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STUDY INTO THE MAGNETIC FIELD FOR A MAGNETOCALORIC COOLING SYSTEM WITH THE USE OF MAGNETOVISION

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Summary

The paper presents measurements of the magnetic field intensity of a magnet used to generate a magnetic field in a magnetocaloric cooling system. The magnet – a Halbach array consisting of several permanent magnets – is cylindrical with a hole in the centre. The special arrangement of these magnets concentrates the magnetic field in the inner gap. The generated magnetic field was examined with the aid of a magnetovision system designed in our laboratory. The investigations confirmed that a magnetic field of 1 T is produced in the hole. In the magnetic pictures one can observe how the direction of magnetic field vector is changing. In addition, the influence of magnetic field screen on the magnetic field range was analysed.

Key words: *experimental mechanics, magnetocaloric effect, magnetic refrigeration, magnetic scanning, magnetovision, Halbach array*

1. Introduction

Magnetic refrigeration is a new method of cooling which is based on the application of magnetic field. The refrigeration results from a change in the magnetic entropy of a magnetocaloric material. When the magnetocaloric material enters the magnetic field, its temperature rises in a split second and at the same time its magnetic entropy decreases. Then the magnetocaloric material leaves the magnetic field. This process leads to a sudden drop in the temperature of the material and an increase in its magnetic entropy. This phenomenon is most pronounced at the Curie temperature which is specific for each material.

The first information about the magnetocaloric effect dates back to 1881 [1]. At that time, Warburg noticed that an iron specimen changes its temperature when placed inside a magnetic field. Initially, the magnetocaloric effect was used in cryogenics. On the basis of this phenomenon, in 1933, a temperature below 1 K was obtained for the first time [2]. In 1949, W. Giauque was awarded the Nobel Prize in chemistry for his contribution to this achievement. A pioneering magnetic refrigerator working at room temperature was built in

1976 [3]. A magnetocaloric material – gadolinium – was used as coolant, while a magnetic field of 7 T was generated by a superconducting magnet.

An important moment in the development of the magnetocaloric effect was the discovery of the giant magnetocaloric effect in the $Gd_5Si_2Ge_2$ alloy in 1997 [4]. Changes in the magnetic entropy observed in this material are more than two times bigger than in gadolinium which is treated as a reference material. The increase in the effect is caused by the fact that the magnetic change is accompanied by a reconstruction of the crystal lattice. This material undergoes a first order phase transition whereas gadolinium undergoes a second order phase transition. In the successive years, a number of other alloys with the giant magnetocaloric effect were discovered, such as MnAsSb [5], NiMnGa [6] and LaFeSi [7]. The disadvantage of these materials is a narrow range of temperatures in which the magnetocaloric effect occurs.

The discovery of the giant magnetocaloric effect has led to the increasing interest in the topic of magnetic refrigeration and has resulted in the intensive development of magnetic refrigerators. So far, several dozens of prototype systems have been created [8]. The most advanced devices can achieve over 2000 W of cooling power [9] and over 20°C of temperature difference between the cold and the hot heat exchanger [10, 11, 12].

Magnetocaloric cooling systems require high magnetic fields. The higher the magnetic field, the bigger is the change in the temperature of the material. When designing the magnetic field generator, one should also pay attention to the mass and volume of the magnet. Both the mass and the volume should be as small as possible. There are three types of magnets: electromagnets, superconducting magnets, and permanent magnets. Electromagnets and superconducting magnets can generate very high magnetic fields. The main drawback of using electromagnets is the large amount of energy needed to operate them and substantial losses caused by the production of heat. Superconducting magnets are also not suitable for magnetocaloric systems because they require additional cooling systems. The cost of these devices is too high for nonindustrial applications. The most appropriate magnetic field source for magnetocaloric systems seems to be a permanent magnet. Permanent magnets are commonly applied in magnetic refrigerators [10, 13] because they do not require additional cooling systems or external power sources. However, the magnetic field that can be generated by permanent magnets is significantly lower and amounts to about 4 T. Furthermore, such strong fields are generated in the air gaps that have very small dimensions (not exceeding a few millimetres) [14]. Magnetic refrigerators require a larger area in which a magnetic field is present because the dimensions of this area affect the quantity of the used magnetocaloric material. The larger the area, the more magnetocaloric material can be placed inside. Usually, a few hundred grams up to a few kilograms of a magnetocaloric material are used [8, 12]. For this reason, the magnetic fields generated by permanent magnets which are useful for magnetic cooling systems can achieve a maximum of 1-2 T.

