Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Eidgenössisches Departement für
Umwelt, Verkehr, Energie und Kommunikation UVEK

Bundesamt für Energie BFE

APPLICATION OF MAGNETIC REFRIGERATION AND ITS ASSESSMENT

A FEASIBILITY STUDY

Final report

Performed by:

Andrej Kitanovski, Marc Diebold, Didier Vuarnoz, Cyrill Gonin, Peter W. Egolf

Haute Ecole d'ingénerie et de Gestion du Canton de Vaud

Route de Cheseaux 1

CH 1401 Yverdon-les-Bains

Switzerland

Peter.egolf@heig-vd.ch

http://www.heig-vd.ch/

Impressum

Datum: *29. April 2008*

Im Auftrag des Bundesamt für Energie
Forschungsprogramm Elektrizitätstechnologien und -anwendungen

Mühlestrasse 4, CH-3063 Ittigen

Postadresse: CH-3003 Bern

Tel. +41 31 322 56 11, Fax +41 31 323 25 00

www.bfe.admin.ch

BFE-Bereichsleiter, thilo.krause@bfe.admin.ch

BFE-Vertrags- und Projektnummer: 101’776/152’191

Bezugsort der Publikation: www.energieforschung.ch / www.electricity-research.ch

INHALTSVERZEICHNIS

ZUSAMMENFASSUNG

Die magnetische Kältetechnik hat das Potenzial die konventionelle Kältetechnik – mit oftmals problematischen Kältemitteln – in mehreren Nischenmärkten oder sogar in einigen Hauptmärkten des Kältebereiches zu ersetzen. Basierend auf dieser Einsicht hat das Bundesamt für Energie (BFE) eine Abteilung der Haute Ecole d'Ingenerie et de Gestion du Canton de Vaud (HEIG-VD) in Yverdon-les-Bains aufgefordert alle möglichen Kältetechnologien aufzulisten und das Potential für die magnetische Kältetechnik für diese spezifischen Anwendungen zu evaluieren. Die HEIG-VD-Forscher haben ein Berechnungs-Hilfsmittel geschaffen, um den „Coefficient of Performance (*COP*)" und den exergetischen Wirkungsgrad als Funktion der magnetischen Feldstärke und der Rotationsfrequenz einer magnetischen Rotations-Kältemaschine zu bestimmen. Die der Studie zugrunde gelegte Maschine entspricht einer, die in einem von diesen Forschern deponierten Patent beschrieben ist. Basierend auf dieser Arbeit wurde herausgefunden, dass vor allem zwei Anwendungen für eine erste mögliche Untersuchung sehr interessant wären: das Haushaltkühlgerät ohne ein Gefrierfach und die zentrale Kälteeinheit (Chiller-Einheit), welche von grosser Abmessung sein kann. In den Kältebereichen, wo magnetische Kühlung erfolgreich angewendet werden könnte, sind die Kosten der magnetischen Kältemaschinen tendenziell etwas höher als jene der konventionellen. Dagegen zeigt die Studie Möglichkeiten auf, wie die magnetischen Kältemaschinen höhere *COP*-Werte als diese der entsprechenden Gas-Kompressions/Expansions-Maschinen erreichen könnten. Somit kann für die magnetische Kühltechnik mit eher tieferen Betriebskosten gerechnet werden. Für grosse Anlagen - wie z.B. den „Chiller-Einheiten" - sollte untersucht werden, ob supraleitende Magnete ökonomisch angewendet werden könnten.

RESUME

La réfrigération magnétique est susceptible de remplacer les systèmes réfrigérants traditionnels dans plusieurs marchés de niche ainsi que certains marchés majeurs de la réfrigération. Le Bureau Fédéral de l'Energie a donc demandé à un laboratoire de la Haute Ecole d'Ingénieurs et de Gestion (HEIG-VD, Yverdon-les-Bains) de recenser toutes les technologies de réfrigération existantes et d'évaluer les possibilités offertes par la réfrigération magnétique. Les chercheurs de la HEIG-VD ont développé des outils de calcul permettant de déterminer le coefficient de performance (COP) ainsi que l'efficacité exergétique de réfrigérateurs magnétiques en fonction de l'intensité du champ magnétique et de leur fréquence de rotation. Le type de réfrigérateur magnétique choisi pour cette étude est basé sur une patente déposée par les collaborateurs de la HEIG-VD. Cette étude a permis de dégager deux applications particulièrement prometteuses: le réfrigérateur domestique sans congélateur et le système de refroidissement central. Dans les domaines de la réfrigération où la réfrigération magnétique pourrait être utilisée avec succès, les coûts des machines fonctionnant avec cette technologie seraient un peu supérieurs aux coûts des machines conventionnelles. Cependant l'étude présente des possibilités qui permettraient aux machines réfrigérantes magnétiques d'atteindre un COP supérieur à celui des machines équivalentes fonctionnant sur le principe de la compression et l'expansion d'un gaz. De plus les coûts opératoires de la réfrigération magnétique devraient être moindres que ceux des technologies classiques. La viabilité économique de systèmes de grande taille (comme par exemple des unités de congélation) utilisant des aimants supraconducteurs devrait aussi être étudiée.

