OPTIMIZATION OF THE MAGNETIC FIELD IN A MAGNETIC REFRIGERATOR

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Key words: magnetic refrigeration, magnetic field, permanent magnets, FEMM program, Hall sensor

Abstract: In this article we describe the development and the optimization of the structure for generation the magnetic field in the magnetic refrigerator. This refrigerator is located in the Laboratory for Refrigeration (LHT) at the Faculty of Mechanical Engineering, University of Ljubljana. Initially, we carried out a numerical simulation of the magnetic field that is generated by the structure, using the FEMM program, and then optimized its geometry. In the second part, we analyzed measurements of the magnetic field density in the device, using a magnetometer with a three-axis Hall sensor, with the aim of confirming the numerical results. The values of the magnetic field density were 0.97 T (measured) and 0.98 T (numerical). At the same time we were able to confirm the suitability of the FEMM program for estimating the static magnetic field, which is generated with magnetic circuits.

Optimiranje magnetnega polja v magnetnem hladilniku

Kjučne besede: magnetno hlajenje, magnetno polje, permanentni magneti, program FEMM, Hallova sonda

Izvleček: Članek prikazuje razvoj in optimiranje strukture za ustvarjanje magnetnega polja v magnetnem hladilniku, ki smo ga izdelali v Laboratoriju za hladilno tehniko (LHT) na Fakulteti za strojništvo, Univerza v Ljubljani. Sprva smo izvedli numerično simulacijo magnetnega polja, ki ga takšna struktura ustvarja (program FEMM) ter na osnovi tega tudi optimizacijo same geometrije strukture. V drugem delu smo, v želji po potrditvi numeričnih rezultatov, prikazali še meritve gostote magnetnega pretoka v magnetnem hladilniku (magnetometer s tri-osno Hallovo sondo). S tem smo v celoti ovrednotili obravnavano strukturo ter prišli do zaključka, da le-ta ustvarja 0,97 T (izmerjeno) oziroma 0,98 T (numerično) gostote magnetnega pretoka. Hkrati smo potrdili primernost programa FEMM za oceno vrednosti statičnega magnetnega polja, ki ga ustvarjajo strukture na osnovi magnetnih krogov.

1. Introduction

Magnetic refrigeration at room temperature is a new, developing technology for refrigeration that could, in the next few years, represent a viable alternative to the vapor-compression refrigeration technology in widespread use today. It is important to realize that, despite continuous development, classical, vapor-compression refrigeration technology is still very energy inefficient and its operation makes use of ozone-depleting refrigerants.

For these reasons researchers and engineers working in refrigeration have started to investigate new technologies for refrigeration, among which the most promising is magnetic refrigeration. Magnetic refrigerators can be 15-20% more efficient than classical refrigerators, using a magnetocaloric material as the refrigerant and water, or even air, as the heat-transfer fluid.

Magnetic cooling has been widely used for refrigeration at very low temperatures, i.e., cryogenic refrigeration, for a long time, but in recent years magnetic refrigeration technology has become interesting for refrigeration at room temperature, too. This is due to the development of new magnetocaloric materials, including gadolinium (Gd) and its alloys and other magnetocaloric materials that exhibit the so-called giant magnetocaloric effect.

Magnetic refrigeration is based on the magnetocaloric effect, which is defined as the change in temperature of a material as it is subjected to an external magnetic field. So in addition to the magnetocaloric material a basic magnetic refrigerator requires the generation of a magnetic field in an air gap, where the magnetocaloric material can be situated during the operation of the magnetic refrigerator.

In general, we can generate a magnetic field in two ways. For the generation of a large magnetic field density, e.g., a few Tesla, we need to use electromagnets or even superconducting magnets; however, they consume a large amount of additional energy for their operation and, in general, they are expensive and have a large volume and mass. Another way to generate a magnetic field is to use permanent magnets, which can generate lower magnetic field densities than electromagnetic devices, but they do not consume any additional energy during their operation, which is a great advantage over electromagnetic devices. In the past few years, investigations have concentrated on developing stronger permanent magnets and constructing ferromagnetic cores for the generation of a magnetic circuit through an air gap.

