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# A REGENERATOR USED IN THE INSTALLATION OF MAGNETIC REFRIGERATION DEVICES

# UPORABA REGENERATORJA ZA MAGNETNO HLAJENJE

Botoc Dorin[ℜ], Jurij Avsec[1], Adrian Plesca[2]

**Keywords:** Energy efficiency, gadolinium material, magnetocaloric effect, alternative technology, AMR

## Abstract

In this article, the mechanism and functioning of a refrigeration system based on the magnetic system and the magnetocaloric effect are examined. Magnetic refrigeration plants operate based on a state-of-the-art technology that does not contain any toxic refrigerant that is harmful to the environment and the ozone layer. The magnetocaloric effect is created by a rare earth metal called gadolinium. We have studied the benefits of using this type of mechanism for both domestic and industrial needs. High efficiency, net energy consumption lower than the classic, silent systems, and a lack of typical refrigerant characterize this type of installation. The following layout describes the initial prototype for AMR in magnetocaloric refrigeration.

## Povzetek

V tem članku je proučen mehanizem in delovanje hladilnega sistema, ki temelji na magnetnem sistemu in magnetokaloričnem učinku. Magnetne hladilne naprave delujejo po najsodobnejši tehnologiji,

ℜ Corresponding author: Botoc Dorin, E-mail address: dorinbotoc@yahoo.com

[1] University of Maribor, Faculty of Energy Technology, Laboratory for Thermomechanics, Applied Thermal Energy Technologies and Nanotechnologies, Hočevarjev trg 1, SI-8270 Krško, Slovenia

[2] Faculty of Electrical Engineering, Energetics and Applied Informatics, Gheorghe Asachi Technical University of Iasi, Department of Power Engineering, Romania

ki ne vsebujejo nobenega strupenega hladilnega sredstva, ki je škodljivo za okolje in ozonski plašč. Magnetokalorični učinek ustvarja redka zemeljska kovina, imenovana goldonij. Proučevali smo prednosti uporabe tovrstnih mehanizmov tako za domače kot industrijske potrebe. Za to vrsto namestitve je značilna visoka učinkovitost in nizka poraba energije. Predstavljen članek opisuje začetni prototip za AMR v smislu magnetokaloričnega hlajenja.

## 1 INTRODUCTION

Magnetic refrigeration is a cooling technology based on the magneto-caloric effect. This technique can be used to attain extremely low temperatures (well below 1 Kelvin), as well as the ranges used in common refrigerators, depending on the design of the system. Magnetic refrigeration technology could provide a "green" alternative to traditional energy-guzzling gas-compression fridges and air conditioners, *[1].* Computer models have shown 25% efficiency improvement over vapour compression systems. The interest of the conventional industries in magnetic refrigeration technology is at present very high. This interest occurs especially in the domain of household appliances, hermetic compressor production and domains related to air-conditioning systems, e.g. in land vehicles. One may recognize that numerous companies working in these areas started with some actions in magnetic cooling research and development, *[2].*

## 2 LITERATURE REVIEW

The research activities of industries in the domain of conventional refrigerators (chillers) are surprisingly small. These companies have also not yet become active in the domain of magnetic cooling. In Europe at least two spin-off companies, Cooltech in France and Camfridge in England, are supported by high-risk capital investors. The second is a spin-off company of Cambridge University in the UK. The Swiss HEIG-VD team, like numerous other research teams, is now starting some activities with European industries, *[3].*

The ultimate goal of this technology would be to develop a standard refrigerator for home use. The use of magnetic refrigeration has the potential to reduce operating cost and maintenance cost in comparison to the conventional method of compressor-based refrigeration. By eliminating the high capital cost of the compressor and the high cost of electricity to operate the compressor, magnetic refrigeration can efficiently and economically replace compressor-based refrigeration. The major advantages to the magnetic refrigeration technology over compressor-based refrigeration are the design technology, environmental impact, and operating cost savings. Magnetic refrigeration utilizes the magnetocaloric effect, which causes a temperature change when a certain metal is exposed to a magnetic field. This effect applies to all transition metals and lanthanide series elements.

These metals, known as ferromagnets, tend to heat up as a magnetic field is applied. As it is applied, the magnetic moments of the atom align. When the field is removed, the ferromagnets cool down as the magnetic moments become randomly oriented. Soft ferromagnets are the most efficient and have very low heat loss due to heating and cooling processes. Gadolinium, a rare-earth metal, exhibits one of the largest known magnetocaloric effects. Most modern magnetic refrigeration designs employ arc-melted alloys of gadolinium, silicon, and germanium, which provide greater temperature ranges at room temperatures, *[4].*

Magnetic refrigeration is a timely topic of research. The discovery of magnetic materials that exhibit a remarkable change in their temperature when they are adiabatically magnetized close to room temperature has produced a surge in the number of publications on the magnetocaloric effect in the previous two decades.

