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STUDY OF SUITABLE ARRANGEMENT OF MAGNETIC CIRCUITS FOR REALIZATION OF MAGNETOCALORIC EFFECT

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Abstract: *The paper is stimulated by one of very prospective physical domains – magnetic cooling based on the magnetocaloric effect. Successful realization of this effect requires a magnetic circuit with permanent magnets producing very strong and uniform magnetic field and the paper deals with arrangements of such circuits. Its crucial point consists in the presentation and consequent discussion of the results that allow estimating the suitability of the considered magnetic circuits.*

Key words: *Magnetocaloric effect, magnetic field, permanent magnets, finite element method.*

Introduction

Numerous natural and technical applications work with strong and uniform magnetic fields. In some of them fields of such properties are produced by a system of permanent magnets. A very prospective domain taking advantage of this conception is magnetic cooling [1] based on the magnetocaloric effect (MCE). This effect was observed in case of a number of magnetic materials subjected to variations of magnetic field. The MCE is characterized by a change of temperature (on adiabatic conditions) or a change of entropy (at an isothermic change with delivery or removal of heat). The change of temperature and amount of the transferred heat depends on the material composition, absolute temperature, and magnetic field. The MCE is best observable in the neighborhood of the magnetic phase transition temperature when a ferromagnetic material changes into paramagnetic one and vice versa.

For practical applications of the MCE it is necessary to realize a series of changes repeated in a certain cycle. Generally, cooling is achieved by a cyclic magnetization and demagnetization of a suitable diamagnetics, for example gadolinium pellets. Every cycle of magnetic cooling consists of four changes: magnetization, demagnetization and two more changes. We distinguish several kinds of these cycles that are called by the names of their authors: Carnot, Stirling, Ericsson, and Brayton [2]. The most suitable cycles for moderate cooling are considered those of Ericsson and Brayton. Particulars of the cooling cycle (that is schematically shown in Fig. 1) described in [3] that represents a predecessor of this paper.

Such a cycle may be achieved by periodical movement (shift or rotation) of the material inside and outside strong magnetic field. Generation of such a strong field may advantageously be realized by an appropriate magnetic circuit excited by permanent magnets. The crucial point of the paper is a study of suitable arrangement of such a magnetic circuit.

1 Formulation of the problem

As stated above, the aim of the paper is to find an appropriate arrangement of magnetic circuit with permanent magnets suitable for MCE with periodic linear motion of working medium, for example gadolinium pellets. Such a circuit must contain a working chamber where

- magnetic field reaches sufficiently high values and is sufficiently uniform,
- allows rotational or periodically linear motion of the working material.

The starting arrangements of the considered circuit are in Figs. 2a and 2b. While Fig. 2a depicts an asymmetric magnetic circuit for the rotational movement of the magnetic medium, Fig. 2b shows symmetric magnetic circuit for the linear movement.