2. The basis of magnetic refrigeration

The development of magnetic refrigeration started with the discovery of the magnetocaloric effect by Warburg in 1881 /1/. The magnetocaloric effect is now very well investigated and is applied in a variety of fields in cryogenics, i.e., refrigeration at temperatures below -70°C. However, in the past few years the use of the magnetocaloric effect and magnetic refrigeration at room temperature has become increasingly interesting. The main reason for this was the discovery and development of new materials and technologies that offered the possibility of many applications in magnetic refrigeration for industrial and domestic situations.

A magnetic refrigerator is composed of a porous magnetocaloric material, the so-called active magnetic regenerator (AMR), which is the "heart" of the magnetic refrigeration device. The basic elements of a magnetic refrigerator are the device for generating the magnetic field, two external heat exchangers and a heat-transfer fluid, which is used to transfer the heat from the magnetocaloric material over the external heat exchangers to the surroundings.

A magnetic refrigerator performs four basic processes during its operation. In general, a magnetic refrigeration cycle consist of the magnetization and demagnetization processes, which are achieved by changing the external magnetic field, and two other, middle, processes of fluid flow from a cold heat exchanger over the magnetocaloric material to a hot heat exchanger and vice versa.

2.1. The magnetocaloric effect

We can view the magnetocaloric effect as the heating or cooling of a magnetocaloric material as it is subjected to an external magnetic field.

For a better understanding of the magnetocaloric effect and its application in magnetic refrigeration, let us consider an adiabatic system or an isolated magnetocaloric material (Fig. 1). When the magnetocaloric material is not exposed to a magnetic field the magnetic moments in the material are disordered or randomly orientated. However, when a magnetic field is applied, the magnetic moments become oriented in the direction of the applied magnetic field. From the magnetic point of view the system has reduced magnetic entropy, which means that in an adiabatic system the temperature of the material must increase in compliance with the law of the conservation of energy. We can see the reverse process taking place when we remove the magnetocaloric material from the magnetic field, and the magnetic moments revert to random orientations, which causes an increase in the magnetic entropy and a corresponding decrease in the temperature. As a result of this the system cools down.

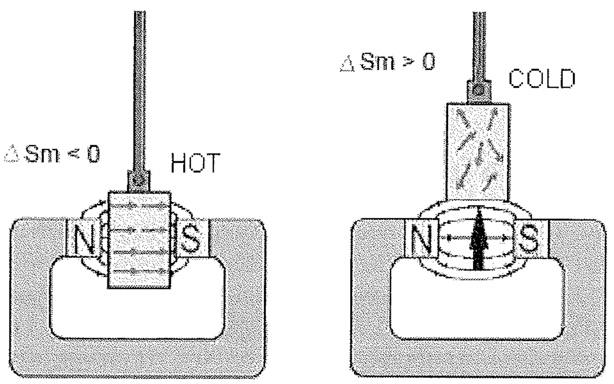

Fig. 1: Schematic illustration of the magnetocaloric effect

3. The form of permanent magnets for the generation of a magnetic field in a magnetic refrigerator

So far there have been 17 prototype magnetic refrigerators built and tested with the magnetic field being generated with permanent magnets. Of these 13 magnetic refrigerators had the magnetic field sources designed on the basis of a classical magnetic circuit and 4 had magnetic refrigerators designed on the basis of a Halbach array. /2/

3.1. Magnetic circuit

In general, the magnetic circuit is designed with a magnetic field source, which in our case was a high-quality permanent magnet, a magnetic flux conductor, usually a soft ferromagnetic material that conducts and directs the magnetic flux, and an air gap, which provides access to the generated magnetic field. A typical example of a magnetic circuit is shown in Fig. 2. The basic purpose of the magnetic circuit is to generate as large a magnetic field density in the air gap as possible. This is achieved by directing the magnetic flux in such a way that it forms a closed path, with the losses being as small as possible. In order to generate the largest possible magnetic field density in the air gap, this gap should be as small as possible to reduce the losses of the magnetic flux to the surroundings.