Simultaneously, as these materials enable the possibility of designing magnetic refrigerators with operation temperatures close to room temperature, there has been a noticeable increase in the development of magnetic refrigerator prototypes, *[5].*

# 3 MAGNETIC REFRIGERATION SYSTEM

Currently, there is a great deal of interest in utilizing the MCE as an alternative technology for refrigeration both in the ambient temperature and in cryogenic temperatures. Magnetic refrigeration is an environmentally friendly cooling technology. Most modern refrigeration systems and air conditioners still use ozone-depleting or global-warming volatile liquid refrigerants. Magnetic refrigerators use a solid refrigerant (usually in the form of spheres or thin sheets) and common heat transfer fluids (e.g., water, water-alcohol solution, air, or helium gas) with no ozone-depleting and/or global warming effects, *[6].*

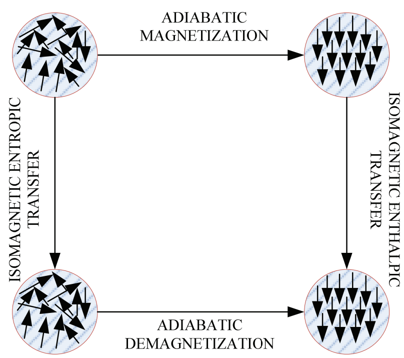


***Figure 1:*** *Thermodynamic processes in magnetic refrigeration*

The manipulation of the magnetic field distribution and the period of the fluid flow gives significant possibilities to form different magnetic refrigeration cycles. The basic goal when introducing new thermodynamic cycles is to reduce the potential magnetic work input and therefore increase the efficiency.

When the magneto-caloric material is subjected to the magnetic field, the magnetic moments of soft ferromagnetic materials become aligned, making the material more ordered. Hence, the material liberates more heat resulting in the decrease of their magnetic entropy. However, when the magnetic material subjected to the magnetic field is reduced isothermally, the magnetic moments become disoriented, due to which the material absorbs heat and, consequently, their magnetic entropy increases, *[7].*

One of the most notable examples of the magnetocaloric effect is in the chemical element gadolinium and some of its alloys. Gadolinium's temperature is observed to increase when it enters certain magnetic fields. When it leaves the magnetic field, the temperature drops back to normal. The effect is considerably stronger for the gadolinium alloy Gd5($Si$2Ge2). Praseodymium alloyed with nickel (Pr$Ni$2) has such a strong magnetocaloric effect that it has allowed scientists to approach within one-thousandth of a degree of absolute zero. Magnetic Refrigeration is also called as Adiabatic Magnetization.

The basic thermodynamic cycle of the magnetic refrigerator is the Brayton Cycle, which operates between two adiabatic and two isomagnetic field lines.

As already discussed, Pure gadolinium may be regarded as being the ideal substance for magnetic refrigeration, just like the ideal gas is for conventional refrigeration. However, just as conventional systems practically cannot be operated with ideal gases, magnetic refrigerators using pure gadolinium are also not possible; they perform better with specially designed alloys. Below is the list of the promising categories of magneto-caloric materials for application in magnetic refrigerators, *[8].*

1. Gadolinium- Silicon- Germanium Compounds
2. Binary and ternary intermetallic compounds
3. Manganites
4. Lanthanum iron-based compounds.

Gadolinium, a rare earth metal exhibits one of the largest known magnetocaloric effects. It was used as the refrigerant in many of the early magnetic refrigeration systems.

In general, at the present stage of the development of magnetic refrigerators with permanent magnets, hardly any freezing applications are feasible, because large temperature spans occur between the heat source and the heat sink. Some current examples are in cooling plants in the food industry or in large marine freezing applications. Some of the future applications are:

1. Magnetic household refrigeration appliances
2. Magnetic cooling and air conditioning in buildings and houses
3. Central cooling system
4. Refrigeration in medicine
5. Cooling in the food industry and storage
6. Cooling in transportation
7. Cooling of electronic

# 4 DESIGN DESCRIPTION

The following layout describes the initial prototype for AMR in magnetocaloric refrigeration. For this purpose, the system is designed in such a way that multiple tubes run along the length of a cylinder of gadolinium. The tubes are arranged in honeycomb orientation to maximize the area packing efficiency.

