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Magnetic Cooling - Development of Magnetic Refrigerator

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The paper describes the development and design of a prototype rotary magnetic refrigerator (MR). The principle of the operation of the presented magnetic refrigerator is based on the rotary movement of active magnetic regenerators (AMRs) with magnetocaloric materials and on the stationary magnetic field generated by permanent magnets NdFeB. After a short description of the basics of magnetic refrigeration, this paper presents the development and analysis of the structure for generating the magnetic field and the basic operational principle of the first prototype magnetic refrigerator, which was developed at the Faculty of Mechanical Engineering. The second part of the paper provides a description of the development process for certain key elements of the complete magnetic refrigeration system.

Keywords: magnetic refrigerator, magnetic field, permanent magnets, magnetocaloric effect, development

0 INTRODUCTION

Despite its continuous development, the nowadays widely used classical vapor-compression refrigeration technology, is still very energy inefficient. Furthermore, its operation more or less makes use of ozone-depleting refrigerants whose use has lately not been desired for environmental reasons. For this reason, 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 up to 15 to 20% more efficient than classic refrigerators [1], using magnetocaloric materials as the refrigerant and water or even air as the heat-transfer fluid, which are environmentally safe and harmless.

Magnetic refrigeration is based on the physical effect known as the magnetocaloric effect. For a long time, the technology of magnetic cooling was known and widely used for refrigeration at very low temperatures, i.e., cryogenic refrigeration. But with the development of new magnetocaloric materials and technologies in recent years, the magnetic refrigeration technology has also become interesting for refrigeration at room temperature. There has been an increasing interest in the widespread use of magnetic refrigeration commercial devices in domestic, industrial and public facilities. Most certainly, a technological breakthrough is to be expected in the next few years, but the research and development of commercially useful magnetic refrigerators still needs plenty of resources and work.

1 BASIC PRINCIPLES OF MAGNETIC REFRIGERATION

The development of magnetic refrigeration started in 1881 when the German physic Emil Warburg discovered the magnetocaloric effect [2] in iron, which was until recently limited to very low temperature. The use of the magnetic cooling at room temperature was practically made possible with the discovery of materials which show the magnetocaloric effect at room temperature (especially some rare metals and their alloys). With this discovery, the technology of magnetic refrigeration also became applicable for the use at room temperature.

1.1 Magnetocaloric Effect

As mentioned above, the magnetocaloric effect was discovered by Warburg [2] in 1881. It is detected as the heating and cooling of magnetocaloric materials subjected to the change of the external magnetic field. But only fifty years later, Debye and Giauque explained the nature of the magnetocaloric effect and applied it to cryogenic refrigeration [2].

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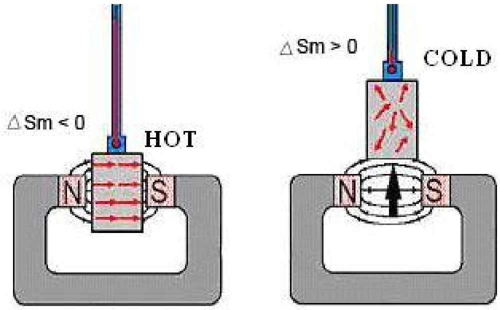


Fig. 1. *Scheme of magnetocaloric effect*

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 (S_m), which means that in an adiabatic system the temperature of the material must increase. A reverse process taking place is observed when the magnetocaloric material from the magnetic field is removed, and the magnetic moments revert to random orientations. This causes an increase in the magnetic entropy and a corresponding decrease in the temperature. As a result, the system cools down.

The magnetocaloric effect can be described as a change of magnetic entropy or adiabatic temperature of the magnetocaloric material subjected to an external magnetic field. Those parameters are defined as [2]:

$$\Delta S_m(T,\Delta H)=\int_{H_0}^{H_1}\left(\frac{\partial M(T,H)}{\partial T}\right)_H dH \qquad (1)$$

$$\Delta T_{ad}(T,\Delta H)=-\int_{H_0}^{H_1}\frac{T}{C_{\mu_0 H}}\left(\frac{\partial M(T,H)}{\partial T}\right)_H dH \qquad (2)$$

From Eqs. 1 and 2 it can be seen that the magnetocaloric effect depends on the change of the magnetic field (ΔH) as well as on the temperature of the material. The magnetocaloric effect is the largest around the Curie temperature of the material, which is a physical property of every ferromagnetic material. For this reason, it is important to use a magnetocaloric material with Curie temperature close to room temperature.