A laboratory test stand for magnetocaloric effect investigations that was built in our laboratory employs a special arrangement of permanent magnets – the Halbach array. This paper presents the results of tests conducted with a magnetic field scanning system whose aim was to determine the magnetic field distribution on a surface of the Halbach array. Moreover, it was examined how a magnetic field screen limits the range of the magnetic field.

2. Design of the laboratory test stand

In our laboratory test stand [15, 16], a magnetocaloric material is cyclically magnetised and demagnetised, thanks to a reciprocating motion of a magnetic bed (Figure 1).

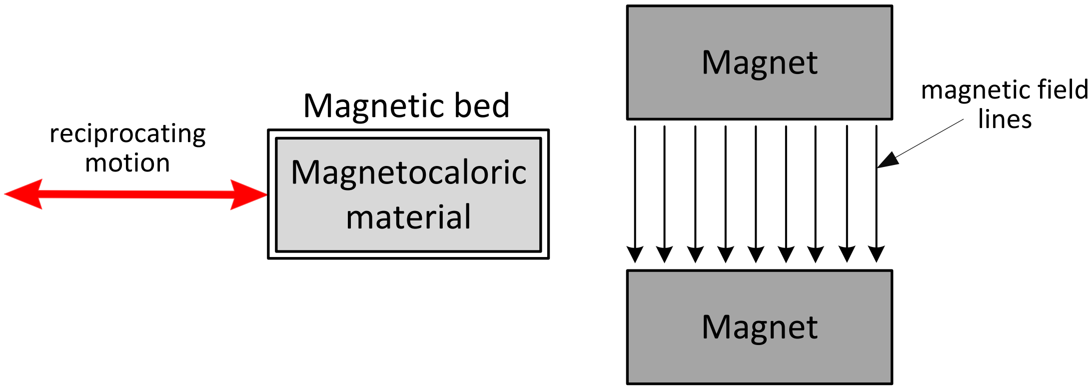

Fig. 1 Cyclical magnetisation and demagnetisation of a magnetocaloric material, caused by the reciprocating motion of a magnetic bed

The magnetic bed is a container for the magnetocaloric material. It is filled with gadolinium which is the most commonly used magnetocaloric material. Gadolinium is a rare earth metal with the Curie temperature close to the room temperature, which determines the temperature range of the system operation. The material is employed in the form of particles ranging from 1 to 2 mm. The heat generated by the magnetocaloric material (when it enters the magnetic field) is carried to the Hot Heat Exchanger. The heat is transferred by the fluid which is moved by a two-directional pump. Cold Heat Exchanger is an insulated reservoir. After the demagnetisation process, the heat from this reservoir is transferred to the magnetocaloric material. The temperature in the system is measured with the aid of thermocouples. There are four measurement points: Cold Heat Exchanger T_{CHEX}, Hot Heat Exchanger T_{HHEX}, cold end of the magnetic bed T_C (the end of the magnetic bed that is close to the Cold Heat Exchanger) and hot end of the magnetic bed T_H (the end of the magnetic bed that is close to the Hot Heat Exchanger). Figure 2 shows a schematic diagram of the laboratory test stand.

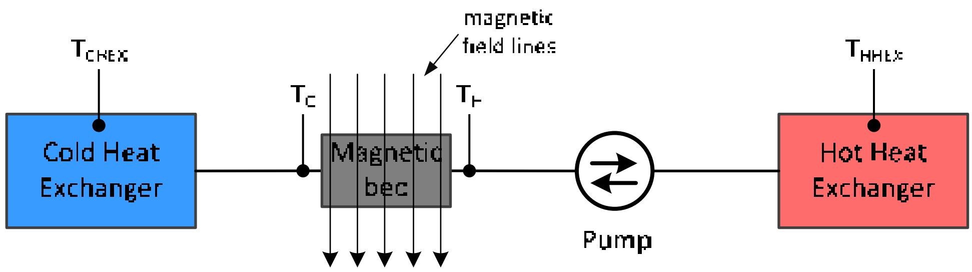

Fig. 2 Schematic diagram of experimental setup

Figure 3 shows an exemplary result of measurement which was obtained using the laboratory test stand . The diagram shows the temperature difference between the hot (T_{HHEX}) and the cold (T_{CHEX}) heat exchanger. The measurement was performed at the room temperature of about 25.3 °C. The initial temperature of both heat exchangers was close to the room temperature. After about 2000s of the device operation, a temperature difference of 1.6 °C was achieved between the hot and the cold heat exchanger [16].