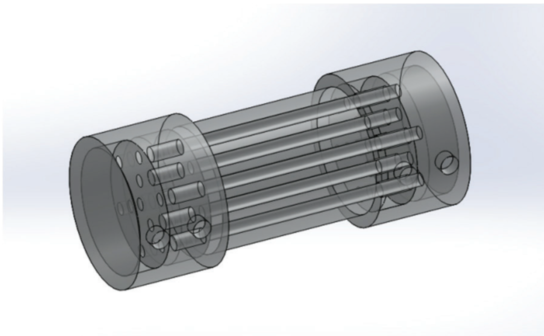

***Figure 2:*** *The 3D regenerator geometry*

Generally speaking, a compressor refrigeration system comprises two exchangers, with one receiving heat from the environment (evaporator) and the other releasing heat to the heating water (condenser) by means of a compressor, an expansion valve, and connecting copper pipes Fig.3. Naturally, a refrigerant is required for the operation of a compressor refrigeration system. Refrigerants are working fluids, transferring heat from a lower temperature level to a higher temperature level. Decades ago, chlorofluorohydrocarbons were widely used for refrigerants in cooling and heating systems. As a result of stricter environmental laws and measures and claims that these refrigerants damage the ozone layer, their application started to be phased out.

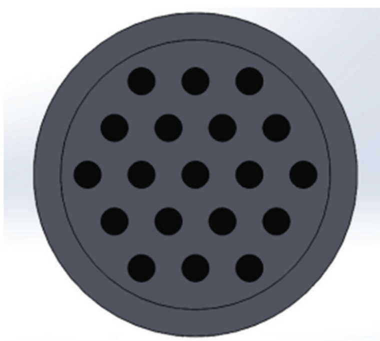

***Figure 3:*** *Arrangement of pipes can be seen in the figure*

The use of new pure refrigerants and mixtures of more environmentally friendly and degradable refrigerants has been increasingly adopted, in case they are unexpectedly released into the

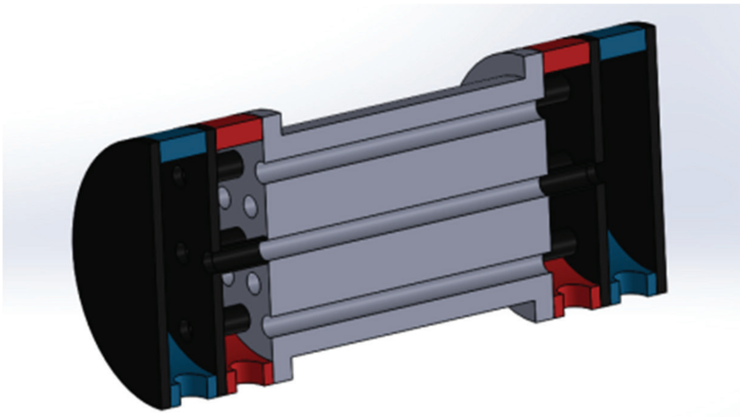

***Figure 4:*** *Section of the regenerator*

The coefficient of performance (COP) of a magnetic refrigerator is the measurement of the thermodynamic quality of the apparatus under consideration; it shows how much (electrical) power P is to be invested for cooling $Q_r$.[10-13]

$$COP = \frac{\dot{Q}_{cold}}{W_{mag}+W_{pump}} = \frac{Q_{cold}}{Q_{hot}-Q_{cold}+W_{pump}} \tag{2.1}$$

In this cross-section view, red is the hot water chamber and blue is the cold water chamber. Black represents the insulated portion, and the grey portion is Gadolinium material. It is worth noting that some portion of cold-water pipes run through the hot water chamber, but they are essentially insulated to prevent inefficiencies. Also, the cold water and hot water pipes are arranged alternatingly to maximize heat transfer for both cold and hot temperature condition.

The arrangement of pipes can be seen in the figure below, which is a cross-section view of one side of the hot water chamber. The grey openings carry hot water into this chamber, and the black openings carry cold water to the next chamber.

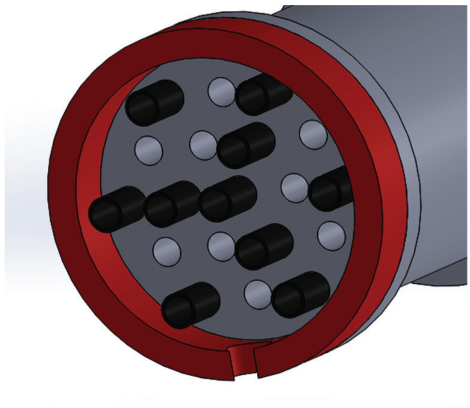

***Figure 5:*** *Cross-section view of one side of the hot water chamber*

In refrigeration units applying superconducting magnets, the efficiency would be further reduced due to the power demand of the magnetic field sources as well as of the supporting cryogen system. In these images, brighter colours represent hotter temperatures.