SUMMARY

Magnetic refrigeration has the potential to replace conventional refrigeration systems - with often problematic refrigerants - in several niche markets or even some main markets of the refrigeration domain. Based on this insight the Swiss Federal Office of Energy has asked a division of the University of Applied Sciences of Western Switzerland (HEIG-VD) in Yverdon-les-Bains to list all possible refrigeration technologies and to evaluate the potential of magnetic refrigeration for these specific applications. The HEIG-VD researchers have developed a calculation tool to determine the coefficient of performance (*COP*) value and the exergy efficiency as a function of the magnetic field strength and the rotation frequency of a rotary type of magnetic refrigerator. The considered machine design is based on a patent, which was deposited by these scientists. Based on this work, it is found that especially two applications are very interesting for a closer investigation: the household refrigerator without a freezing compartment and the central chilling unit, which may be of large size. In the domains of refrigeration, where magnetic refrigeration could be successfully applied, the costs for magnetic refrigeration machines would be a little higher than those of the conventional ones. On the other hand the study shows possibilities how the magnetic refrigeration machines could reach higher *COP* values than those of the corresponding gas compression/expansion machines. Therefore, for magnetic refrigeration one may assume lower costs of operation. For large systems - as e.g. chiller units - it should be studied, if superconducting magnets could be economically applied.

1. INTRODUCTION

1.1 State of the art

Magnetic refrigeration is a technology which applies the magnetocaloric effect (MCE). The MCE was first discovered by Warburg [1], who observed in 1881 an increase of temperature when he brought an iron sample into a magnetic field and a decrease when the sample was removed out of it. In 1890 Tesla [2] and Edison [3] independently and unsuccessfully tried to benefit from this effect by running heat engines for “magnetic power conversion”. In 1918 Weiss and Piccard [4] explained the magneto-caloric effect. Later Debye [5] and Giauque [6] proposed a method of magnetic refrigeration for low temperature physics in order to obtain sub-Kelvin temperatures. In 1933 Giauque and MacDougall [7] successfully verified the method by experiment. Since the 1930’s magnetic refrigeration is a standard technique in low temperature physics. It has shown to be useful to cool down from a few Kelvin to some hundredths, or in very skilful applications to a few thousandths of a Kelvin.

In 1976 Brown (see Ref. [8] and [9]) designed the first magnetic refrigerator working at room temperature. Then a number of patents describing such refrigerators were announced. This may be noted as the time of the first generation of magnetic refrigerators. The first “room temperature” magnetic refrigerator – containing permanent magnets – was designed and built in 2001 by Astronautics Corporation in the USA [10].

Then the development of the second generation of magnetic refrigerators began. The early prototypes were able to reach high magnetic flux densities in the magnetocaloric material only if superconducting magnets were applied. At present one may find in the technical and scientific literature numerous prototypes based on permanent magnets operating at magnetic field densities between 1.5 and 2.4 Tesla [11]. This tendency marks a significant improvement of the magnetic cooling technology. Furthermore, the discovery of the “giant” magnetocaloric effect by Gschneidner and Pecharsky in 1996 (e.g. see In Ref. [11]) brought the magnetic cooling technology closer to practical applications. The research in magnetic refrigeration is nowadays focused on improvements on magnetocaloric materials, magnets and an optimal design and building of devices.

Our team at the HEIG-VD is at present developing the so called third generation of magnetic refrigerators (patent files have recently been sent for protection). This new machines hopefully will bring the Swiss developments a step closer to some suitable market applications. The interest of the conventional industries in the 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. On the other hand, the research activities of industries working in the domain of conventional or industrial refrigerators (chillers) are surprisingly small. These companies are not yet active in the domain of magnetic cooling although their domain shows a large potential for this “new” raising technology. Beside industry also venture capital holders are developing some interest in magnetic refrigeration. 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, as numerous other research teams, are now starting some actions with European industries.

1.2 Magnetic refrigeration and magnetocaloric effect

Magnetic refrigeration is an adiabatic cooling method which applies the magnetocaloric effect (MCE). The entropy is used to measure the order in a magneto-thermodynamic system: a well-ordered system has low entropy and vice versa. The total entropy of a magnetocaloric material results of three contributions (magnetic, electronic and lattice). If the electronic spins in a paramagnet, a ferromagnet or a diamagnet are oriented in the same direction, the order and also the magnetization are high. It is clear that applying a magnetic field aligns electronic spins and lowering the temperature (by releasing energy from the system) also leads to a more ordered system. Therefore, in the sense of the theory of critical phenomena, the external magnetic field yields the stress parameter and the magnetization the order parameter of such magnetic materials. If a magnetocaloric material is moved into a magnetic field, this usually is a fast process. Practically no heat will be exchanged with the environment. Then for this adiabatic process the total entropy s - which in usual cases is the sum of the magnetic s_M, electronic s_E and lattice entropy s_L - rests constant: $s=s_M+s_E+s_L=const$. If the magnetization increases the magnetic entropy s_M decreases and the remaining electronic and lattice entropies, s_E and s_L, must increase. By spin-lattice couplings - which occur in milliseconds - phonons or lattice vibrations are created. These oscillatory movements can be compared with Brownian motion of atoms or molecules in a gas. They increase the temperature of the solid material. Now it becomes clear that removing the magnetocaloric material out of the magnetic field lowers its lattice vibrations and its temperature, because now the magnetic moments and spins take up energy from the lattice and become disordered again.

The magnetic refrigeration may be compared with the conventional vapour compression technology, as shown in Figure 1, especially for the processes of magnetization-demagnetization (compression and expansion respectively). Despite analogy, the physics of the processes are different and some differences may also be observed in heat transfer processes. For example the heat addition and rejection in a gaseous refrigerant is a rather fast process, because turbulent motion transports heat very fast. Unfortunately this is not the case in the solid magnetocaloric materials. Here the transport mechanism for heat is the slow molecular diffusion and therefore filigree porous structures are considered to be the best solution to overcome this problem. Having small distances from centre regions of the material to the adjacent fluid domain (heat transport fluid) is ideal to make the magnetic cooling process faster. Furthermore, the not very large adiabatic temperature differences of magnetocaloric materials will require more often a design of cascade or regenerative stages in magnetic refrigerators compared to the number of stages in conventional refrigerators and hence require additional heat transfer steps.

