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THE EFFICIENCY OF MAGNETIC REFRIGERATION AND A COMPARISON WITH COMPRESSOR REFRIGERATION SYSTEMS

UČINKOVITOST MAGNETNEGA HLAJENJA IN PRIMERJAVA S KOMPRESORSKIM HLADILNIM SISTEMOM

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Abstract

The objective of this paper is to study the magnetic refrigeration process that makes use of solid materials, such as gadolinium silicon compounds, as the refrigerant. This effect was observed many years ago and was used for cooling to low temperatures. Recently, materials are being developed with which sufficient temperature and entropy change are produced which makes them useful for a wide range of refrigeration applications. Magnetic refrigeration is an emerging technology that utilizes this magnetocaloric effect found in a solid state to produce a refrigeration effect.

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Povzetek

Namen prispevka je preučiti magnetno hlajenje, v katerem se kot hladilno sredstvo uporabljajo trdni materiali, kot so na primer goldolinijeve silicijeve spojine. Ta učinek je bil opazen pred mnogimi leti in je bil uporabljen za hlajenje blizu absolutne ničle temperature. V zadnjem času se razvijajo materiali, v katerih se proizvaja zadostna temperaturna razlika in sprememba entropije, zaradi česar so uporabne za uporabo v širokem razponu temperature. Magnetno hlajenje je nastajajoča tehnologija, ki uporablja ta magnetno-kalorični učinek v trdnem stanju, da proizvede hladilni učinek.

1 INTRODUCTION

Modern society mostly uses vapour compression cycles and vapour absorption cycle processes. Moreover, using refrigerants such as chlorofluorocarbons or hydrochlorofluorocarbons (CFCs and HCFCs) have adverse effects on our environment. Recently, the developments of new technologies such as magnetic refrigeration and thermoelectric refrigeration, have brought alternatives to the conventional gas compression technique. One of the most important researchers in this field was Prof. Emil Gabriel Warburg (1846-1931) *[1]*, a German physicist and a professor of physics at the Universities of Strasbourg, Freiburg and Berlin. In 1881, he discovered the magnetocaloric effect in an iron sample. Magnetic refrigeration is a cooling technology based on this effect. This method can be used to attain low temperatures, as well as the ranges used in common refrigerators, depending on the design of the system.

2 WORKING PRINCIPLE OF MAGNETIC REFRIGERATION SYSTEM

Magnetic refrigeration works on the principle of the magnetocaloric effect (MCE), which is a magneto-thermodynamic phenomenon in which a reversible change in temperature of a suitable material is caused by exposing the material to a changing magnetic field, *[1-8].*

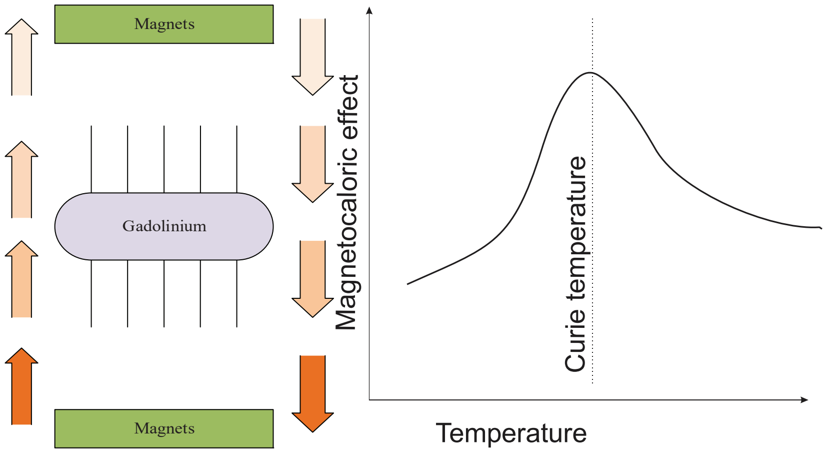

Figure 1: *Magneto-caloric effect*

MCE is the behaviour of a magnetic solid when it is exposed to a changing magnetic field: its temperature may be appreciably increased or decreased, with both the sign and the extent of the temperature difference between the final and the initial states of the material being dependent on numerous intrinsic and extrinsic factors. The chemical composition, the crystal structure, and the magnetic state of a compound are among the most important material parameters that determine its MCE. Magnetic refrigeration is based on a fundamental thermodynamic property of magnetic materials: the so-called magnetic effect, which causes a temperature change if the material is subject to an applied magnetic field under adiabatic conditions.