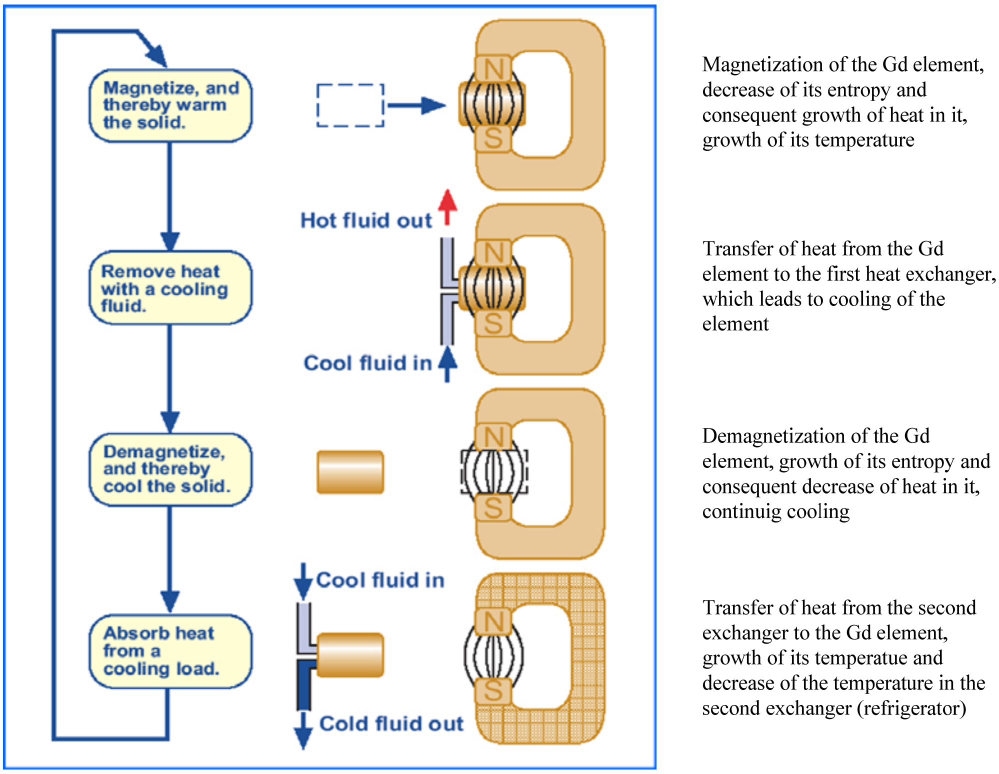


Fig. 1: Scheme of the cooling cycle

The circuits contain:

- Permanent magnets of type NdFeB (Grade GSN-40, Anisotropic Sintered [4]) whose basic physical parameters are listed in Tab. 1
- Focusators and bypasses (functioning also as shielding elements) made from carbon steel CSN 12 040. For its characteristic $B(H)$ see [5] and Fig. 3.

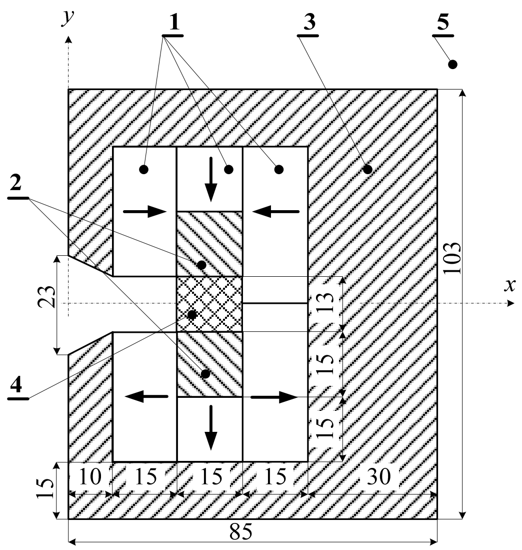


Fig. 2a: Starting arrangement of the magnetic circuit for the rotational movement
1 – *permanent magnets,* **2** – *Fe-focusators,* **3** – *Fe-bypass (shielding element),* **4** – *working chamber,* **5** – *air*

2 MATHEMATICAL MODEL

Magnetic field in the magnetic circuits depicted in Figs. 2a or 2b generated by a system of permanent magnets of the given remanence $\boldsymbol{B}_\mathrm{r}$ and coercive force $\boldsymbol{H}_\mathrm{c}$ is generally described by partial differential equation for magnetic vector potential $\boldsymbol{A}$ in the form [6]

$$\operatorname{curl}\left(\frac{1}{\mu}\operatorname{curl}\boldsymbol{A}-\boldsymbol{H}_\mathrm{c}\right)=\mathbf{0}\,. \qquad (1)$$

Tab. 1: Physical parameters of permanent magnets NdFeB (Grade GSN-40)

Parameter	Value
coercive force H_c	9.555×10^5 A/m
magnetic remanence B_r	1.27 T
maximum working temperature T_w	150 °C
relative permeability μ_r	1.0577

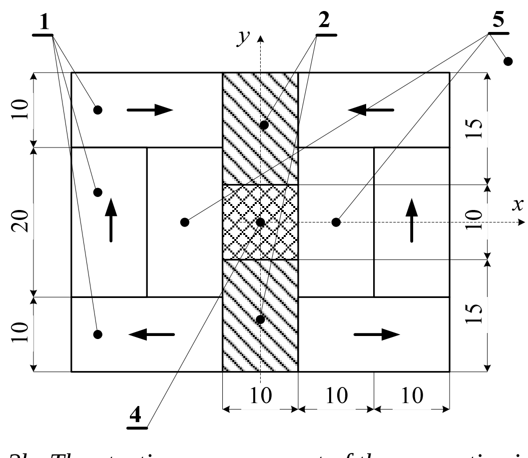


Fig. 2b: The starting arrangement of the magnetic circuit for the linear movement (positions see Fig. 2a)