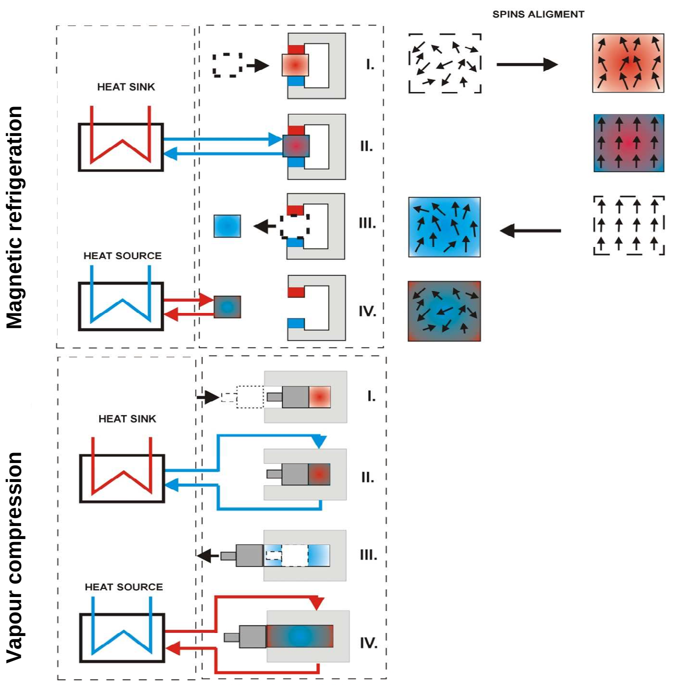


Figure 1: *The analogy between magnetic refrigeration and conventional vapour compression cycle. Here the four basic steps of a conventional gas compression/expansion refrigeration process are shown. These are the compression of the gas, rejection of heat, expansion of the gas and addition of heat. The two process steps (rejection of heat and expansion) are responsible for a cooling process in two steps. The main cooling usually occurs by the expansion of the gas. The steps of a magnetic refrigeration process are analogous. By comparing the two cycles, one can see that instead of compression of a gas a magnetocaloric material is moved into a magnetic field and that instead of expansion it is moved out of the field. As explained in the previous section these processes change the temperature of the material and heat may be extracted, respectively added just as in the conventional process.*

The achievable temperature increase of gadolinium, $\Delta\vartheta$, for different "magnetic field" changes, $\mu_0 H$, are shown in Figure 2. For all field changes the temperature decrease occurs at the higher temperature $\vartheta+\Delta\vartheta$, with the same absolute value of the temperature change, $|\Delta\vartheta|$, in the heating and cooling case.

1.3 Magnetocaloric materials

Optimal properties of magnets and magnetocaloric materials are required to apply the magnetocaloric effect with high performance. For this all the different families showing a large magnetocaloric effect have to be taken into consideration. The properties of the actual best magnets can not be discussed in this brief note, but they can be found e.g. in Ref [12].

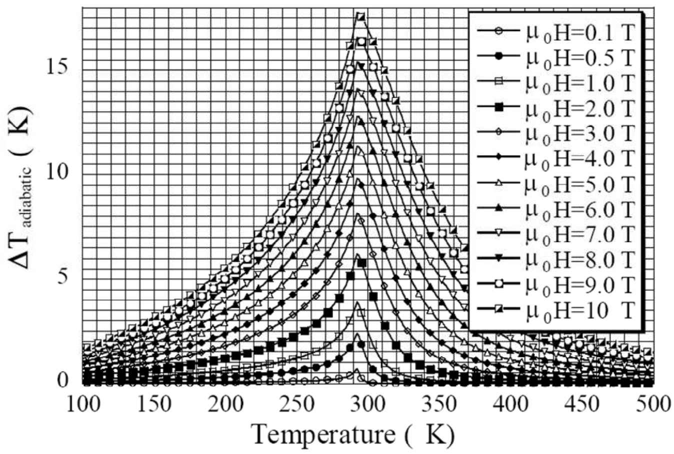


Figure 2: *The adiabatic temperature change of gadolinium in the vicinity of the Curie temperature $T_c \cong 20°C$. In Ref. [13] a slightly improved version of this graphics will be shown.*

Pure gadolinium may be regarded to be the ideal substance of magnetic refrigeration, just as the ideal gas is for conventional refrigeration. But as conventional systems are usually not operated with ideal gases, magnetic refrigerators will perform better with specially designed alloys (see below). An advantage of pure gadolinium is that its physical properties may be described by basic physical laws, as e.g. the Brioullin function for the magnetization or the Debye function for the specific heat, etc. This allows the numerical calculation of magneto-thermodynamic charts of high resolution (see Ref. [13]). To produce such charts for magnetocaloric alloys would demand a tremendous amount of high-quality experimental data, which usually are not available. Therefore, it generally makes sense to begin a first testing of a magnetic refrigerator prototype with a gadolinium filling. After the teething troubles of a new machine have been solved with the gadolinium content, it may be replaced by better magnetocaloric alloys.

Gschneidner and Pecharsky [14] have published the following list of promising categories of magnetocaloric materials for an application in magnetic refrigerators:

- Binary and ternary intermetalic compounds
- Gadolinium-Silicon-Germanium compounds
- Manganites
- Lanthanum-Iron based compounds
- Manganese-Antimony Arsenide
- Iron-Manganese-Arsenic Phosphides
- Amorphous fine met-type alloys (very recent).

At present some toxic substances in such compounds are being replaced by more accepted elements. A discussion of the different types of materials with their distinct properties can be found in extended topical reviews as Ref.'s [14, 15]. Currently the total entropies and the related refrigeration capacity, the adiabatic temperature change and the costs of the materials are under investigation. Brück states that in the near future other properties will also become important, such are the corrosion resistance, mechanical properties, heat conductivity, electrical resistivity and the environmental impact [15].