In recent years, the development of new magnetocaloric materials, which are more and less suitable for magnetic refrigeration at room temperature, has increased rapidly. Nevertheless, it is yet not perfectly clear which magnetocaloric material is to take primacy and be considered as the best one. A detailed review of magnetocaloric materials and a description of their development are presented by Gschneidner et al. [3].

1.2 Operation of Magnetic Refrigerator

In general, the magnetic refrigerator is composed of a magnetocaloric material in the form of a porous structure called the active magnetic regenerator (AMR). AMR has the role of a refrigerant (it contains the magnetocaloric material) as well as the role of a regenerator. Heat regeneration between the particular phases of the cooling process assures an increase of the temperature range, which is crucial to the magnetic cooling at room temperature. So, AMR configuration overcomes the limitations imposed by relatively small magnetocaloric effect of the, so far known magnetocaloric materials.

In addition, the basic elements of the magnetic refrigerator are the following: a structure to generate a magnetic field (electromagnetic device or permanent magnet), two external heat exchangers and the fluid which transfers heat from the magnetocaloric material in the AMR through two external heat exchangers from the cooling space and to the surroundings.

The magnetic refrigerator with AMR during its operation performs the following four processes (Fig. 2):

a) Adiabatic magnetization: AMR is exposed to a change – an increase of the magnetic field – and consequently each piece of the magnetocaloric material in AMR heats up.

b) Fluid flow from the cold external heat exchanger (Fig. 2 - CHEX on the left side) through the heated magnetocaloric material into the hot external heat exchanger (Fig. 2 - HHEX on the right side) where the heat received from the magnetocaloric material is transmitted to the surroundings.
c) Adiabatic demagnetization: AMR is exposed to a change – decrease of the magnetic field – and consequently each piece of the magnetocaloric material in AMR cools down.
d) Fluid flow from the hot external heat exchanger (HHEX) through the cooled magnetocaloric material (where fluid is cooled down) into the cold external heat exchanger (CHEX) where the heat is absorbed from the surroundings (the refrigerator's chamber).

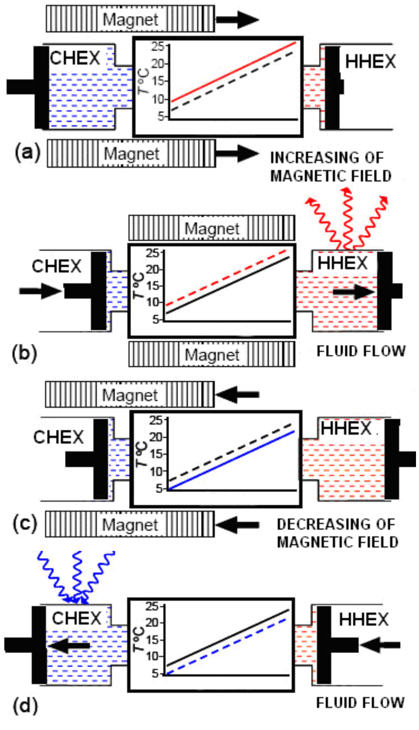


Fig. 2. *Schematic show of four operational phases of magnetic refrigerator with AMR, where dotted lines indicate the temperature profile along the AMR at the beginning of each phase and the full lines indicate the temperature profile at the end of each phase [4]*

In general, we can generate a magnetic field to magnetize and demagnetize AMR in two ways. For the generation of the large magnetic flux 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 and are therefore, unsuitable for wide use in magnetic refrigerators. 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 compared to electromagnetic devices. In the past few years, the main focus of investigations has been the development of materials for stronger permanent magnets and structures of permanent magnets to direct and focus the magnetic field (a magnetic circuit and the Halbach structure [5]) for use in magnetic refrigerators.

1.3 Development of Prototype Magnetic Refrigerators

The development of the magnetic refrigeration technology has followed the typical skewed "S" shape grown pattern (Fig. 3). At the beginning (between 1881 and 1930), after the discovery of the magnetocaloric effect, the development was very slow due to a lack of interest in this effect and its possible applications. In the next period, between 1930 and 1975, the interest in magnetic refrigeration among researchers started to increase. At that time, numerous significant papers were published, but all focused on the cooling below 20 K. During the last 30 years, starting with the year 1976 when Brown made the design of the first prototype magnetic refrigeration at room temperature, the development in this area has greatly expanded. The number of papers has greatly increased but it has probably not reached its maximum yet. This will hopefully happen in the future, thus making the technology of magnetic refrigeration competitive to vapor-compression refrigeration devices [6].