3 THERMODYNAMICS OF THE MAGNETIC REFRIGERATION SYSTEM

The basic thermodynamic cycle of the magnetic refrigerator is the Ericsson cycle, which operates between two adiabatic and two isomagnetic field lines. The magnetic refrigeration system can be divided into four fundamental steps (Fig. 2, Fig. 3). The temperature of hot and cold heat exchangers has agreat influence on the refrigeration performance, *[1-8]*.

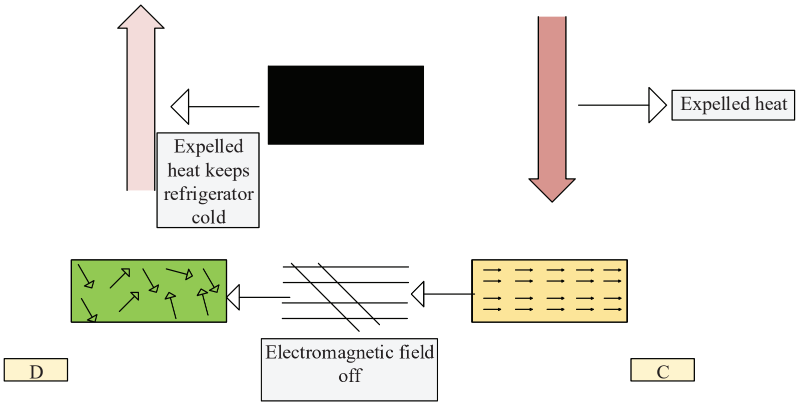

***Figure 2**: Thermodynamic processes in magnetic refrigeration*

1. Adiabatic magnetization: A magnetocaloric material, when placed in an insulated environment(Q=0) and the external magnetic field is increased (+H), causes the magnetic dipoles of the atoms to align, thereby decreasing the material's magnetic entropy and heat capacity.
2. Isomagnetic enthalpy transfer: The magnetic field is held constant during this process (H=0) and the heat added during the adiabatic magnetization is then removed (-Q) by a fluid or gaseous substance to prevent the dipoles from reabsorbing the heat.

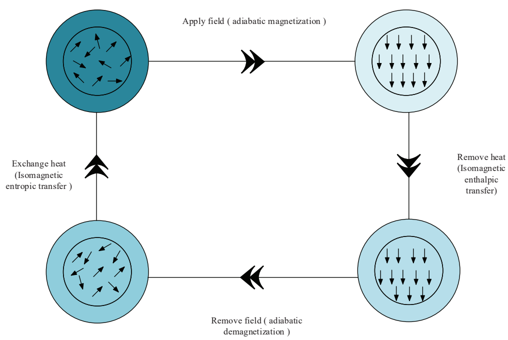

***Figure 3:** Thermodynamic processes in magnetic refrigeration*

3. Adiabatic demagnetization: The substance is returned to another adiabatic process (Q=0), and hence the total entropy remains constant. However, this time the magnetic field is reduced, the thermal energy causes the magnetic moments to overcome the field, and thus the sample cools, i.e. an adiabatic temperature change.
4. Isomagnetic entropic transfer: The magnetic field is held constant to prevent the material from heating back up.

The magnetic field sources that can be used in magnetocaloric devices are permanent magnets and electromagnets. From the theory, we could divide magnetic refrigeration systems into refrigeration systems with moving parts (rotary, linear) or without moving parts. This machine uses as magnetocaloric suspensions working fluid.