The theoretical maximum specific refrigeration capacity and its derivation are described in Appendix 3. For pure gadolinium, this is reaching 977 J/kg at a change of 1 Tesla "magnetic field" strength and is then slightly converging at higher field changes (e.g. 1450 J/kg at a change of 2 Tesla). One should notice that at present the best magnetocaloric materials can reach around twice the specific refrigeration capacity of that of gadolinium. Materials with low magnetic hysteresis are favourable, because the area of a hysteresis curve in coordinates of *M* vs. *H* corresponds to an energy dissipated to the environment in each cycle. Because all magnetocaloric materials are limited by a restricted domain of operation around the Curie temperature, with the maximal magnetocaloric effect at Curie temperature, it makes sense to perform layered beds (with different magnetocaloric materials) in the direction of a changing temperature distribution, in order to obtain at each temperature an optimal or close-to optimal magnetocaloric cooling effect.

1.4 Magnetocaloric machines

To occur in a magnetocaloric material, the magnetocaloric effect requires a magnetic field change. This can be performed with different magnetic refrigeration principles:

- Alternatively changing magnetic fields in static blocks of magnetocaloric material by an application of electro magnets
- Rectilinear motion of magnetocaloric material with static permanent magnet assemblies
- Rectilinear motion of permanent magnet assemblies with static magnetocaloric material blocks
- Rotary motion of magnetocaloric material with static permanent magnet assemblies
- Rotary motion of permanent magnet assemblies with static magnetocaloric material blocks
- Rotary or rectilinear motion of soft permeable materials with static magnets and magnetocaloric materials.

The four basic magneto-thermodynamic cycles are the Carnot cycle, the Brayton cycle, the Ericsson cycle and the Stirling cycle. A review of the magneto-thermodynamics of magnetic refrigeration is given in Ref [16]. In this article also cascade and regeneration processes are explained. Another concept is the application of the active magnetic refrigeration principal (AMR) [14]. Up-to-present some thirty prototypes have been published and some of their characteristics were listed (for a partial overview see Ref [11]). The frequency of operation determines the power of a magnetocaloric machine. None of the above mentioned prototypes does exceed the frequency of 5 Hz. However, our analysis has shown that higher frequencies of operation are feasible and are limited mostly by the speed of heat diffusion (conduction) through the magnetocaloric material. In future applications very small porous structures may enable frequencies even beyond 10 Hz.

1.5 Advantages, drawbacks and future perspectives of magnetic refrigeration

The magnetic refrigeration has many advantages in comparison with the direct evaporation refrigerating machines:

- "Green" technology, no use of conventional refrigerants (negligible Global Warming Potential (GWP) and Ozone Depletion Potential (ODP))
- Noiseless technology (no compressor) and low vibrations
- Higher energy efficiency. In analogy to conventional compression cycles, the magnetization ("compression") and demagnetization ("expansion") are close to reversible, leading theoretically to a 20-30% higher exergy efficiency
- Simple design of machines with small number of moving parts
- Low maintenance costs
- Low (atmospheric) pressure. This is an advantage for e.g. air-conditioning and refrigeration units in automobiles.

On the other hand some disadvantages are:

- Magnetocaloric materials and permanent magnet materials are costly, especially without mass production
- Magnetocaloric materials as well as machines need to be developed to allow higher frequencies of rectilinear and rotary magnetic refrigerators
- Electronic components must be protected from magnetic fields. But notify that these fields are static, of short range and may be shielded
- Permanent magnets have limited field strength. Electro magnets and superconducting magnets require additional cooling and are (too) expensive
- Temperature changes are limited. Multi-stage machines loose efficiency by the heat transfer between the stages
- Moving machines require a high precision to avoid a magnetic field reduction due to gaps between the magnets and the magnetocaloric material.

Considering the present developments of magnetocaloric materials, permanent magnet assemblies and magnetocaloric devices, one may predict the following for a medium term period:

- high magnetic flux densities provided (e.g. > 1.5 Tesla)
- special layered or even hybrid magnetocaloric materials with a at least higher magnetocaloric effect than that of gadolinium and with a small hysteresis effect

- low pressure losses and improved heat transfer efficiencies of magnetocaloric porous structures
- higher frequencies of operation of magnetic refrigerators (e.g. ≥ 5 Hz).

2. PROJECT DESCRIPTION WITH GOALS

The objective of this project is a broad overview study of the potential of feasible applications of the magnetic cooling and refrigeration technology. It should result in the evaluation or even selection of some domains, where magnetic refrigeration could be competitive compared to conventional cooling technologies. Always the corresponding vapour-compression based refrigerator is taken to define the standard for a comparison with the magnetic cooling system under consideration. Therefore, the project comprises different tasks as listed in the following section:

1. Overview of the magnetic refrigeration technology
2. Advantages and drawbacks of magnetic refrigeration
3. Comparison with existing refrigeration technologies
4. A list and short descriptions of possible applications of magnetic cooling or refrigeration
5. Model, analysis and presentation of results on key technical characteristics for selected applications, e.g. coefficient of performance, exergy efficiency, etc.
6. World market potential for selected applications
7. Comparison of selected applications with the conventional ones
8. Proposal for further work.

The study was focused primarily on investigating the following conventional refrigeration technologies:

1. Household refrigeration and freezing appliances
2. Cooling and air conditioning in buildings
3. Cooling and freezing in medicine
4. Cooling, heating, freezing and storage in food industry
5. Cooling and freezing in transportation
6. District cooling systems
7. Cooling and heating in industrial processes
8. Supermarket applications
9. Electronics cooling.