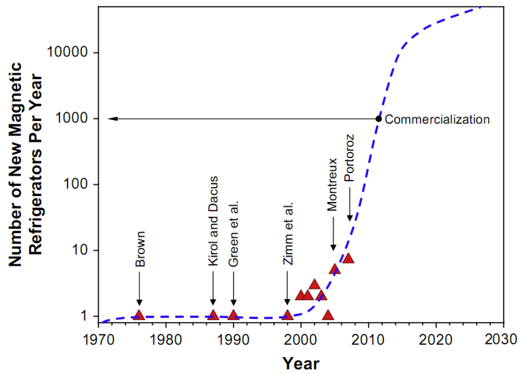


Fig. 3. *The number of developed magnetic refrigerators at room temperature per year [6]*

Although the development of magnetic refrigeration started with the discovery of the magnetocaloric effect by Warburg, two other events brought major advances to the technology of magnetic refrigeration at room temperature. The first of these events was the design of the first magnetic room temperature refrigerator developed by Brown in 1976. The second milestone was year 1997 when Gschneidner and Pecharsky discovered the giant magnetocaloric effect in the $Gd_5Si_2Ge_2$ alloy. The effect in this alloy is approximately 50% higher than the magnetocaloric effect of Gd metal [2] and its discovery spurred a broad international interest in the field of magnetic refrigeration. Since this groundbreaking discovery, numerous universities and institutes across the globe took up the development of prototype magnetic refrigerators. More than 25 prototype magnetic refrigerators capable of operating with a varying degree of efficiency at room temperature have been built and tested to date. The prototypes show a cooling power of up to 100 W and a temperature span of up to 30 °C, depending on the magnetic flux density and the amount of magnetocaloric material. The most advanced of all the prototypes are the three devices made by Zimm et al. which seem to be setting the trend for the magnetic refrigeration development [7] to [9]. A full review of room temperature magnetic refrigerators was undertaken by Gschneidner and Pecharsky [6].

The magnetic refrigerator developed by the Laboratory for Refrigeration and the Laboratory for Modeling Machine Elements and Structures (both Faculty of Mechanical Engineering, University of Ljubljana) is based on the rotary movement of active magnetic regenerators (AMRs), placed in a rotating drum and the magnetic field generated by permanent magnets Nd-Fe-B. Through the use of connecting elements made of soft ferromagnetic material, four permanent magnets with focus elements inside and outside the rotating drum create a strong and homogenous magnetic field in the air gaps. On the circumference of the rotating drum, four air gaps interchange with four slightly wider demagnetization areas with a low magnetic field.

2 STRUCTURE FOR MAGNETIC FIELD GENERATION

The structure for magnetic field generation in a developed magnetic refrigeration device is designed on the basis of two magnetic circuits (Fig. 5). Its geometry was chosen in close consideration of the financial aspect and future trends in magnetic refrigeration which seem to focus on developing rotating magnetic refrigerators with several regions of large magnetic fields [6]. Such solutions ensure a higher operating frequency of the magnetic refrigerator as the magnetocaloric material is exposed to several processes of magnetization and demagnetization in one working cycle of the rotating drum.

In the first step of the process, the geometry of the structure was optimized and a numerical simulation of the magnetic field generated by the magnet structure was carried out. In order to verify the obtained numerical results, the magnetic field was then measured to identify the exact values of the magnetic flux density.

2.1 Numerical Simulation

As there are several commercial programs that can solve very complex problems without the need to develop specific algorithms, the finite-element method is currently the most accessible and widely used for conducting a numerical simulation of the magnetic field. On account of its simple use, the FEMM (Finite Element Method Magnetics, version 4.0) program, able to solve two-dimensional and low-frequency electromagnetic problems [10], was used to simulate the magnetic field which is generated by the structure containing permanent magnets and a soft ferromagnetic material. First, the geometry needed to be optimized in order to ensure that the minimum amount of material is used and the magnetic field is strongest in areas where the magnetocaloric material is to be magnetized and weakest in areas where the magnetocaloric material is to be demagnetized. Additionally, the height of the air gaps was optimized in order for the gaps to meet the purpose of the research: they have to be as small as possible to generate the highest magnetic flux density possible; on the other hand, the air gaps have to contain the maximum amount of the magnetocaloric material in order to reach the maximum cooling power of the refrigerator. The optimization was performed by plotting charts of the average magnetic flux density in the air gap based on 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) [11]. The scheme of the structure with optimized dimensions is shown in Fig. 4 in a 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 the area of air gaps the structure is reduced to 55 mm.