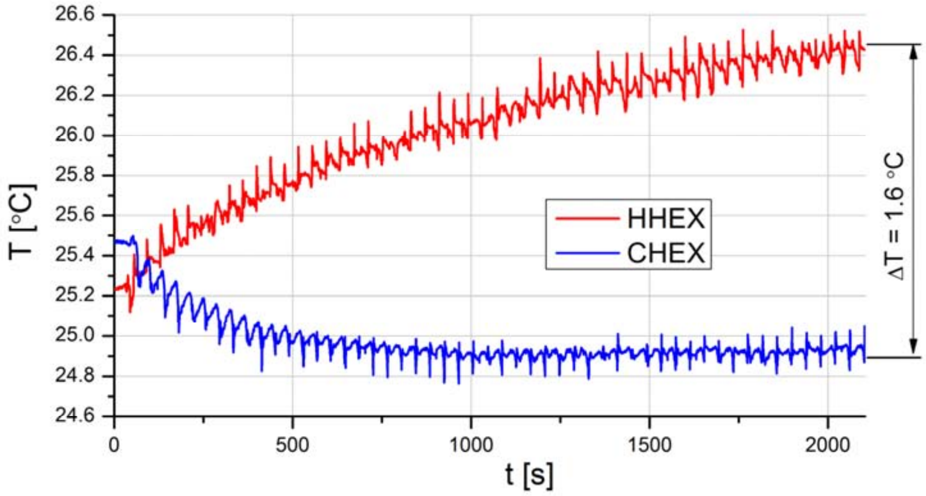

Fig. 3 Temperature difference between the hot and the cold heat exchanger [16]

3. Magnetic scanner

The magnetic field generated by the Halbach array was examined using the Magscanner-Maglab System (MMS) [17] that was developed in the laboratory. This system allows us to collect signals from magnetic sensors and to obtain magnetic images of scanned objects. It is possible to measure both flat and cylindrical elements. The magnetic scanner is mobile and can be used autonomously or in combination with a material testing machine for static load and fatigue tests. The system is capable of measuring the magnetic field around ferromagnetic objects. MMS makes it possible to investigate magnetomechanical phenomena and to detect strain fields, plastic deformations and cracks.

The magnetic scanner is used to determine 3 components of a magnetic field vector, B_x, B_y, and B_z. Measurements are taken without any contact with the object. It is possible to set different distances d from the investigated object. The shortest distance d_{min} amounts to 0.1 mm. By performing scans of successive planes, each at a distance of Δd from one another, it is possible to determine the magnetic flux lines in the area of the investigated object. Figure 4 shows the general idea of the measurement.

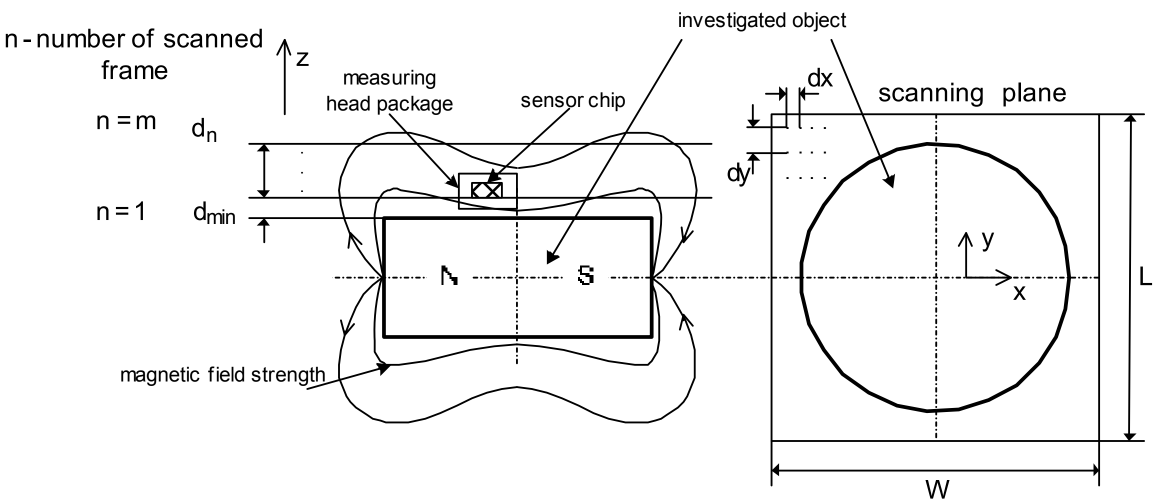

Fig. 4 Idea of the magnetic field scanning [17]