3. EVALUATION METHODS

For the purpose of this feasibility study, special methods were developed for the evaluation of efficiencies, dimensions and masses of magnetic refrigerators. Here these methods are described only briefly. More comprehensive information is obtained by consulting Appendix 3. The following works led to the development of these unique studies or methods:

- Study of magnetocaloric material properties (e.g. Gadolinium)
- Study and numerical simulation of the properties of permanent magnet assemblies
- Collecting and presenting data on conventional cooling and refrigeration technologies
- Development of a model to determine the heat transfer efficiency of a magnetic cooling device
- Development of a model to predict the fluid flow efficiency in a magnetic cooling device
- Modification of an existing geometrical model describing the magnetocaloric porous structure
- Mathematical-physical description of energy losses and their related efficiency reductions
- The implementation of exergy and *COP* efficiency calculations into the physical model
- The development of models (by empirical and numerical analysis) for the volume and mass determination of different parts of a magnetic cooling device as also their overall quantities.

The calculations were based on Excel and its macros, Matlab and some finite element analysis tools frequently applied in the field of magnetism (on the market available standard software). The large number of different refrigeration applications studied in this project required a rather simple calculation method, which on the other hand could be applied successfully in a study of a very broad range of different technologies.

Comparing magnetic cooling and refrigeration technologies with the conventional counterpart, usually for the conventional technology the available data is related to the evaporation and condensation temperature of the considered machine. This required defining the magnetic refrigeration temperature levels with a certain analogy to the ones of conventional systems. The corresponding temperatures are the two temperatures of the magnetocaloric material in the porous heat exchangers of a magnetic refrigerator on the cold and hot side. But be aware that these latter may be not as constant as they are in a condensation or evaporation process. Because of this choice, here the external heat exchangers of the source and sink were not considered.

In most cases the comparison between the conventional and the magnetic refrigeration is not as it actually should be. For the conventional technology experimentally determined values are taken and compared with pure theoretically determined values of the magnetic refrigeration systems. Because of the present state of development of the magnetic refrigeration technology, it is impossible to already have measured data available. Therefore, to make a fair comparison, it is very important to take all the possible losses into consideration. Only in a future stage the predicted results may be experimentally verified. The losses, which were incorporated into the physical model, are the following:

1) Energy to turn the rotary wheel against the occurring magnetic force (moment)
2) Hysteresis effct of magnetocaloric material
3) Eddy currents in magnetic parts
4) Heat transfer losses between the numerous stages of the process
5) Heat transfer losses in the heat exchangers at the source and sink
6) Heat gains from the environment
7) Energy losses given by the fluid flows through the porous structures with their pressure drops
8) Internal losses of pumps or ventilators.

Only the energy loss of the fluid boundary flow between the rotating porous cylindrical wheel and the not moving cylindrical outer wall of the machine was neglected, because at the investigated low frequencies this leads to minor contributions.

4. ACCOMPLISHED WORK AND ACHIEVED RESULTS

A comprehensive study on all refrigeration technologies led to an evaluation and a selection of best possible applications in the area of magnetic refrigeration technologies. In such a study, where mainly the newest developments are discussed, the following facts were taken as basis for the evaluation:

- magnetic flux density in the magnetocaloric material should be higher than 1 Tesla in order to obtain comparative or better efficiencies than those of conventional compressor systems
- magnetic refrigeration should preferably not be applied for deep freezing, especially when working with magnetic sources. Such sources are permanent magnets. For freezing applications the magnetic flux density should be beyond 2 Tesla!
- the volume fraction of magnetocaloric material should be above 10%, but lower than approximately 40-50% in order to guarantee small pressure losses and a fast heat diffusion through the magnetocaloric porous structure
- the optimal frequency of operation strongly depends on the magnetocaloric porous structure, but also on the volume fraction and the magnetic flux density. In certain cases, the frequency of operation may be beyond 10 Hz. This influences positively the compactness of devices.

An interesting solution to successfully realize magnetic freezing applications is the application of superconducting magnets. However, this may only be economic for large refrigeration units. Such units are used for freezing, e.g. in cooling plants in food industry or in large marine freezing applications. Another possibility is the application of a hybrid system, resulting in a combination of magnetic cooling with another kind of cooling technology, which even could be the conventional one.

A more comprehensive description of most refrigeration technologies is given in Appendix 1. There, the chapter on industrial refrigeration is mainly dealing with food industry, because it presents the largest domain of industrial refrigeration. Furthermore, refrigeration in polygeneration (e.g. trigeneration) systems was not separately studied, because it is tightly related to centralized or district cooling systems. Based on the analysis the following technologies seem to be feasible, and the selection of most appropriate technologies are named after the first list:

a) Magnetic household refrigeration appliances

- Household refrigerator without freezer
- Wine/beverage refrigerator.

b) Magnetic cooling and air conditioning in buildings and houses

- Magnetic RAC (RAC – Room Air Conditioning unit), window, wall or ceiling mounted
- Magnetic split system (e.g. single outside heat rejection unit, multiple inner cooling units).

c) Central cooling system

- Magnetic water cooled water or brine chillers (water/water, brine/brine)
- Magnetic air cooled water or brine chillers (water/air, brine/air).

Both units may be used for fan coils, ceiling cooling devices or in air-conditioning systems.

d) Refrigeration in medicine

- Blood plasma storage refrigerators, chromatography and other laboratory refrigerators
- Walk in rooms (refrigeration, not freezing).

e) Cooling in food industry and storage

- Food production:
    - Refrigerated silos, vessels or blenders, e.g. in diary industry
    - Wine and beer fermenters
    - Beverage carbonation.