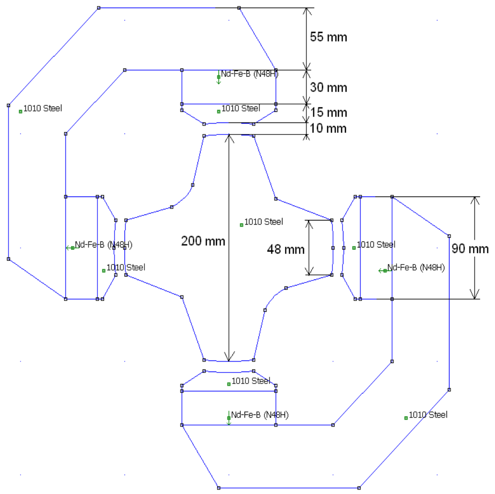


Fig. 4. *Scheme of magnetic structure with optimized dimensions*

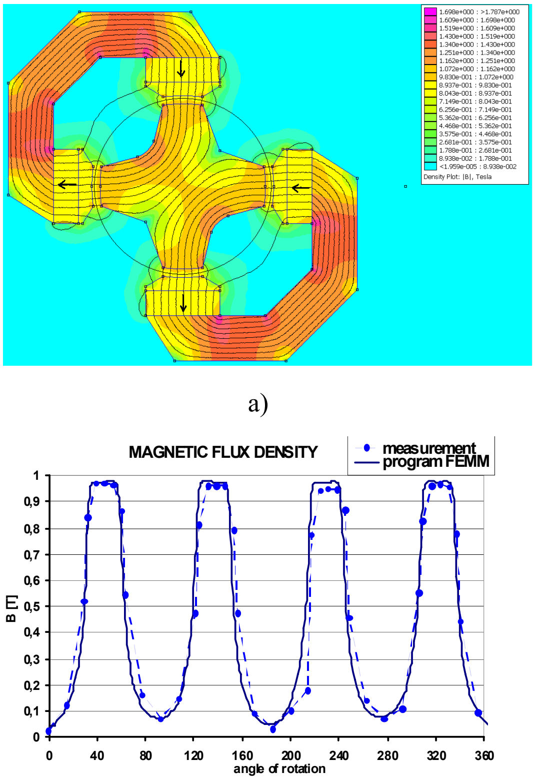
The magnet structure is designed on the basis of four neodymium-iron-boron permanent magnets (Nd–Fe–B with 40 MGOe maximum energy product). These magnets are currently among the strongest permanent magnets available due to their maximum energy product, which is the most important factor to be considered in selecting a permanent magnet. Low-carbon 1010 steel was used as a soft ferromagnetic material for conducting and focusing the magnetic flux. Although magnetically not ideal, the material was chosen for its low price and good machining properties. The structure has four air gaps with a strong magnetic field and four areas of a low magnetic field where the magnetocaloric material (rotating drum) circulates during the operation of the magnetic refrigerator.

After finalizing the geometry of the magnetic structure, the magnetic field generated by it was simulated. The results are presented graphically with the distribution of the magnetic flux density and with a graph of the magnetic flux density (B) as a function of the angle of rotation of the AMRs (Fig. 5).

2.2 Measurement of Magnetic Flux Density

To verify the analyses or the simulation of the magnetic field generated by the presented magnetic structure, the research team built and assembled the prototype and, in order to study the magnetic field generated by the presented structure in detail, measured the magnetic flux density in the magnetic 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 [12]), which is the most appropriate instrument for such measurements on account of its small size and precision. The magnetic flux density was measured at 40 measuring points arranged in such a way that three measurement points were in the middle of each air gap, two on the internal edge and two on the external edge of each air gap, while three measurement points were in each demagnetizing area, thus covering the entire circle where AMRs with the magnetocaloric material are rotating.

The obtained results are shown in Fig. 5b. For comparison, the graph also presents the results obtained using the FEMM program. Fig. 5 shows that in the air gaps where the magnetocaloric material is expected to magnetize the magnetic flux density amounts to 0.98 T. It is also evident that in the area where the magnetocaloric material is expected to demagnetize, the magnetic flux density is around 0.05 T, which means that the magnets and soft steel are at a sufficient distance from the expected demagnetization areas to provide a suitably low magnetic flux density.



a)

b)

Fig. 5. *a) magnetic flux density distribution b)density for the AMRs pitch circle)*

To estimate the homogeneity of the magnetic flux density in the air gaps, which is very important for the efficient operation of the magnetic refrigerator, the magnetic flux density was measured at different heights (radial direction on the magnetic structure) and depths (axial direction on the magnetic structure) of the air gaps. It was concluded that the magnetic flux density varies considerably with the height in the air gap. In the middle of the gap, the magnetic flux density is almost perfectly homogenous. However, in the vicinity of the magnets and at the largest distance from them, the magnetic flux density homogeneity is much lower and varies between air gaps by as much as 0.2 T. At the same time, the homogeneity of the magnetic flux density is much better for different depths of the air gaps due to the 0.95 T magnetic flux density at the front and back edges of the air gaps.