The system is equipped with different types of magnetic field sensors in order to measure in a wide range of magnetic field strength values. The sensors form measuring heads. The scanner employs:

- Honeywell HMC1053 sensors for weak and medium magnetic fields (0.1 µT – 10 mT) and
- Allegro Micro RMT34 Hall elements for high magnetic fields (10 mT – 2000 mT).

To control the scanning operations a dedicated software was designed. The software was named Maglab. It enables us to collect and process signals as well as make a 3D visualisation (a map) of the magnetic field distribution. Maglab is compatible with CAD systems (e.g. ProEngineer and SolidWorks) and NURBS (Rhinoceros).

MMS makes it possible to collect points at a speed of up to 50 000 points per second. The maximum resolution amounts to 2160 DPI (0.02 mm), whereas the maximum quantity of scanned points is 20 000 000. The working area is 410 mm x 180 mm x 200 mm. The scanner is equipped with a rotational system analyser. It enables us to measure and study the magnetic field distribution of axisymmetric objects.

Figure 4 gives an overview of Magscanner-Maglab System. Figure 5 a) presents all the parts of the scanner setup. One can notice that the operator console is wireless. Figure 5 b) shows the measurement area. It consists of a measuring head and a CCD camera that is used to record the scanning process. Figure 5 c) presents a subsystem for axisymmetric object scanning.

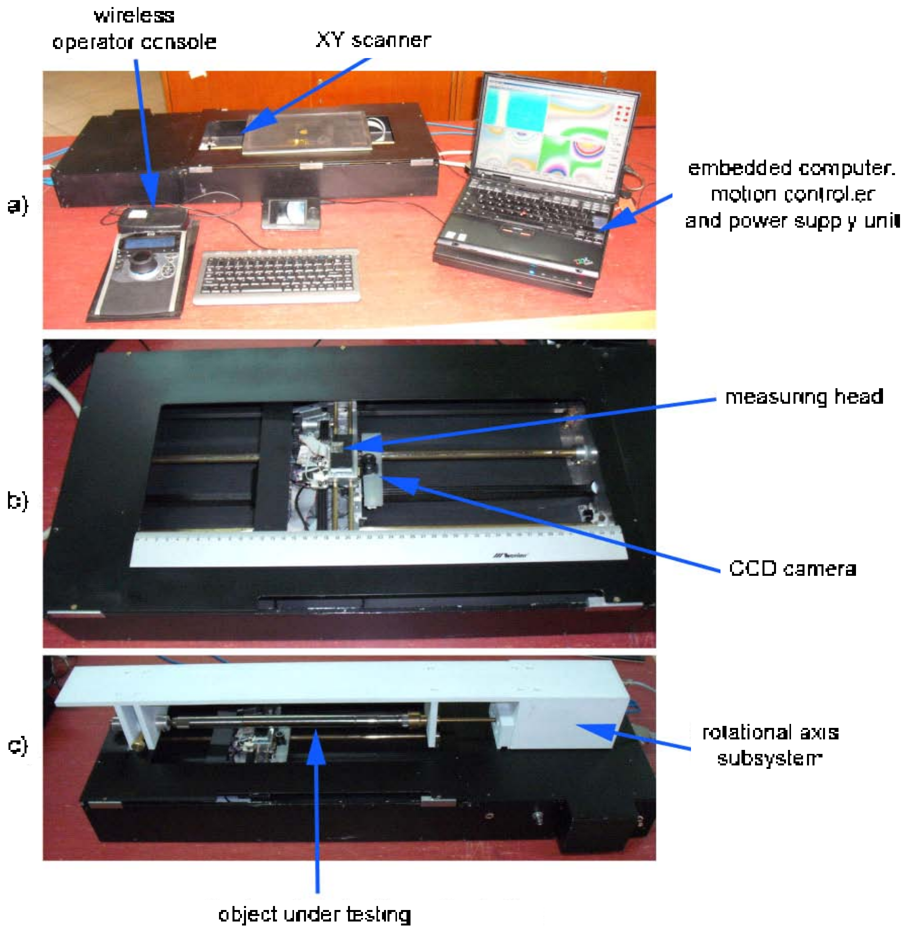

Fig. 5 General view of the Magscanner-Maglab System: scanner setup (a), measuring area (b), subsystem for axisymmetric measurements (c) [17]