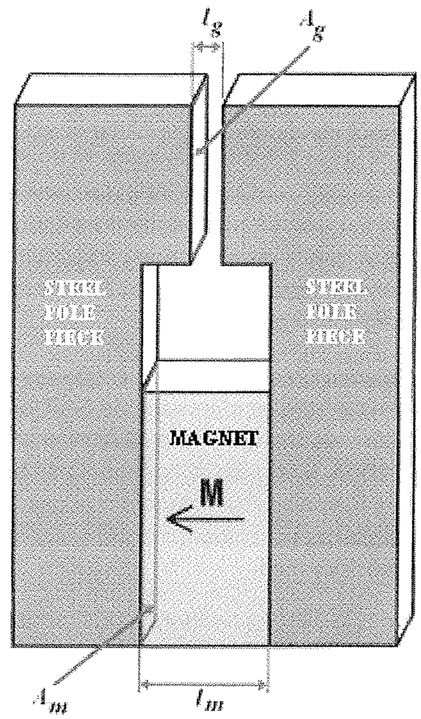

Fig. 2: Example of a simple magnetic circuit

3.2. Halbach array

Conventional structures of permanent magnets, like the magnetic circuit in Fig. 2, can generate a magnetic field density of up to 1 T in the air gap. Until the discovery of the so-called Halbach array in the 1970s, to generate larger magnetic field densities (of about 2 T and more) required the use of electromagnetic devices. However, permanent magnets arranged in a Halbach array can achieve magnetic field densities that were previously only possible with an electromagnet.

The basic concept of a Halbach array is in the structure of several permanent magnets that are magnetized in such a way as to cooperate in generating a stronger, more coherent magnetic field density, which can be even larger than the remanence of the permanent magnets being used. A circular Halbach array, which is the basis of some structures for the generation of a magnetic field in a magnetic refrigerator, is shown in Fig. 3. /3/

With the discovery of the Halbach effect a lot of researchers from all over the world started to investigate the effect and its applications. Since then there have been many modified Halbach arrays, with which even larger magnetic field density than are possible with the classical circular Halbach array have been reported. In the early 1990s Leupold et al. /4/ presented the possibility of augmenting the magnetic field density in the air gap by using a soft ferromagnetic material in the air gap of a circular Halbach array.

The development of magnetic refrigerators has indicated that modified Halbach arrays are very convenient for the needs of magnetic refrigeration. Among the modified Halbach arrays that are the most promising for magnetic refrigeration, two in particular stand out. Both were developed by Lee et al. /5, 6/ and could generate about 2.5 T of magnetic field density in a 10-mm air gap.

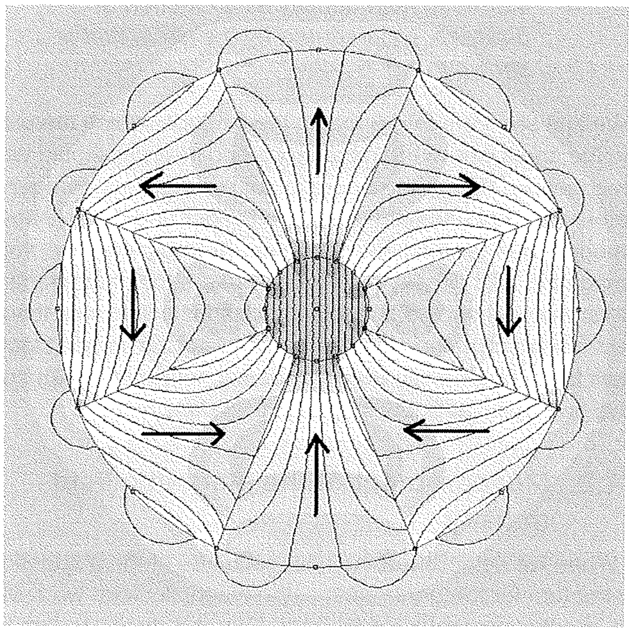

Fig. 3: Magnetic field density generated with a circular Halbach array of 8 permanent magnets

4. Development and analysis of the magnets' structure for the generation of a magnetic field in the magnetic refrigerator in the LHT

The generation of a magnetic field in the device for magnetic refrigeration in the Laboratory for Refrigeration (LHT) in the Faculty of Mechanical Engineering is designed on the basis of two parallel magnetic circuits (Fig. 5). This geometry was chosen based on price and the future trends in the development of magnetic refrigeration, which is focused on the development of rotating magnetic refrigerators with several regions of large magnetic fields /2/. In this way we can ensure a higher operating frequency of the magnetic refrigerator.

First, we carried out a numerical simulation of the magnetic field that is generated by the magnet structure and then we measured the magnetic field, with the intention being to confirm the numerical results. In this way we obtain the exact values of the magnetic field density in the magnet structure.