- Food processing for storage:
  - Hydrocooling of vegetables and fruits (by immersing)
  - Forced air cooling of vegetables and flowers
  - Spray chilling or brine cooling of meat
  - Dry air coolers for meat.

- Food storage:
  - Cold storage of fruits, vegetables and flowers
  - Short term storage of meat products
  - Refrigerated walk in rooms
  - Cold storage rooms with temperatures above freezing.

f) Cooling in transportation

- Air conditioning in land transport

Too large temperature spans avoid that the magnetic refrigeration technology can occur for such applications. On the other hand an application of a hybrid system, namely magnetic refrigeration combined with another cooling technology, may be a feasible solution. Another option is an off-board cooling of PCM's (Phase Change Material) and their introduction to vehicles as a passive non-mechanical cooling method. This is at present mostly applied in trains.

- Marine air conditioning

Sea water cooled magnetic refrigerators serving as central cooling units in e.g. yachts and ships (e.g. ship carriers, ship cruisers). In large ships the possibility of introducing a superconducting magnet based magnetic refrigerator seems feasible. This method could also allow freezing.

- Refrigeration of food or other goods in transportation

  - Refrigeration of vegetables or cut flowers in truck trailers, refrigerated mechanical rail cars, ship containers
  - Centralized or decentralized magnetic refrigeration units in ships (use of sea water for heat rejection) for food storage (e.g. walk in rooms, compartments in ships, cold rooms, etc). Large carrier or cruiser ships enable use of refrigerators (or even freezers) based on superconducting magnets.

g) District cooling systems

These systems could enable the application of permanent magnets as well as refrigerators with superconducting magnets, especially because the total cooling power of such systems is usually higher than 10 MW.

h) Supermarket applications

- Living comfort (see e.g. b) and c))
- Food storage (see e.g. e))
- Display cabinets (refrigerators only) and the glass-door and chest-type refrigerators (all such applications may be centralized or decentralized by the application of magnetic refrigeration).

j) Cooling of electronics

Cooling of electronics by the magnetic refrigeration technology may be provided rather by e.g. central cooling systems than by local devices. The main reason for this is that in the local devices a strong shielding of the magnetic fields is demanded. But still they may be applied in certain special cases, e.g. in the surroundings of certain units (e.g. mobile telephone, etc).

5. BEST SUITABLE APPLICATIONS

5.1 Introduction

A detailed evaluation by an analysis on the above listed technologies - which is shown in succeeding sections - led to a choice of four best suited examples for an application of magnetic cooling:

1) ***Household refrigerator appliances***
2) ***Central cooling systems***
3) ***Room air conditioners***
4) ***Supermarket refrigeration applications.***

Central magnetic chillers units are applied in a large number of different domains. This may be also recognized when looking at the more detailed sections corresponding to the above presented list of applications. Other very important applications are the household refrigerator appliances without freezers, which are for instance household refrigerators, hotel minibar refrigerators and wine/beverage refrigerators. Those applications show similarities to refrigerators used in medicine, as well as with supermarket applications with glass door refrigerators or display cabinet refrigeration.

5.2. Household refrigeration appliances

The world production of compressors for household refrigerators and household freezers presented in 2003 was approximately 100 million units [18]. The estimated world market is approximately 4 billion US $ per year. The ambient room temperature for household refrigerators varies between 16 to 32℃. The lowest temperature in the cooling compartment is usually around 4℃, depending on the specific application. One should note that the operating conditions strongly depend on the outer or/and inner temperature level. Usually a free convection heat transfer occurs in the inner compartment as well as on the condenser side out in the room. Because these heat transfers are low, the evaporation of the refrigerant in conventional household refrigerators occurs approximately 10 K below the required temperature in the internal space of the refrigerator. The same is true for the condensing temperature; it is usually at least 10 K higher than the temperature of the ambient room air. These two temperature differences lead to high irreversibilities and they have a negative influence on the efficiency of the cooling machine. Now it is not surprising anymore to understand that usually *COP* values lower than 2 occur. Household refrigerators without a freezing compartment do not require a very high cooling power. Maximal values are around 200 W. In the case of an application of the magnetic refrigeration technology, water or brine should be taken as heat transfer fluid. It has to be emphasized that this has to be related to the design of the condenser as well as to the “cold” heat exchanger, which replaces the evaporator. Therefore, one may assume that the development of magnetic household refrigerators will lead to slightly different internal designs of refrigerator containers. Figure 3 shows an example of a conventional refrigerator without a freezing compartment and Figure 4 a schematic drawing of a magnetic household refrigerator, how it could be successfully realized.

Figure 3: *Example of a conventional household refrigerator (www.liebherr.com). The condensing tubes are mounted to the back side of the refrigerator. It is highly insulated and has low power consumption. The minimal temperature is usually 4℃, depending on the specific application. Such types of refrigerators have a low cooling power, e.g. less than 100 W.*

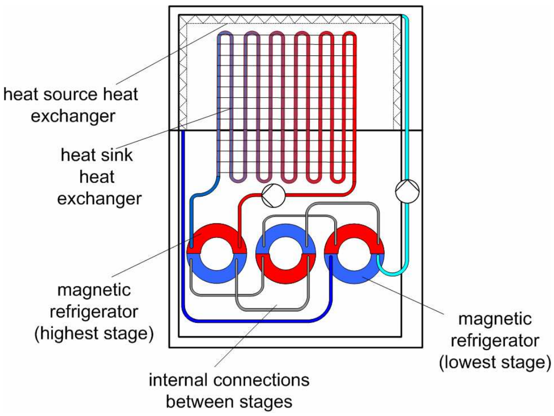


Figure 4: *A schematic sketch shows how a three-stage magnetic household refrigerator could be designed, if it is based on a patent, which was deposited by HEIG-VD/SIT. The three red/blue rotor wheels are connected to perform regeneration cycles. Notify that the design may permit to only have two pumps in such a multi-stage machine.*