4. Magnetic field source

The Halbach array that is employed in our laboratory test stand has a cylindrical shape [18]. Figure 6 shows a photograph of this array. In the centre there is a hole with a diameter of 25.4 mm and a length of 25 mm. The Halbach array consists of 12 permanent magnets. The arrow on each piece shows the orientation of the magnetic field vector. The suitable arrangement makes it possible to concentrate and homogenise the magnetic flux in the gap. On the outer side of the array, the value of the magnetic field is close to 0 T. According to the manufacturer (Gaussboys Super Magnets), the purchased Halbach array can generate a magnetic field of about 1 T in its inner space.

Fig. 6 Photograph of the used Halbach array [16]

4.1 Magnetic field investigations

In order to obtain a magnetic picture of the Halbach array, a magnetic scanner was used. The magnetic field was examined for different measurement distances. Investigations showed that the magnetic field range amounted to 15 cm from the surface of the Halbach array (beyond this distance the magnetic field is not more than 0.1 T). It means that to demagnetise the magnetocaloric material, the magnetic bed has to move away from the magnet by at least 15 cm. Figure 7 shows the magnetic field distribution on the surface of the magnetic flux source. It is the *Z* component of the magnetic field vector. This component is perpendicular to the surface.

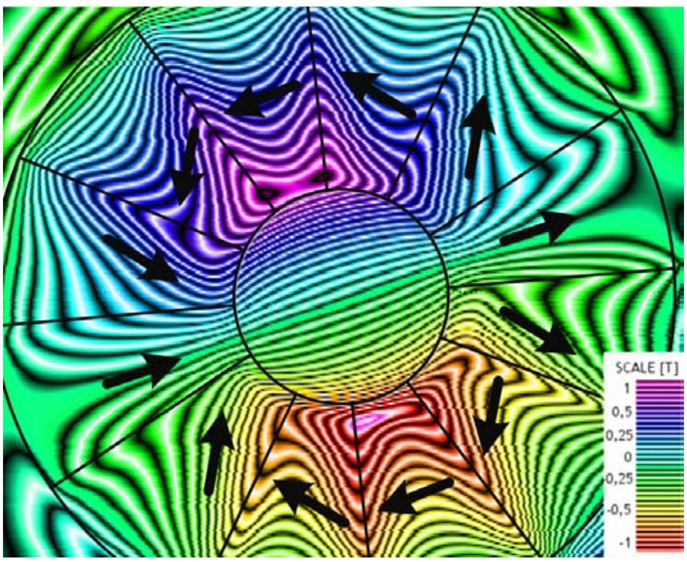

Fig. 7 Magnetic field distribution on the surface of the Halbach array - value of the *Z* component of the magnetic field vector, perpendicular to the surface. Contours of the magnets are also marked

One can observe how magnetic field intensity is altering. The value of the magnetic field is changing from -1 T to 1 T. In the middle of the hole there is a line where the *Z* component of the magnetic field vector amounts to 0 T. In this area the vector is perpendicular to the surface.

Figure 8 also shows a magnetic image of the Halbach array surface, but this picture presents the magnetic field vector distribution. The inset shows a scanned area marked with the red square. In the picture, three components of the vector are presented. One can see in which way the magnetic field is changing its direction. Moreover, the length of each vector represents its value. Hence, it is possible to observe changes in the magnetic field value in the scanned area.