A comparison of the results obtained with the FEMM program and the measured magnetic flux density values (Fig. 5b) indicates a very good agreement of results, which confirms the suitability of the FEMM program for estimating the magnetic field generated by the magnet circuit structures.

3 OPERATION OF MAGNETIC REFRIGERATION SYSTEM

The operation of the rotary magnetic refrigeration (MR) system is based on AMRs rotating through air gaps and through demagnetization areas, as shown in Figs. 5 and 6.

The scheme and the picture of the magnetic refrigeration system are given in Figs. 6 and 7. The basic operating principle of the system is as follows (regarding to Fig. 7). The fluid (distilled water) flows from the hot reservoir 1 (6) through the demagnetized AMRs, situated in demagnetization areas at the time, to the cold reservoir 2 (7). From there the fluid flows through the cold heat exchanger to the cold reservoir 1 (8) and further through the magnetized AMRs, situated in the air gaps at the given moment, to the hot reservoir 2 (5). The fluid then flows through the expansion vessel (13) and the pump (14) to the hot heat exchanger (15). The circuit is complete when the fluid returns (through filter (16)) to the hot reservoir 1 (6). The fluid flow is controlled by a sliding flow divider (4) which uses relative movement of the two areas to direct the fluid flow through regularly placed chambers with AMRs, depending on their position in the magnet structure.

Fig. 8 presents a detail of the rotating drum into which AMRs are placed and which rotates through air gaps and demagnetization areas. In the first stage of the research gadolinium (Gd) is used, a material that has established itself as a prototype magnetocaloric material. AMRs are made of Gd (thickness of 0.3 mm) plates linked into plate packs with spacers that ensure gaps for the fluid flow and porosity of 0.59. This AMR geometry was used due to the thermo-hydraulic characteristics [13] of the then available form and state of Gd.

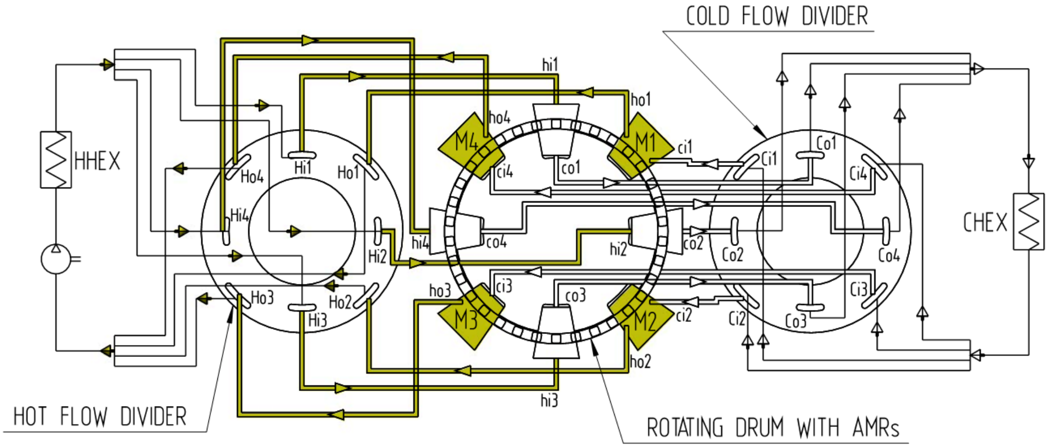


Fig. 6. *Flow diagram of the MR with the hot (left) and cold (right) flow dividers and four magnetization (M1 to M4) and demagnetization areas*

