when external magnetic field changes its magnetization in adiabatic conditions causing quick change of magnetic field of the material. The change of magnetic field in turn changes the internal energy of the magnetic material sending it to heat up or cool down. If material is a paramagnet, the entropy of magnetic subsystem decreases during magnetization. During adiabatic process, the entropy of the system as a whole (magnetic subsystem and crystal lattice) is constant, so the crystal lattice absorbs heat and heats up. After switching off the field, the magnetic matter becomes demagnetized. The entropy of magnetic subsystem increases, and the working substance, namely the crystal lattice, cools down [6]. As is known, the maximal MCE is obtained near magnetic phase transitions. Because of numerous potential applications of this effect, nowadays, investigators continue their intensive search of materials with giant MCE.

In accordance with Ref. [2], the efficiency of the refrigerator based on MCE achieves 80–90% of Carnot cycle efficiency, which is considerably higher than that for up-to-date compressor refrigerators. The refrigerators based on MCE materials are particularly effective near room temperature [3, 4]. Since the magnitude of MCE is proportional to the strength of applied magnetic field H, in the earliest models of such refrigerators, superconducting solenoids were used. Permanent magnets proved to be more effective and economical sources of strong fields as compared with the superconducting magnets.

As the efficiency of cooling process depends on properties of materials with MCE, on properties of permanent magnet materials, and on design of magnetizing system of refrigerator, so main investigation efforts are concentrated in two directions: 1) search of materials with giant MCE; 2) development of permanent magnet systems generating strong stray fields.

Nowadays, there is information about pilot models of refrigerators based on MCE-alloy of Gd (Ge, Si) and refrigerator magnetizing systems identical in design to Halbach cylinder [3]. As will be shown below, despite such systems allow high magnetizing fields, they are not optimal in design.

2. RESULTS AND DISCUSSION

In this paper, we analyse different systems of magnets for application in the above-mentioned refrigerator devices. Our goal consists in optimization of magnetizing systems of refrigerator. This problem is poorly investigated to the present day. As a starting point, we use strong stray field sources based on RE-materials with a giant anisotropy, *e.g.*, $SmCo_5$, which we studied earlier [7, 8]. Strong stray fields are fields with strength H, which exceeds the saturation induction of the magnet material B_S ($H > B_S \approx 4\pi M_S$, where M_S is the saturation magnetization).

It is necessary to emphasize that magnetizing systems for refrigerators must generate strong fields in a large working volume. Besides, in parallel with the value of the field in the working volume, the volume of the magnetic system as a whole is also of importance.

In the paper [3], Halbach cylinder is suggested as a source of the field for the refrigerator device. However, there is a little sense in talking about high efficiency of such magnet system, since a volume of strong stray field ($H > 20$ kOe) in this system is small as compared with the size of the whole cylinder. Authors of [3] do not optimize their magnetizing system and say nothing about parameters, by which it should be optimized. In contrast to this and in order to account the volume of magnetic system and so to estimate an optimality of magnetizing systems, we introduce here a special parameter—specific field H_{SP}. The parameter H_{SP} is given by the following expression:

$$H_{SP} = \frac{\int\limits_{V_W} H(x,y,z)\,dV}{V_W + V_M}, \qquad (1)$$

where V_M is a volume of magnet; V_W is a volume of a working space; $H(x, y, z)$ is the strength of stray fields concentrated in this space. Calculation of $H(x, y, z)$ was provided according to methodology described in [8] with the use of MATHCAD mathematical software.

Expression (1) is correct on condition that MCE dependence on the magnetizing field is linear. This linearity was confirmed experimentally in the papers [9, 10]. It is important that the value of the specific field H_{SP} could be used to compare different magnetizing systems of refrigerators.

It should be noted that a problem concerning MCE field dependence is studied insufficiently now. A nonlinear field dependence of MCE materials is not ruled out. Therefore, in general, the concept of specific field H_{SP} should be generalized using some specific function $f(H)$ in the integral of Eq. (1) instead of linear dependence, which adequately describes MCE field dependence of the particular material. Hence, the MCE field dependence of working material is an important characteristic for design of the specific magnet system.

When solving the optimization problem, we carried out a comparative analysis of following three types of magnet systems: 1) system 1 of permanent magnets formed as cylindrical disks magnetized radially (Fig. 1, *a*); 2) system 2 of cylindrical magnets, magnetized uniformly and perpendicularly to their plane surfaces (Fig. 1, *b*); 3) system 3 of cylindrical disks, in which magnetization vectors have both radial and axial components (Fig. 2).