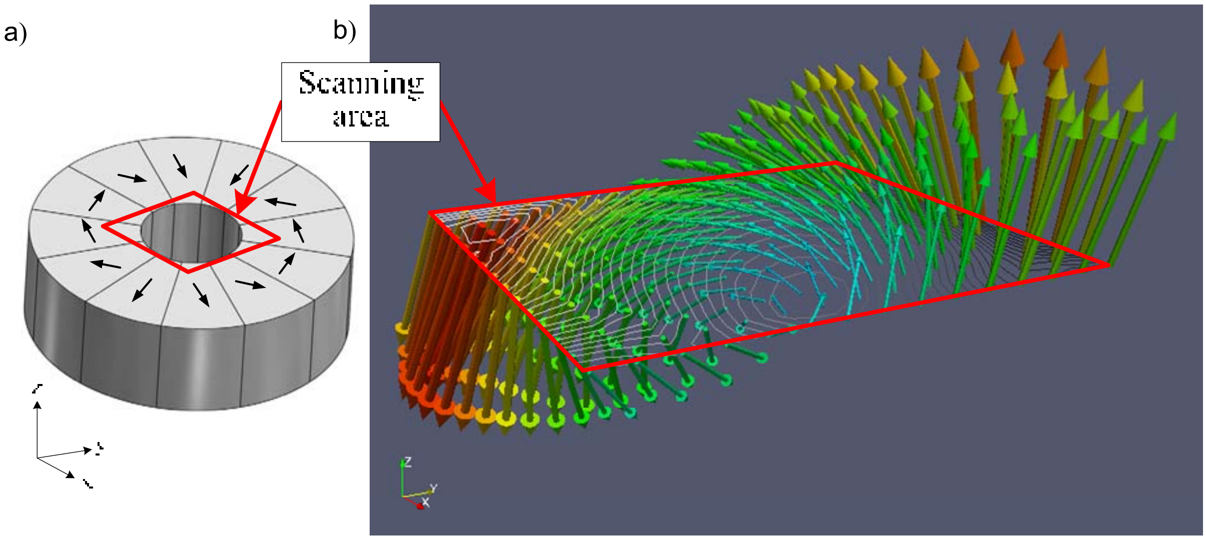

Fig. 8 Model of the Halbach array with a marked scanning area (a) and magnetic field vector distribution on the surface of the Halbach array in the scanning area (b)

Figure 9 presents the magnetic field vector with a marked contour of the Halbach array. The highest magnetic field in the inner space of the Halbach array is close to its edge. Inhomogeneity of the magnetic field is unfavourable to the magnetocaloric system because magnetocaloric particles will move and gather in the area where the magnetic field is the highest. This will cause problems with heat exchange between the particles and the fluid. The fluid will choose the easiest path where resistance to flow is the lowest, hence part of the gadolinium will not come into contact with the fluid.

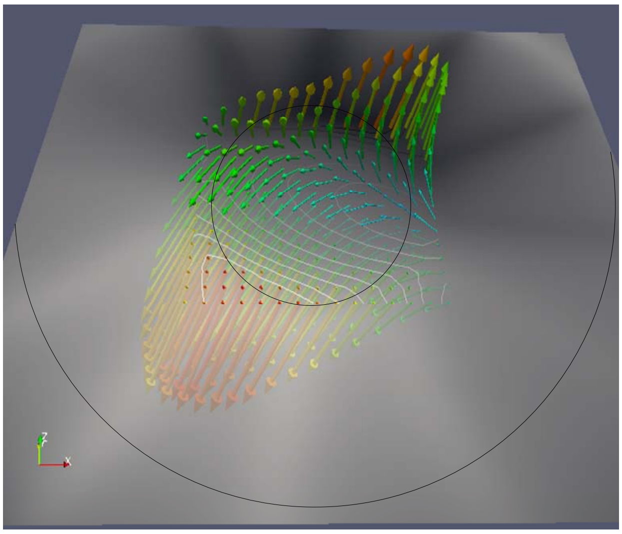

Fig. 9 Magnetic field distribution with a marked contour of the Halbach array

4.2 Magnetic field screen

As mentioned before, to demagnetise the magnetocaloric material, the magnetic bed has to move away from the surface of the Halbach array by at least 15 cm. In order to obtain a higher operation frequency, this distance has to be shortened. For that purpose, a magnetic field screen was used. The screen was placed next to the Halbach array. Figure 10 shows the location of the screen relative to the magnet and the magnetic bed. The magnetic field screen, the Halbach array, and the magnetic bed are positioned in a tube. Other parts of the system are located outside the tube.