A comprehensive analysis was performed to investigate household refrigerators with a cooling power of 50 W. The comparison was made between a magnetic refrigerator and a compressor-based machine of usual size as applied in a typical household appliance. According to the operating characteristics one also expects that in compression/expansion refrigerators the temperature difference between the refrigerant and the internal, respectively external temperature level is higher than in a magnetic refrigerator. Figure 5 shows the comparison of the *COP* of a rotary magnetic household refrigerator (magnetic flux density 2 Tesla) with the one containing a hermetic compressor. A star in Figure 5 (*) denotes that the temperatures are identical to the condensing, respectively to the evaporation temperature of the refrigerant. From Figure 5 it follows that the frequency of operation depends on the characteristics of a magnetic refrigerator. The reason for that is that a higher velocity of the working fluid leads to a higher pressure drop and, therefore, also to higher irreversibilities. Also Figure 6 - which presents the exergy efficiency - shows that a magnetic household refrigerator is competitive to one containing a compressor. This is especially the case when the frequency is low, e.g. below 5 Hz. In order to be competitive to compressor refrigerators, for a high magnetic flux density change the frequency should also be high.

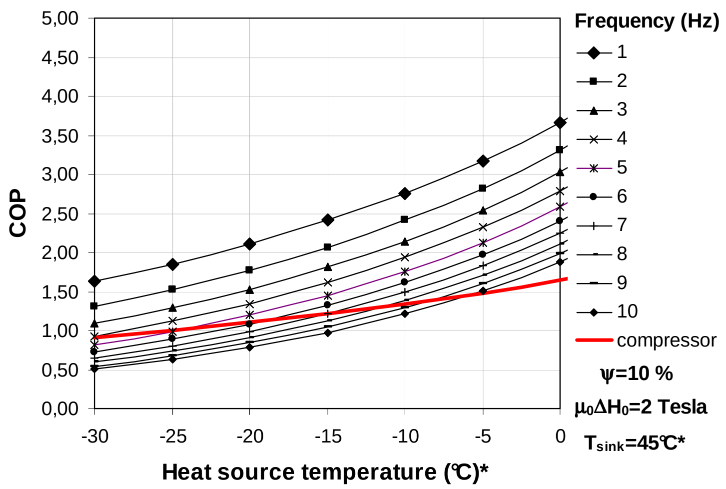


Figure 5: *The COP of a magnetic household refrigerator as a function of the heat source temperature and the frequency of operation for a magnetic flux density change of 2 Tesla is shown. The red line corresponds to the COP of Danfoss hermetic compressors (LBP/MBP and MBP/HBP, R404a/R507, type FR 6CL, condensing temperature 45 ℃).*

Very valuable information is also the total mass and volume of a magnetic refrigerator and their comparison with the corresponding values of the conventional compressor equipment. They depend on the magnetic flux density, frequency of operation as well as on the volume fraction of the applied magnetocaloric material. Figures 7 and 8 show a comparison of the total mass and volume between a magnetic household refrigerator with 50 W power consumption and the conventional hermetic compressor system. Volume fractions of 10% of the porous magnetocaloric structure lead to a large total mass. On the other hand, the volume does not differ so drastically. This is a good result, because of limits of the available volume in a household appliance. As one may conclude from Fig.'s. 5 to 8, designing a machine with only 10% volume fraction and 2 Tesla magnetic flux density requires a rather high temperature of the heat source (e.g. > -5℃ of equivalent temperature to evaporation) or a low temperature of heat sink (<45℃). This statement applies, if the fr equency has to be kept high (e.g. up to 10 Hz) in order to perform a compact device with an efficiency higher than the one of the usual conventional compressor device.

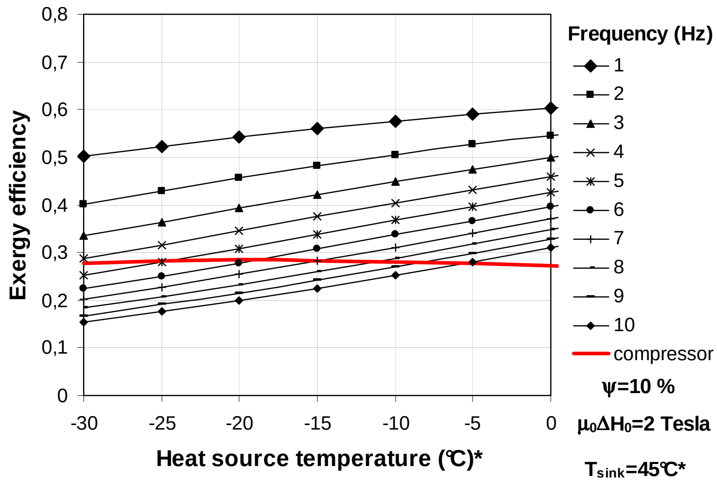


Figure 6: *The exergy efficiency as a function of the heat source temperature when a magnetic flux density change of 2 Tesla is applied. The data are shown for numerous rotation frequencies of operation. The red thick line shows the exergy efficiency of the same hermetic compressors as described in the figure caption of Fig. 5. A star (*) denotes that the temperatures are identical to the condensing, respectively to the evaporation temperature of the refrigerant.*