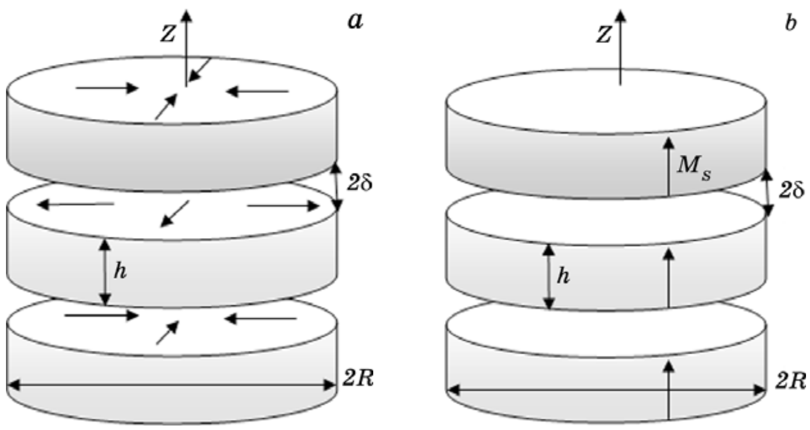

Fig. 1. Systems of cylindrical magnets with radial (*a*) and uniform (*b*) magnetization distribution.

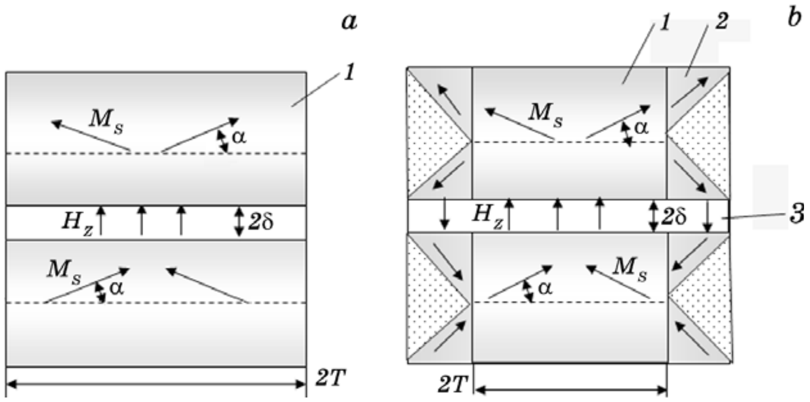

Fig. 2. Systems of cylindrical magnets possessing both radial and axial components of magnetization: simple system (*a*) and system with cores (*b*). *1*—basic cylindrical magnets; *2*—auxiliary magnet (core); *3*—working space between auxiliary magnets; 2δ is the width of working gap.

It is obvious, at $\alpha = 0°$, system 3 turns into system1, and at $\alpha = 90°$, system 3 turns into system 2, *i.e.* systems1 and 2 are the special cases of system 3. We should note here that the field in gaps between plane surfaces of the permanent magnets previously named is a working field, *i.e.* the MCE material must be placed inside the gaps.

We have formulated before [7] the average field concept as applied to nonuniform stray field and it was shown there that a system consisting of two magnets with radial magnetization (Fig. 1) generates the strong stray field with average value $\langle H\rangle > B_S$ practically across the gap diameter. It should be noted that we have found strong stray fields in other systems as well (see [7, 8]). The necessary condition of their appearance is an employment of hard magnetic materials with giant anisotropy.

In the narrow gap of the system [7] (in the space between two magnets), the average field is given by the formula

$$\langle H\rangle = \int H \frac{dV_W}{V_W}. \quad (2)$$

As follows from (2), the value of the average field for this system twice exceeds B_S. From relations (1) and (2), we have that the value of the specific field lies always below the value of the average field. However, for the specified system of magnets the values of these fields are in direct ratio. Since density of magnetic flow in uniformly magnetized magnet equals to $B_S = 4\pi M_S$, assuming linear MCE dependence on the field, we see that the value of specific field does not exceed the saturation induction $B_S \approx 4\pi M_S$.