4.1. Numerical simulation

The finite-element method is the most useful way to numerically simulate a magnetic field because there are several commercial programs that can solve very complex problems without the need to develop specific algorithms. We decided to use the FEMM (Finite Element Method) program for the numerical simulation of the magnetic field. FEMM is able to solve two-dimensional, low-frequency electromagnetic problems /7/. In its solving phase the program solves the appropriate Maxwell equations for each node of the numerical mesh. The Maxwell equations are a system of six equations that describe the electromagnetic field. We only work with a static magnetic field, so only three of the Maxwell equations are required in our case. If we consider the magnetic vector potential (A_{mag}), we could write down only one equation, which is the basis for the numerical simulation of a static magnetic field with the FEMM program /7/:

$$\nabla \times \left(\frac{1}{\mu_0} \nabla \times \vec{A}_{mag} \right) = \vec{j} \tag{1}$$

Where μ_0 is the permeability of a vacuum, which is $4\pi \cdot 10^{-7}$ H/m, and j is the electric flux density.

We simulated the magnetic field that is generated by the structure of permanent magnets and soft ferromagnetic material with the FEMM program. First, we had to optimize the geometry, because we want to use the minimum amount of material, and at the same time we want to have the strongest magnetic field possible in the air gaps, which means in the areas where the magnetocaloric material would be magnetized, and the smallest magnetic field possible in areas where the magnetocaloric material would be demagnetized. We also optimized the height of the air gaps, because from the magnetic point of view we want to have the smallest air gap, but from the refrigeration point of view we want to use the largest amount of magnetocaloric material possible, and so for this reason we need to have the largest air gap possible. The optimization was performed by plotting charts of average magnetic field density in the air gap as a function of the different dimensions of the basic parts of the structure (the width and the height of the magnet, the thickness of the external ring and the height of the air gap) /8/. The scheme of the structure with optimized dimensions is shown in Fig. 4 in two-dimensional form. The depth of the structure in axial direction is 170 mm (external ring) and 90 mm (magnets and inner yoke), while in area of air gaps it is further focused on 55 mm.

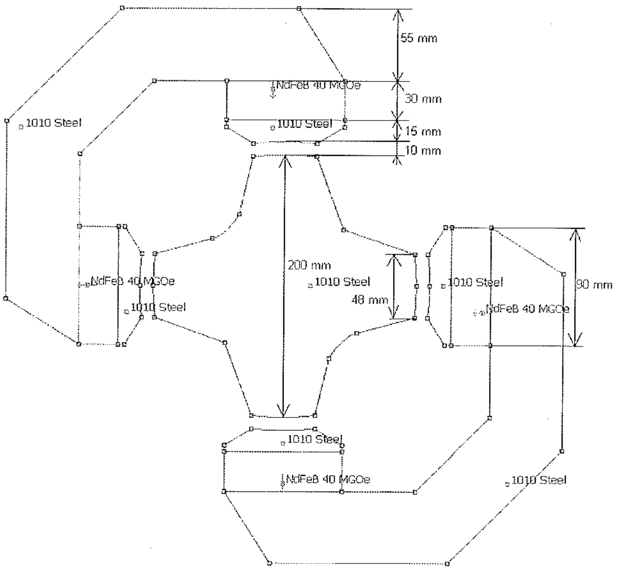

Fig. 4: The scheme of the structure for generating the magnetic field with marked optimized dimensions and used materials

The magnet structure is designed on the basis of four neodymium-iron-boron permanent magnets (Nd-Fe-B with 40 MGOe maximum energy product). These magnets are currently some of the strongest permanent magnets available, based on their maximum energy product, which is the most important factor when selecting a permanent magnet. As a soft ferromagnetic material for conducting and focusing the magnetic flux we used low-carbon 1010 steel, which is magnetically not ideal, but we chose it because of its low price and good forming properties. The structure has four air gaps with a strong magnetic field and four areas of low magnetic field where the magnetocaloric material is circulating during the operation of the magnetic refrigerator.

After defining the final geometry of the magnetic structure we simulated the magnetic field that is generated by it. When the program completed the calculations the results were outputted in graphical form with the distribution of the magnetic field density (Fig. 5) or with a graph of the magnetic field density (B) as a function of distance (Fig. 6); this represents the circle where the magnetocaloric material would be placed during the operation of the magnetic refrigerator and is shown in Fig. 5.