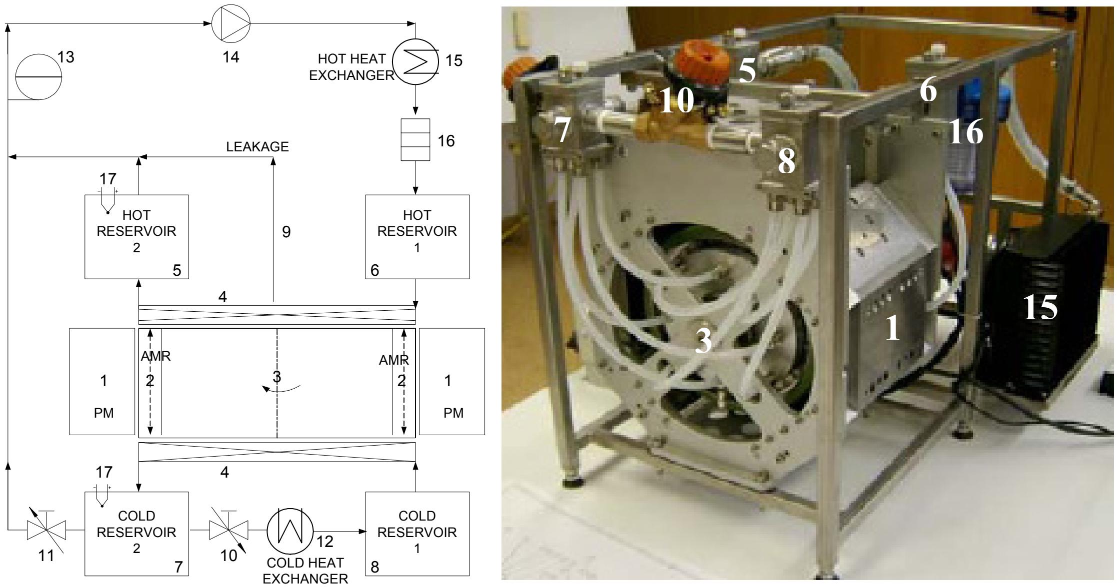


Fig. 7. *Magnetic refrigerator (MR): scheme (left) and picture (right)*

Table1. *Technical properties of the MR*

Magnetic flux density	0.05 T – 0.98 T
Operating frequency	0 Hz – 4 Hz
Heat transfer fluid	Distilled water
Number of AMRs	34
Magnetocaloric material	Gd
Mass of magnetocaloric material	~ 0.6 kg
Dimensions of AMR	10 mm x 10 mm x 50 mm

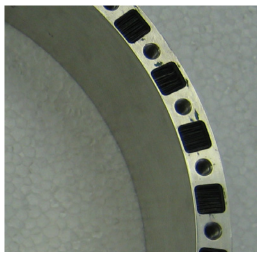


Fig. 8. *A detail of the drum with chambers for AMRs*

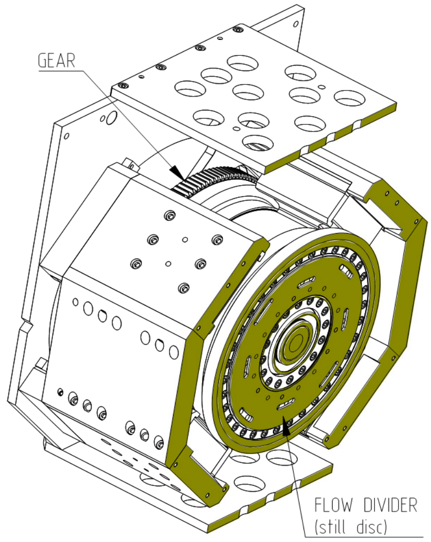
4 CONCEPTS AND DESIGN OF MAGNETIC REFRIGERATOR

The primary goal in designing our first prototype was to make the central part of MR as small and compact as possible and at the same time to ensure that all its component parts could be fabricated to high-quality standards and under general toolmaking principles using standard machining methods. In short, our aim was to avoid any demanding and/or costly material conversion procedures. Nevertheless, the design of the magnetic refrigerator would have to allow for subsequent redesigning, in the process of which the components could be redesigned to meet the requirements for mass production mainly through the use of conversion procedures and unconventional materials (polymers, ceramics).

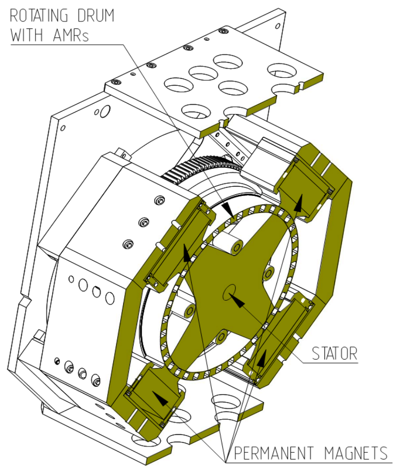
The rotor containing a magnetocaloric material (AMRs) is drum-shaped and rotates around the static axis, so the AMRs are rotating through the magnetization and demagnetization areas (Figs. 5 and 9b). In order to minimize the thickness of its wall and chambers, i.e. to ensure maximum cross-section of the AMRs, the drum is made from Al-alloy and the chambers for AMRs were cut using the Wire Electrical Discharge Machining (WEDR) method.