## 5 MODELLING HEAT TRANSFER BOUNDARIES

We have modelled the preliminary heat transfer model for multichannel AMR. It is done so that internal heat transfer boundaries are modelled as constant flux, and the external gadolinium cylinder boundary is modelled as an insulated boundary. After adiabatic heating, the cold temperature channels do not have any fluid flowing through them, so the convection coefficient is assumed to be 5. Similarly, after adiabatic cooling, the water is only flown through cold water pipes, so the hot pipes have a heat transfer coefficient that is assumed to be 5. For flowing fluid, the convective coefficient is assumed to be 5000.

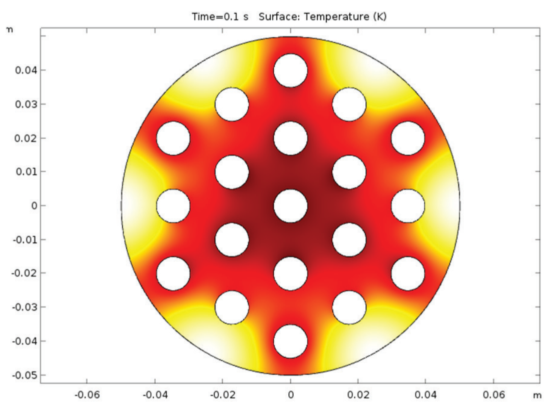


***Figure 6:*** *Iso-field heating*

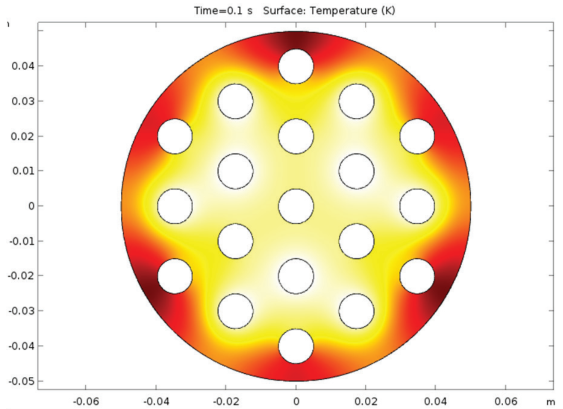


***Figure 7:*** *Iso-field cooling*

The thermal model is based on the finite difference method and solved by the implicit method. It also calculates the thermal capacity and conductivity of the material as functions of H and T and deduces the new temperatures (in fluid and material) with good precision.

# 6 THE ADVANTAGES AND DISADVANTAGES OF THE MAGNETIC REFRIGERATION SYSTEM

## 6.1 Advantages

The environmentally friendly refrigerant used is solid and non-volatile and thus has no greenhouse effect. Conventional refrigerators use refrigerants that contain CFC or HCFC, which have been linked to ozone depletion and global warming. Some refrigerants, such as ammonia, are toxic and flammable.

Low running and operating cost - There is no compressor, which is the most inefficient and costly part, in magnetic refrigerators. This leads to less energy consumption resulting in low running costs.

Higher efficiency - Because it eliminates the need to expand and compress the liquid, a magnetic refrigerator consumes less energy and can operate at 60% efficiency.

Reliability - High energy density and more compact device, fewer moving parts in comparison to traditional systems and thus more reliable.

Quiet operation - This refrigerator unit is substantially quieter than traditional refrigeration systems.

Compactness: - It is possible to achieve a high energy density compact device, because in the case of magnetic refrigeration the working substance is a solid material (e.g., gadolinium) and not a gas, as in the case of vapour compression cycles

## 6.2 Disadvantages

The initial investment is very high in comparison to conventional refrigeration.

The magnetocaloric materials are rare earth materials; thus their availability also becomes a disadvantage. These materials need to be developed to allow larger frequencies of rectilinear and rotary magnetic refrigerators.

Electronic components must be shielded from magnetic fields. However, it must be noted that the fields are static, of short-range and may be shielded.

Permanent magnets have limited field strength, while electromagnets and superconducting magnets are very expensive.

Temperature changes are limited. Multi-stage machines lose efficiency through the heat transfer between the stages.

Moving machines need high precision to avoid magnetic field reduction due to gaps between the magnets and the magnetocaloric material, *[11-12].*

# 7 CONCLUSION

In this article, the mechanism and functioning of the refrigeration system based on the magnetic system and the magnetocaloric effect has been examined, and the initial prototype for AMR in magnetocaloric refrigeration has been described. This is an interesting subject with important applications both in domestic and industrial fields. The industrial applicated will have a significant impact on energy consumption as well as a minimal impact on the environment. The layout in this paper describes the initial prototype for heat exchanger in magnetocaloric refrigeration. For this purpose, the system is designed in such a way that multiple tubes run along the length of a cylinder of gadolinium. The material which was chosen for the study was widely used in the research of magnetocaloric materials. Other alloys are members of the lanthanide period.

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## Nomenclature

| | |
|---|---|
| $t$ | time |
| $\rho$ | density |
| $Q$ | heat released |