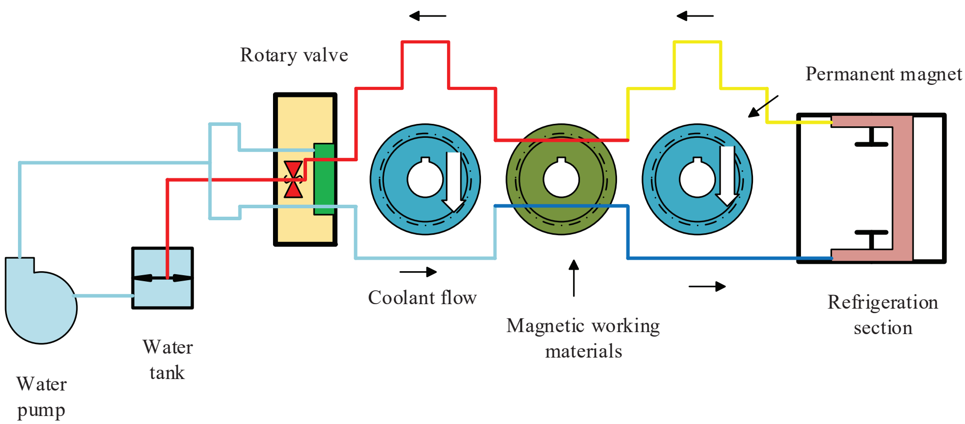

Figure 4: *Components of a magnetic refrigeration system*

Fig. 4 presents a rotational magnetic refrigeration system. Heat is exchanged by means of a circulating coolant (water). Because the magnets rotate, the magnetic working material is repeatedly heated and cooled. The well-timed switching of the direction of coolant flow in coordination with the rotation of the magnets enables cooled coolant to be supplied to areas to be cooled, *[17].*

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 (Figure 5). 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. 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 environment.

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, [16]

$$COP = \frac{\dot{Q}_r}{P} \tag{3.1}$$

$$\dot{Q}_r = \begin{Bmatrix} \dot{Q}_L - \Delta\dot{Q}, \Delta\dot{Q} > 0 \\ \dot{Q}_{L,} \Delta\dot{Q} < 0 \end{Bmatrix} \tag{3.2}$$

$$\Delta\dot{Q} \quad = \dot{Q_{bc}} - \dot{Q_{da}} \tag{3.3}$$

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 this way, the compressor coefficient of performance (COP) in the cooling mode may be defined (Figure 5):

$$COP = \frac{\dot{Q}_{evap}}{P} = \frac{\dot{m}(h_1 - h_4)}{P} \tag{3.4}$$

4 COMPARISON BETWEEN MAGNETIC AND COMPRESSOR REFRIGERATION SYSTEMS

In this chapter, we will analyse magnetic and compressor refrigeration systems for a family house with the required cooling heat of 11 kW. As the refrigerant, we have used refrigerant R-134a in an ideal compression refrigeration cycle. For the modelling of the compressor refrigeration process, we have used the following boundary conditions:

- temperature in the condenser 40^0C
- temperature in the evaporator $-7^0 C$.

The presented analysis is used for the 11 kW required refrigeration heat for summer house cooling.

$$h_1 = 574, h_{2s} = 600\frac{kJ}{kg}, h_3 = h_4 = 480\frac{kJ}{kg} \tag{4.1}$$

With the isentropic efficiency of the compressor of 85% we obtain the enthalpy h_2:

$$h_2 = h_1 + \frac{1}{\eta_s}(h_2 - h_1) = 574 + \frac{1}{0.8}(600 - 574) = 606 \;\; kJ/kg \tag{4.2}$$

The performance of refrigerators and heat pumps is expressed in terms of the coefficient of performance (COP) defined as:

$$COP_R = \frac{Desired\ output}{Required\ input} = \frac{Cooling\ effect}{Work\ input} = \left|\frac{h_1 - h_4}{h_1 - h_2}\right| = \left|\frac{574 - 480}{574 - 606}\right| = 2.94 \tag{4.3}$$

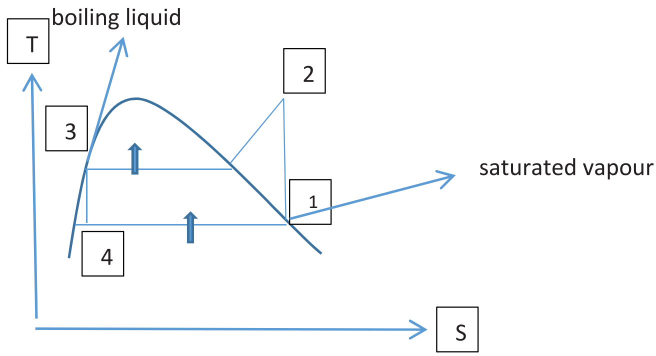

Figure 5: *Ideal compressor refrigeration cycle*

Table 1: *Processes in compressor refrigeration cycle*

Process	Description
1-2	Isentropic compression
2-3	Constant pressure heat rejection in the condenser
3-4	Throttling in an expansion valve
4-1	Constant pressure heat rejection in the evaporator