The heat transfer fluid flows, alternately, through the drum in the axial direction (Figure 10). In order to control the fluid flow between the channels with AMRs, a fluid flow divider is needed on each side of the drum. The dividers were designed so as to take up the minimum width of the system and minimize the fluid channel length. To achieve this, their shape resembled axial journal bearings where the contact force is controlled through a set of pressure springs. Stainless steel (rotating area – frontal wall of the drum) and PTFE coating glued and processed on the base Al-alloy plate (still area) are used as the sliding pair. The rotating and still parts are sealed using standard rubber radial shaft seals (Figure 10), whereas the drum with AMRs and the frontal plate of the drum (polyamide) are sealed using laser-cut flat seals compressed with a bolt connection.

With a view to reduce the heat transfer through the parts of the refrigerator, the design of the drum and the flow dividers is such that it minimizes the length of fluid channels (Fig. 10) and allows the highest possible number of parts to be fabricated from low thermal conductivity materials (polyamide, PTFE). The main limitation during the process came from the WEDM technology of manufacturing the AMR chambers (which was the only one available during the prototype design process).



a)



b)

Fig. 9. *a) magnetic refrigerator cross-section through the flow divider*
b) through the drum with AMRs, inner stator and magnets

This is also the main reason why the rotating drum was made from Al-alloy, which in terms of thermal conductivity was not the most favorable choice of material.

The drum is driven by a gear transmission system. The pinion (z_1 = 23) is mounted directly on the output shaft of the frequency controlled 8 pole asynchronous electromotor (n_{EM} = 700 rpm), and the toothed ring (z_2 = 123) is fitted on the ring of the drum top plate. During the testing we came to a conclusion that the performance of the magnetic refrigerator is highest at the lowest level of the stable and permanently achievable rotational speed of the drum (~ 1 rpm) which, considering the restrictions of the toothed ring (gear ratio and dimensions) and the frequency controlled electric motor (EM), can be achieved. For experimental purposes we wish to have a bigger gear ratio of the gear pair which would enable us to determine optimal working point of the refrigerator.

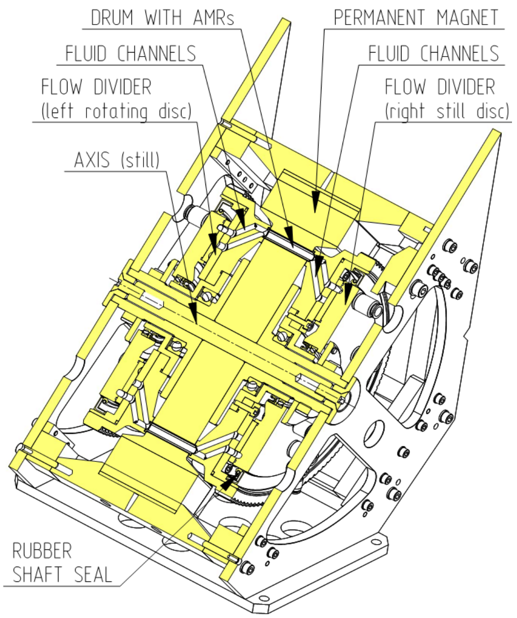


Fig. 10. *Crossection along drum axis*

After assembly, the performance of the construction was within expectations. However, several disadvantages of the construction became evident. Any generation of heat and excess thermal conductivity of component parts causes problems or thermal losses, which was expected. Several problems arose, however, that were connected to machining technology. The stability of the shape and dimensions and the precision of polyamide-made parts were found to be in close connection with temperature and humidity absorption. Heat generation was known to severely affect the maximum cutting precision in the process of machining. During the operation of MR, the condition deteriorated further largely due to the presence of fluid (humidity) and local heat generation (friction). The key parts of the system should therefore, be made from time- and temperature-stable materials with low thermal conductivity (ceramics).