Calculating H_{SP}, we did not take into account the volume of auxiliary magnetic cores, which are included in all constructions of magnet systems in order to reduce influence of stray fields generated by opposite magnetic 'charges' induced on external surfaces of the magnets [7, 8]. It is clear that the accounting of sizes of auxiliary magnetic cores diminishes the value of specific field. However, if auxiliary cores of the system are made of permanent magnets, as it is represented in Fig. 2, *b*, similar decay will be insignificant. Besides, stray fields of opposite direction in areas 3 between auxiliary magnets (Fig. 2, *b*) also can be working fields, as MCE is an even effect [6].

The values of specific field were computed with consideration of Z-component of the stray field denoted as H_Z. The calculations were carried out for systems 1, 2 and 3 at different values of disk thickness h, distance 2δ between the disks and the angle α between M_S and plane of the disk. During calculation, we assumed that V_M is a volume of one magnet, and V_W is a volume of gap between pair of magnets. In addition, we supposed that the generated stray fields did not change radial distribution of magnetization in the magnets. It is ensured if materials with giant magnetic anisotropy are used. The radial component of the stray field H_r is small, so it was not considered.

The results of calculations are shown in Table 1. When values of H_{SP} are compared, it is apparent that the system of magnets with radial and axial magnetization components (Fig. 2) is the most effective. The maximal specific field equals to $H_{SP} \approx 5.2M_S$ and is reached at $h \approx \approx 1.2R$, $\delta \approx 1.2R$ and $\alpha = 30°$. In the system of magnets composed of plates uniformly magnetized along their normal, the specific field is small: $H_{SP} \approx M_S$.

It should be noted that estimates of specific field of systems [3] including Halbach cylinder [11] show that $H_{SP} < M_S$. The reason lies in small specific volume of the working space in the design of magnetic system proposed in [3]. To reach higher values of H_{SP} in such a system, it should be optimized by both geometrical parameters of the system and distribution of magnetization in the magnets. As far as we know, this problem is not solved yet.

TABLE 1. Calculated values of specific field $H_{SP(Z)}$ for the system of double cylindrical magnets (Figs. 1 and 2). When calculating, the Z-component of the stray field was taken into account.

α	0°	30°	45°	60°	90°
$h = R$, $\delta = R$	$4.45M_S$	$5.0M_S$	$4.77M_S$	$4.2M_S$	$\cong M_S$
$h = 1.2R$, $\delta = 1.2R$	$4.86M_S$	$5.2M_S$	$4.86M_S$	$4.17M_S$	—
$h = 1.5R$, $\delta = 1.5R$	$4.245M_S$	$4M_S$	$3.37M_S$	$2.57M_S$	—

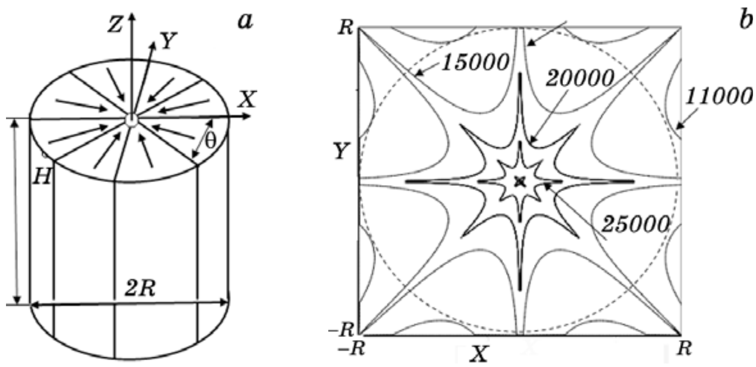

Fig. 3. Quasi-nonuniform system composed of eight sectors (*a*); isolines of the $H_Z(x, y)$ dependence in the gap of $\delta = 0.01R$ between two similar quasi-nonuniform magnets (*b*). Field strength H_Z is expressed in oersteds.

As follows from calculations, which were carried out, rather high specific fields can be achieved in systems of permanent magnets with nonuniform distribution of magnetization (Figs. 1, *a* and 2) and, consequently, such systems should be the most effective when used as field sources in refrigerators based on MCE materials. A limitation of these systems lies in difficulties of manufacturing of monolithic magnets with radial distribution of magnetization. Nevertheless, this limitation can be overcame, if we use so-called quasi-nonuniform system, which represent magnets composed of some sectors instead of monolithic ones (Fig. 3, *a*).The sectors are uniformly magnetized and magnetization vectors possess both radial and axial components. We have studied these systems in [7].