The task is formulated as a 2D problem in Cartesian coordinate system x, y, so that $\boldsymbol{A} = \mathbf{i}\cdot 0 + \mathbf{j}\cdot 0 + \mathbf{k}\cdot A_z$. The coercive force $\boldsymbol{H}_\mathrm{c}$ in (1) appears only in the domain of permanent magnets **1**. Magnetic permeability μ must be respected in the domain of permanent magnets where its value $\mu = |\boldsymbol{B}_\mathrm{r}| / |\boldsymbol{H}_\mathrm{c}| = \mathrm{const}$ and in focusators **2** and bypass **3** where $\mu = B/H = \mu(B)$ must be found from the characteristic in Fig. 3.

Magnetic field is bounded by the artificial boundary Γ_∞ sufficiently distant from the investigated system. The boundary condition along this boundary is of Dirichlet's type and reads

$$A_z(\Gamma_\infty) = 0\,. \qquad (2)$$

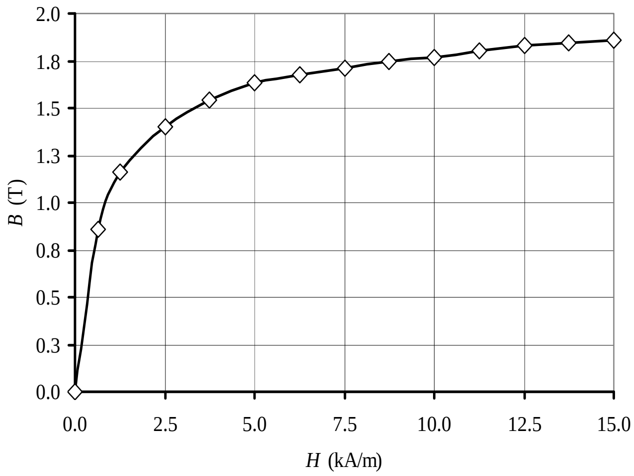


Fig. 3: Magnetization characteristic of carbon steel CSN 12 040

This equation was solved by the finite element method using commercial code QuickField [6] supplemented with a number of own procedures and scripts. Checked were both the position of the fictitious boundary Γ of the definition area and numerical convergence of the results. For achieving accuracy on the level of three nonzero digits during the calculation of the average value of magnetic flux density $\boldsymbol{B}_\mathrm{a}$ in the working chamber **4** it was necessary to use a mesh with about 90000–100000 nodes, in the dependence on the particular shape of the magnetic circuit.

For illustration, Figs. 4a and 4b show the distribution of magnetic field generated by the "initial" magnetic circuit in Fig. 2a, both with and without focusators.

3 RESULTS AND THEIR DISCUSSION

In order to meet the goals of this paper – to evaluate the influence of arrangement of the considered magnetic circuits on the distribution of magnetic field (and the average value of magnetic flux density $|\boldsymbol{B}_\mathrm{a}|$) in the working chamber **4** (see Figs. 2a and 2b), we numerically analyzed a number of arrangements with mutually differing geometrical dimensions of the Fe-bypass, Fe-focusators and permanent magnets. The results are summarized in Tabs. 2a and 2b in the forms of maps of the corresponding magnetic fields.

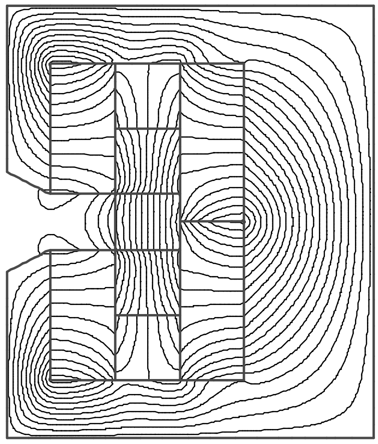


Fig. 4a: Distribution of force lines in the system corresponding to the initial arrangement with shielding bypasses