Standard shaft seals are a financially attractive option that can be used in the production of prototype but this is functionally inappropriate. Owing to its size, the outer seal is much too robust, causing excess rotational resistance despite tolerance adjustments. Similar problems arose with regard to the sliding divider (large cross-section and surface - Fig. 9a). The above mentioned issues were considered in determining engine power but the friction in seals and sliding flow dividers generates a substantial amount of heat that reduces the efficiency of the refrigerator. Reduced friction (lower clamping force) leads to an increased loss of fluid (leakage), which returns to the system but still negatively affects the performance of the refrigerator. The research showed that the selected materials and machining technologies make it hard to achieve the desired accuracy of form (flatness) of contact surfaces of the sliding divider, which would allow the divider to operate at a suitably low clamping force (and consequently lower friction) and with minimum leakage.

5 CONCLUSIONS

The main problem of the used concept lies in large dimensions of the connecting structure (made from soft ferromagnetic steel) for determining the magnetic field between permanent magnets. The size of the construction itself is linked to large weight, which in the given concept cannot be significantly reduced. As the magnetic refrigerator needs large quantities of magnetic material to operate, the total weight of the device will continue to be the main problem, especially when comparing magnetic refrigerators with classic refrigeration devices. Another issue to be addressed is the relatively demanding and complex structure of the refrigerator, which increases production costs and hinders assembly and subsequent maintenance.

The experience obtained in the development of the first prototype magnetic refrigerator to date has pointed to the positive and negative aspects of the project and introduced several new ways and ideas. Certain deficiencies observed will be eliminated through changes and partial reconstructions of the existing prototype. However, most of the results obtained and new ideas emerging in the course of the development process have been utilized in the design of a new prototype magnetic refrigerator which is already in its planning phase.

6 NOMENCLATURE

$C_{\mu H}$	total heat capacity at constant magnetic field (J/K)
H	magnetic field (A/m)
M	magnetization (A/m)
T	temperature (K)
ΔH	magnetic field change (A/m)
ΔS_m	magnetic entropy change (J/K)
ΔT_{ad}	adiabatic temperature change (K)

7 REFERENCES

[1] Yu B.F., Gao Q., Zhang B., Meng X.Z., Chen Z. (2003) Review on research of room temperature magnetic refrigeration, *International Journal of Refrigeration* 26, p. 622-636.

[2] Tishin A.M., Spichkin Y.I. (2003) The Magnetocaloric Effect and its Applications, Institute of Physics Publishing, London

[3] Gschneidner K.A. Jr., Pecharsky V.K., Tsokol A.O. (2005) Recent development in magnetocaloric materials, *Reports on Progress in Physics* 68, p. 1479-1539.

[4] Gschneidner K.A. Jr., Pecharsky V.K. (1999) Magnetocaloric effect and magnetic refrigeration, *Journal of Magnetism and Magnetic materials* 200, p. 44-56.

[5] Halbach K. (1980) Design of permanent multipole magnets with oriented rare earth cobalt material, *Nuclear Instruments and Methods* 169, p. 1-10.

[6] Gschneidner K.A. Jr., Pecharsky V.K. (2008) Thirty years of near room temperature magnetic cooling: Where we are today and future prospect, *International Journal of Refrigeration* 31, p. 945-961.

[7] Zimm C.B., Sternberg A., Jastrab C., Pecharsky V.K., Gschneidner K.A. Jr., Osborne M., Anderson I. (1998) Description and performance of a near room temperature magnetic refrigerator, *Adv. Cryog. Eng.* 43, p. 1759-1766.

[8] Zimm C.B., Boeder A., Chell J., Sternberg A., Fujita A., Fujieda S., Fukamichi K. (2006) Design and performance of a permanent-magnet rotary refrigerator, *International Journal of Refrigeration* 29, p. 1302-1306.

[9] Zimm C.B., Auringer J., Boeder A., Chell J., Russek S., Sternberg A. (2007) Design and initial performance of a magnetic refrigerator with a rotating permanent magnet, *Proc. 2nd International Conference on Magnetic Refrigeration at Room Temperature. Portorož, Slovenia*, p. 341-347.

[10] Meeker D (2006) Finite Element Method Magnetics, version 4.0., User`s manual.

[11] Tušek J. (2007) Developing of a regenerator for the magnetic refrigerator, *Diploma Thesis, University of Ljubljana, Faculty of Mechanical Engineering.*

[12] Popović D.R., Dimitrijević S., Blagojević M., Kejik P., Schurig E., Popovic R.S. (2007) Three-axis teslameter with integrated hall probe, *IEEE Transactions on Instrumentation and Measurement* 56, p. 1396 – 1402.

[13] Šarlah A. (2008) Thermo-hydraulic properties of heat regenerators for magnetic refrigerator, *PhD Thesis, University of Ljubljana, Faculty of Mechanical Engineering.*