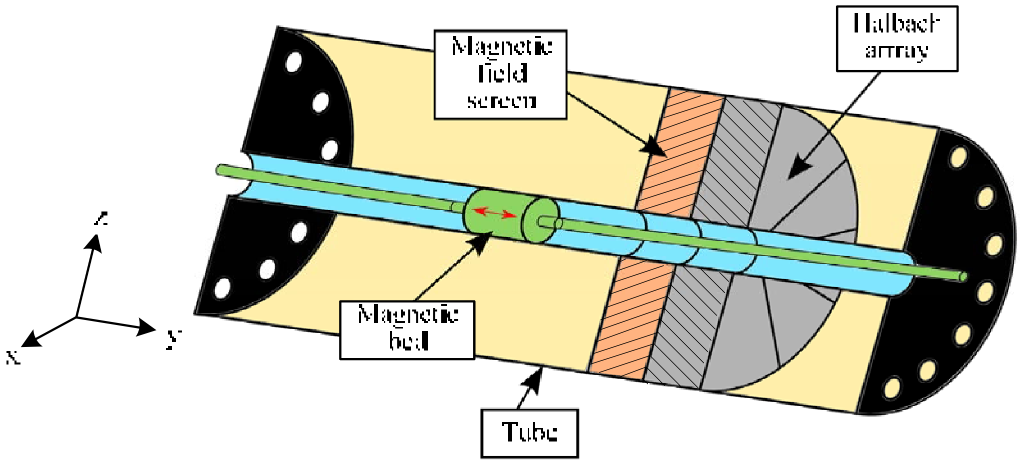

Fig. 10 Cross-sectional view of the tube

The magnetic field screen was made of quenched steel. Its thickness amounted to 15 mm. The magnetic scanner was used to determine how the screen reduces the range of the magnetic field generated by the Halbach array. As in the previous case, the part was scanned in different distances from the surface of the screen. Figure 11 shows the magnetic field distribution on the surface of the magnetic field screen.

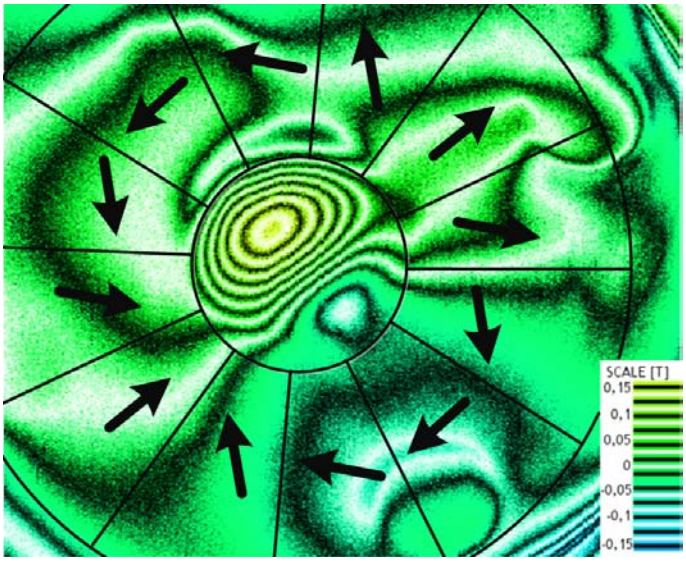

Fig. 11 Magnetic field distribution on the surface of the magnetic screen when the Halbach array is placed under the screen - value of the *Z* component of the magnetic field vector, perpendicular to the surface. Contours of magnets are also marked

Investigations showed that the magnetic field screen reduced the magnetic field range from 15 cm to 3 cm. Therefore, the distance to demagnetise the magnetocaloric material is significantly shorter. On the surface of the screen, the magnetic field ranges from -0.15 T to

0.15 T. However, the use of the magnetic screen also results in losses such as the magnetic field reduction inside the hole of the Halbach array. The screen causes a decrease of about 10% in the magnetic field value. Still, this disadvantage is outweighed by the substantial shortening of the magnetic field range.

5. Conclusions

Magnetic field intensity investigations on the surface of the Halbach array have been presented. The research was conducted with the aid of Magscanner-Maglab System that was designed in our laboratory. The studies showed that the magnetic field value in the inner gap is close to 1 T. The highest magnetic field is near the edge of the hole. On the surface of the Halbach array, the magnetic field vector changes its direction from -1 T to 1 T. The heterogeneity of the field is disadvantageous because it causes a problem with the heat exchange between gadolinium particles and the fluid.

The range of the magnetic field amounted to 15 cm. In order to reduce this distance, the magnetic field screen was employed. Magnetic scanning showed that the screen made it possible to reduce this distance to 3 cm; hence the operation frequency of the system can be higher.

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