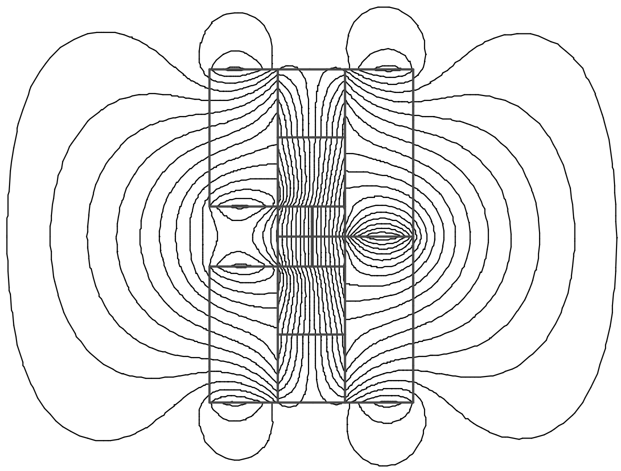
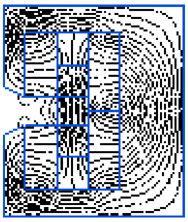
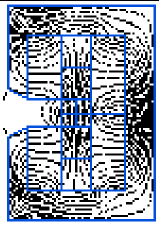
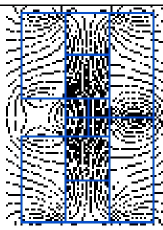
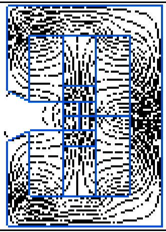
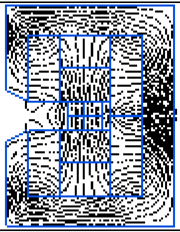
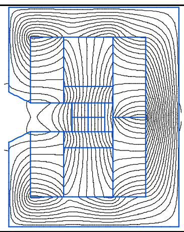
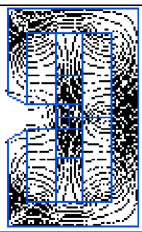
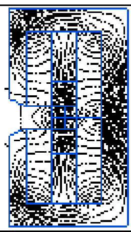
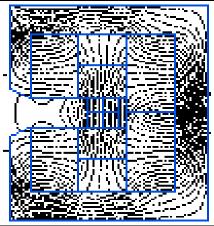


Fig. 4b: Distribution of force lines in the system corresponding to the initial arrangement without shielding bypasses

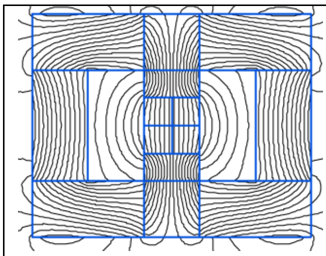
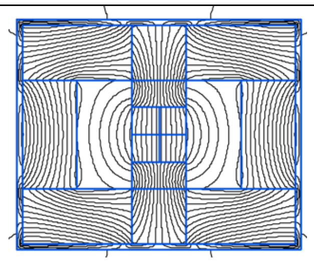
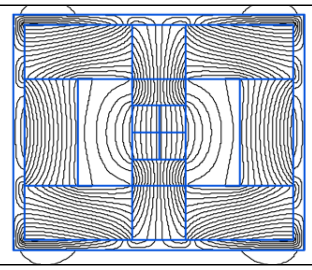
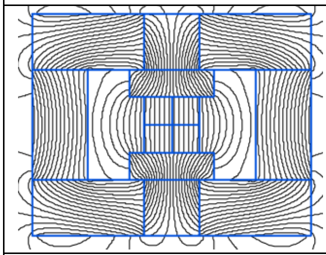
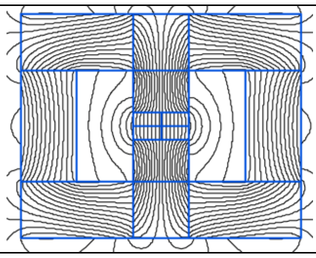
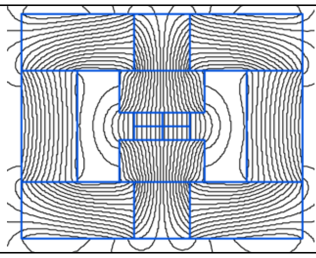
The results listed in Tabs. 2a and 2b lead to the following conclusions:

- Magnetic circuits manufactured from the same permanent magnets of larger dimensions produce greater magnetic field in the working chamber (compare Figs. 2a and 2b and also Tab. 2a,I and Tab. 2b,I – the initial arrangement. It is due to higher potential magnetic energy accumulated in the circuit. This energy is manifested by higher magnetic flux density in its local part (working chamber) in comparison with magnetic flux density in the equally large and equally positioned local part that is, however, assigned to a smaller magnetic circuit, with smaller total energy.
- The influence of the focusators (compare Figs. 2a and 2b, item **2**) is equal both in the case of the asymmetric and symmetric arrangements – a shorter and wider focusator is (from the viewpoint of magnetic flux density in the working chamber of the corresponding magnetic circuit) more advantageous, see Tab. 2a,II and 2a,IV, or Tab. 2b,IV and 2b,V. It is due to higher magnetic resistance of such a focusator, which results in positive changes of magnetic flux and its density in the working chamber.

Tab. 2a: The influence of the magnetic circuit on magnetic flux density in its working chamber (asymmetric versions, for the initial arrangement see Fig. 2a)

				
I. Initial arrangement, see Fig. 2a $B_a = 1.438\,\mathrm{T}$	II. Right-hand shielding narrowed by 50 % $B_a = 1.406\,\mathrm{T}$	III. Without shielding $B_a = 1.084\,\mathrm{T}$	IV. Focusators shortened by 50 % $B_a = 1.409\,\mathrm{T}$	V. Focusators broadened by 50 % $B_a = 1.286\,\mathrm{T}$
				
VI. Focusators broadened by 50 %, and shortened by 50 % $B_a = 1.310\,\mathrm{T}$	VII. Magnets prolonged by 25 %, $B_a = 1.549\,\mathrm{T}$	VIII. Magnets prolonged by 50 %, $B_a = 1.629\,\mathrm{T}$	IX. Magnets in the initial length, broadened by 50 %, $B_a = 1.351\,\mathrm{T}$	

Tab. 2b: The influence of the magnetic circuit on magnetic flux density in its working chamber (symmetric versions, for the initial arrangement see Fig. 2b)

		
I. Initial arrangement, see Fig. 2b $B_a = 0.936\,\mathrm{T}$	II. With shielding of thickness 1 mm $B_a = 0.896\,\mathrm{T}$	III. With shielding of thickness 2 mm $B_a = 0.859\,\mathrm{T}$
		
IV. Without shielding, focusators longer by 50 % $B_a = 0.822\,\mathrm{T}$	V. Without shielding, focusators broader by 50 % $B_a = 1.190\,\mathrm{T}$	VI. Without shielding, focusators broader and longer by 50 % $B_a = 1.009\,\mathrm{T}$

- The influence of the magnetic shielding – Fe bypass (see Figs. 2a and 2b, item 3) is opposite in the case of the asymmetric shielding with respect to the symmetric magnetic circuit. The ground lies in the fact that in the case of the symmetric circuit the shielding ferromagnetic shell is closed and a part of the magnetic flux generated by the permanent magnets closes in it instead of closing through the focusators and working chamber, i.e., through the branches with higher magnetic resistance (see Figs. 2b,I and 2b,II in Tab. 2b). On the other hand, in the case of the asymmetric arrangement the permanent magnets are oriented in such a manner that the magnetic flux is (due to open shielding ferromagnetic shell) forwarded to the focusators and, consequently, to the working chamber. When, however, the shielding shell does not exist, the magnetic flux leaks to ambient air, i.e., to a medium with higher magnetic resistance. The magnetic flux density in the chamber is them smaller (see Tab. 2a,II and Tab. 2a,III). But with the growing thickness of the ferromagnetic shell this positive effect decreases (even when it permanently exists, see Tab. 2a,II and Tab. 2a,I).

The results presented in Tabs. 2a and 2b together with the above conclusions allow suggesting a magnetic circuit securing successful realization of the magnetocaloric effect.

4 CONCLUSION

The paper shows that contemporary computing art allows finding a suitable arrangement of magnetic circuit with permanent magnets for realization of the magnetocaloric effect. Nevertheless, the presented, numerically obtained conclusions should be confirmed by relevant experiments. On the other hand, the experiments can start from the above results and, therefore, they can be relatively simple.

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