Compressor power can be calculated from the relation:

$$P_{comp} = \frac{Q_{evap}}{COP} = \frac{11}{2.94} = 3.74\ kW \quad (4.4)$$

The energy consumed by the compressor per day

$$W_{day} = 3.74 \cdot 24 = 89.67\ kW\ per\ day \quad (4.5)$$

The energy consumed by the compressor per month

$$W_{month} = 89.67 \cdot 31 = 2782\ kWh\ per\ month \quad (4.6)$$

The cost of energy per month

$$C = 2782 \cdot 0.13 = €361.6 \quad (4.7)$$

Cost per kWh –€0.13 (4.8)

The magnetic refrigeration system

The most important characteristic's of a magnetocaloric device is its efficiency. It is usually defined by the Coefficient Of Performance (COP). The COP presents a ratio between the refrigeration energy and the total electric energy input. According to the literature [9] the required electric power could be determined this way:

$$P_{el} = \frac{Q_r}{COP} = \frac{11}{9.09} = 1.21\ kW$$
(4.9)

Where:

P_{el} – the energy consumed by the electric motor

The energy consumed by the motor per month

W_{month} =1.21·24·31=900.2 (4.10)

The cost of energy per month

$C = 900.2 \cdot 0.13 = 117.0€$ (4.11)

***Table 2**: Compression Efficiency between classical heat pump and with magnetic heat pump*

Efficiency for heat pump	Efficiency for magnetic heat pump
2.94	9.09
Consumed energy for compressor	Consumed energy for compressor
2782 kWh/month	900.2 kWh/month
The cost of energy/month	The cost of energy/month
€361.6	€117

***Table 3:** Economic analyses for, cost of installation, energy, maintenance and equipment for classical heat pump and magnetic heat pump [16]*

Initial cost		Compressor refrigeration system	Magnetic refrigeration system		
Cost of equipment	€	10000	25000	Difference	15000
Cost of installation	€	3000	1500	Difference	1500
Total initial cost	€	13000	26500	Difference	13500

Annual operating cost		Heat pump	Magnetic heat pump		
Energy consumption	kWh	25176	9816	Difference	15360
Cost of energy	€	3276	1276	Difference	2000
Cost of maintenance	€	1800	1200	Difference	600
Total annual cost	€	5073	2476	Difference	2597

From the analysis of Tables 2 and 3, it can be seen that the purchase of the magnetic cooling system is still significantly more expensive, while the cost of the heating is considerably lower, especially due to a better cooling number. The purchase of the magnetic cooling system pays for itself after around six years. Some benefits and disadvantages of the magnetic refrigeration system are as follows, *[16].*

Benefits:

1. Environmentally friendly - Refrigerant used is solid and non-volatile and hence 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.
2. 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 and hence low running costs.
3. 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.
4. Reliability - High energy density and more compact device, fewer moving parts in comparison to traditional systems and thus more reliable.
5. Quiet operation - This refrigerator unit is substantially quieter than traditional refrigeration systems.
6. Compactness: - It is possible to achieve a high energy density compact device. This is because in 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

Disadvantages:

1. The initial investment is very high in comparison to conventional refrigeration.
2. The magnetocaloric materials are rare earth materials hence their availability also becomes a disadvantage. These materials need to be developed to allow larger frequencies of rectilinear and rotary magnetic refrigerators.
3. Protection of electronic components from magnetic fields. However, it must be noted that they are static, of short range and may be shielded
4. Permanent magnets have limited field strength, while electromagnets and superconducting magnets are very expensive.
5. Temperature changes are limited. Multi-stage machines lose efficiency through the heat transfer between the stages.
6. Moving machines need high precision to avoid magnetic field reduction due to gaps between the magnets and the magnetocaloric material.

5 CONCLUSION

This article presents thermodynamic and economic analysis between magnetic refrigeration system and a conventional refrigeration system. From the analysis, it can be seen that the purchase of the magnetic cooling system is still significantly more expensive, while the cost of heating is considerably lower. The return period for the purchase of the magnetic cooling system is approximately six years.

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Nomenclature

t	time
v	specific volume
COP	coefficient of performance
Q	heat released