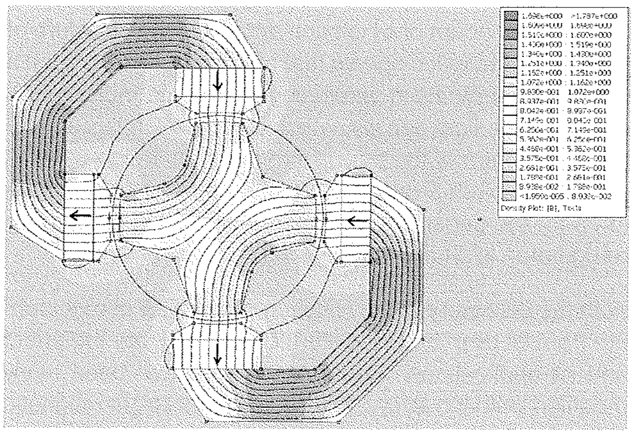

Fig. 5: Distribution of the magnetic field density

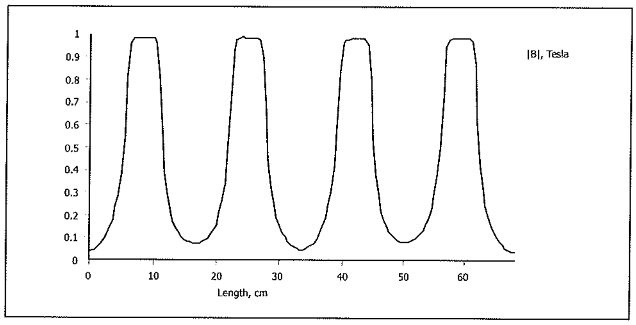

Fig. 6: Magnetic field density as a function of distance, represented by the circle that is shown in Fig. 5

We can see from Fig. 6 that in the air gaps, which means in the areas where the magnetocaloric material should be magnetized during the operation of the magnetic refrigerator, the magnetic field density is 0.98 T and suitably homogeneous for efficient operation. At the same time the magnetic field density in the areas where the magnetocaloric material should be demagnetized is a little less than 0.05 T, which means that the magnets and the carbon steel are far enough away from the demagnetization areas so we have a suitably low magnetic field density.

4.2. Measurement of the magnetic field density

When we established the final geometry of the magnetic structure for the generation of the magnetic field, we built it into the magnetic refrigerator. Out of a desire to know accurately the magnetic field we also measured the magnetic field density in the magnet structure.

The measurements were made using a three-axis magnetometer with an integrated three-axis Hall probe (SENIS transducer x-H3x-xx_E3D-2.5kHz-0.1-2T /9/), which is the most appropriate for this kind of measurement because of its accuracy and small dimensions.

The structure and the measurement points are shown in Fig. 7 (the front supporting plate covers the view to the basic elements of the structure). The magnetic field density was measured at 40 measuring points, which are marked in Fig. 7. The measurement points are arranged in such a way that three measurement points are in the middle of each air gap, two in the internal edge and two in the external edge of each air gap, while three measurement points are in each demagnetizing area. In this way we cover the whole of the circle in which the magnetocaloric material is situated.

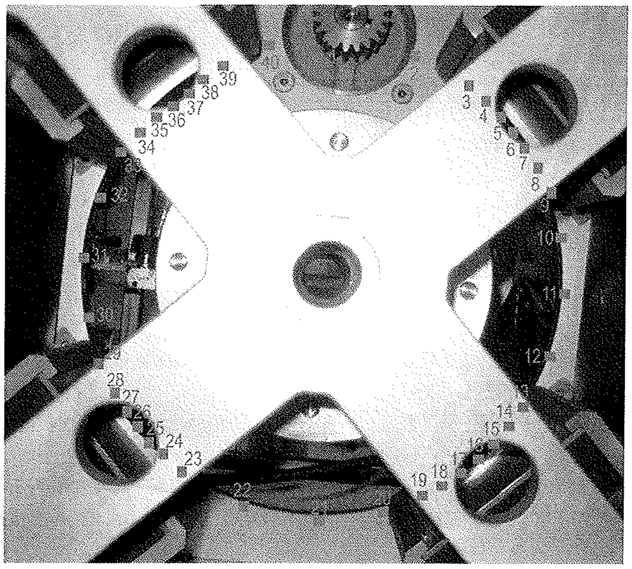

Fig. 7: Structure for generating the magnetic field in the magnetic refrigerator and the points where the measurements were made

At each of the marked measurement points we measured the magnetic field density and the results are shown in Fig. 8. For comparison the results obtained with the FEMM program are also presented in Fig. 8.