It was shown that quasi-nonuniform systems are similar in their basic parameters to the systems of cylinder magnets with radial distribution of magnetization. Quasi-nonuniform systems have large localization area of strong field similar to magnets with radial magnetization. This can be seen in Fig. 3, *b*, where lines of equal field strength are shown in the narrow gap between two composite magnets (Fig. 3, *a*). Because of large localization area of the strong field, high values of average field are realized.

Data shown in Fig. 4, where values of average field $\langle H_Z \rangle$ are compared for various angles α for the systems with radial magnetization (upper curve) and quasi-nonuniform systems (middle and lower curves), also demonstrate the similarity of these two systems. As can be seen, the values of average field components $\langle H_Z \rangle$ in the narrow gap between the pair of such magnets are closely allied. The qualitative similarity in dependences of the average field (Fig. 4) and the special field (Table 1) on α is also noteworthy: in both cases, they reach maximum at $\alpha = 30°$. It follows that quasi-nonuniform systems should also

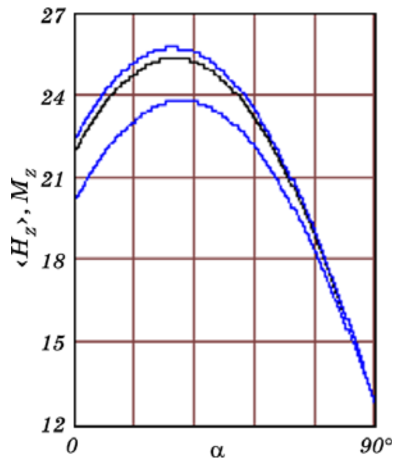

Fig. 4. Dependences of average field $\langle H_Z \rangle$ on the angle α in the narrow gap between two cylindrical magnets with radial and axial components of magnetization (upper curve). Middle and lower curves represent the dependences of $\langle H_Z \rangle$ on α for quasi-nonuniform systems with 8 and 4 sectors, respectively.

provide high values of special field.

3. CONCLUSION

Various magnet systems for refrigerators on the base of materials with giant magnetocaloric effect MCE were analysed. The specific magnetic field H_{SP} was introduced as a new parameter for characterization of stray fields generated by the systems. It was shown that the system consisting of monolithic magnets in the form of cylindrical discs with radial and axial components of magnetization is the most optimal from three systems considered and provides field generation with the highest values of the specific field. For such systems, H_{SP} reaches $5.2M_S$. It was also found that a quasi-nonuniform system, in which discs are composed of uniformly magnetized sectors, should generate stray field with high values of H_{SP} close to corresponding values of special field for the systems of monolithic cylindrical discs, in which the distribution of magnetization is characterized by radial and axial components.

REFERENCES

1. F. M. Tishin, *Handbook of Magnetic Materials. Vol. 12* (Ed. K. H. J. Bushow) (Elsevier Science B.V.: 1999).
2. F. I. Abramovich, A. V. Michurin, O. Yu. Gorbenko, and A. R. Kaul', *Phys. Solid State*, **43**: 687 (2001).
3. S. J. Lee, J. M. Kenkel, V. K. Pecharsky, and D. C. Jiles, *J. Appl. Phys.*, **91**:

8894 (2002).
4. S. Gama, A. Coelho, A. Campos et al., *Phys. Rev. Lett.*, **93**: 237202 (2004).
5. Yi Long, Chen Yanping, Li Lihui et al., *Chinese Science Bulletin*, **48**, No. 17: 1791 (2003).
6. S. V. Vonsovskiy, *Magnetism* (Moscow: Nauka: 1971) (in Russian).
7. V. N. Samofalov, D. P. Belozorov, and A. G. Ravlik, *J. Magn. Magn. Mater.*, **320**, No. 8: 1490 (2008).
8. V. N. Samofalov, A. G. Ravlik, D. P. Belozorov, and B. A. Avramenko, *J. Magn. Magn. Mater.*, **281**: 326 (2004).
9. K. P. Belov, M. A. Belianchikova, R. Z. Levitin, and S. A. Nikitin, *Rare-Earth Ferro- and Antiferromagnetics* (Moscow: Nauka: 1965) (in Russian).
10. K. P. Belov, *Magnetocaloric Phenomena in Rare-Earth Magnetics* (Moscow: Nauka: 1990) (in Russian).
11. K. Halbach, *J. Appl. Phys.*, **57**, No. 1: 3605 (1985).