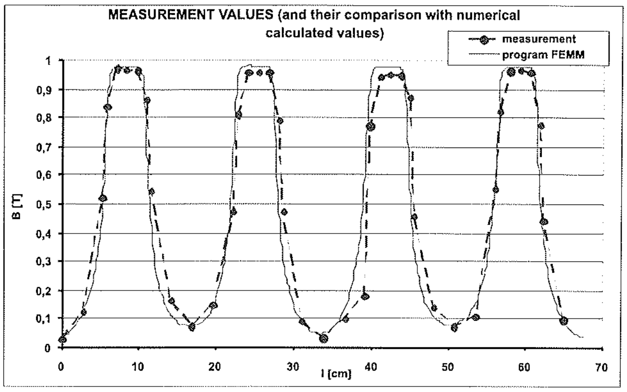

Fig. 8: Magnetic field density in the structure

It is clear that the magnetic field density in the air gaps is 0.97 T and in the demagnetizing areas it is around 0.05 T.

In addition, to estimate the homogeneity of the magnetic field density in the air gaps, which is very important for the efficient operation of the magnetic refrigerator, we also measured the magnetic field density at different heights (radial direction) and depths (axial direction) of the air gaps. We concluded that the magnetic field density varies a lot with the height in the air gap. In the middle of the air gap the magnetic field density was almost perfectly homogenous (Fig. 8), but close to the magnets and far from the magnets, which means on the upper and lower edges of the air gaps, the homogeneity of the magnetic field density is much worse and varies in the air gaps by as much as 0.2 T. At the same time the homogeneity of the magnetic field density is much better for different depths of the air gaps, because at the front and back edges of the air gaps the magnetic field density is 0.95 T.

The uncertainty in the measurement results is a combination of two factors. First, is the uncertainty due to the accuracy of the magnetometer, which is 0.1 % of the linear measurement range (0-2 T). On this basis we can calculate the relative measurement uncertainty due to the accuracy of the magnetometer, which is between ±0.1 % and ±2.3 %. The accuracy is the poorest in the air gaps and the best in the demagnetizing areas, where the values of the magnetic field densities are the smallest.

Second, is the uncertainty that is caused by the positioning of the magnetometer's probe during the measurement. We were not able to use mechanical positioning because of the compactness of the structure, which is why the measurement was made manually. The inaccuracy due to the positioning of the probe is the main contribution to the uncertainty of the measured values in the intermediate areas, where the inhomogeneity of the magnetic field density is at its greatest, whereas in the air gaps and the demagnetizing areas, because of the good homogeneity, the error in the positioning was negligible. We were able to estimate the absolute accuracy due to the positioning of the probe as ±2.5 mm. On this basis and with the distribution of the magnetic field density in the intermediate areas we calculated the relative measurement uncertainty in the intermediate areas due to the positioning of the probe to be between ±5 % (near the air gaps) and ±46 % (near the demagnetizing areas). This latter value is large and so in those areas the measured results are clearly not very accurate.

5. Conclusion

If we compare the results obtained with the FEMM program and the measured values of the magnetic field density (Fig. 8) we can conclude, on the basis of the numerical results, that our structure provides a 0.93 T change in the magnetic field density. On the basis of the measurement results the structure provides a 0.92 T change. The small difference between the values means that the agreement is very good, and so we can confirm the suitability of the FEMM program for estimating the magnetic field that is generated by the symmetrical magnetic circuits. The difference between the measured and the calculated values is in the range of the measurement uncertainty of the magnetometer we used and the uncertainty due to the positioning of the Hall probe. Furthermore, the reason for the deviation of the results can be attributed to three sources of error. First, is that the FEMM program allows only two-dimensional simulations, which can cause some error. Second, is that some changes were made to the structure, i.e., the inhomogeneity of the structure (e.g., the screws and the holders for the magnets), but these were not considered in the simulation. Third, we did not know accurately the properties of the permanent magnets and the carbon steel that were used in the simulation. This is why we used these assumed materials in the simulation.

With the development and analysis of the structure we were able to obtain sufficiently accurate values for the change in the magnetic field density that is possible with this magnet structure. This represents the basic information for further analyses and research on our magnetic refrigerator.

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Prispelo (Arrived): 12.03.2009 Sprejeto (Accepted): 09.06.2009