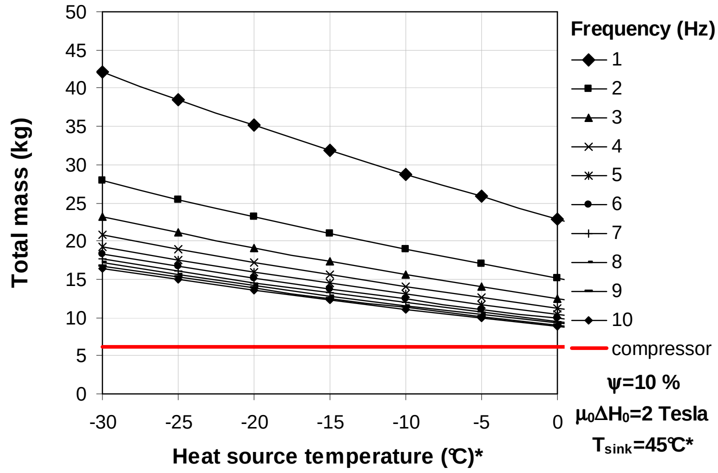


Figure 7: *The total mass of a 50 W refrigerator as a function of the heat source temperature when a magnetic flux density change of 2 Tesla is applied. The data are shown for numerous rotation frequencies of operation. The red thick line shows the approximate mass of hermetic compressors as described in the figure caption of Fig. 5. A star (*) denotes that the temperatures are identical to the condensing, respectively to the evaporation temperature of the refrigerant.*

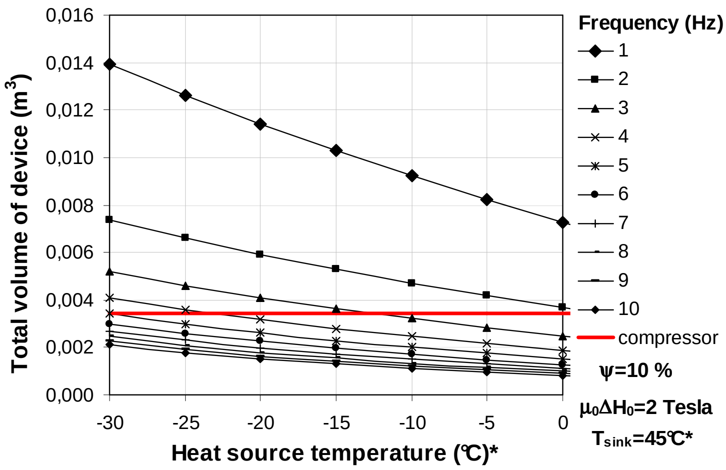


Figure 8: *The total volume of a 50 W refrigerator as a function of the heat source temperature when a magnetic flux density change of 2 Tesla is applied. The data are shown for numerous rotation frequencies of operation. The red thick line shows the approximate mass of hermetic compressors as described in the figure caption of Fig. 5. A star (*) denotes that the temperatures are identical to the condensing, respectively to the evaporation temperature of the refrigerant.*

Therefore a question arises: What is the limiting magnetic flux density, which still enables an efficiency comparable to that of a compressor based refrigerator, especially when considering also a limited volume and total mass of the machine? Figures 9-12 show such results for a volume fraction of 10%.

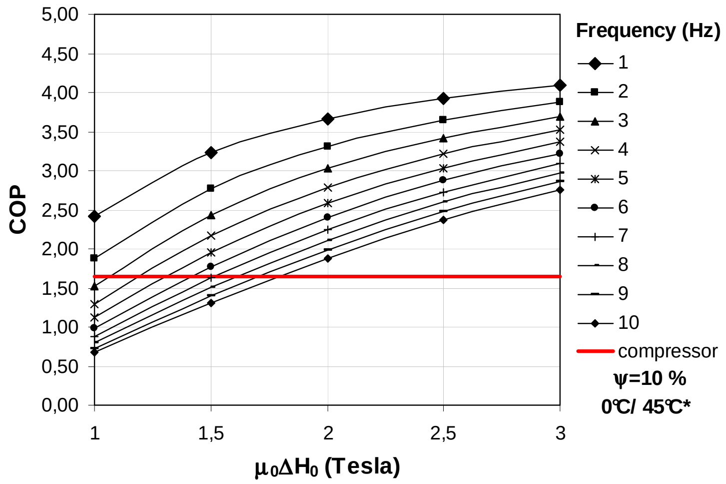


Figure 9: *The COP of a magnetic household refrigerator as a function of the frequency of operation for different magnetic flux densities is shown. The red line corresponds to the COP of a Danfoss hermetic compressor (MBP/HBP, R404a/ R507, type FR 6CL, condensing temperature 45 ℃). A star (*) denotes that the temperatures are identical to the condensing/evaporation temperature of the refrigerant.*

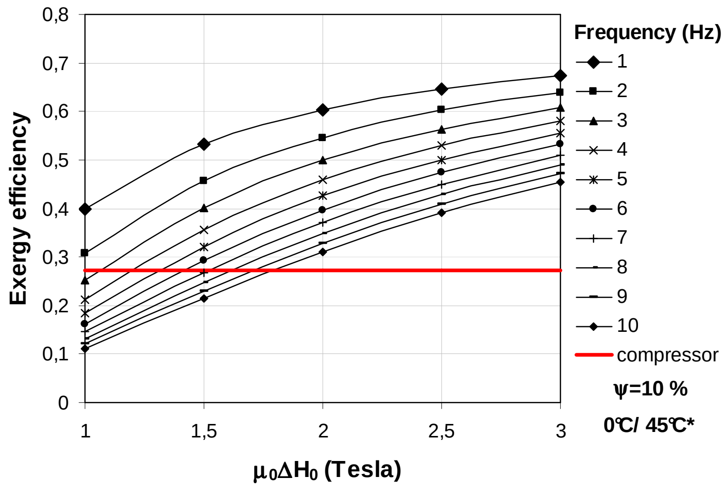


Figure 10: *The exergy efficiency of a magnetic household refrigerator as a function of the frequency of operation for different magnetic flux densities is shown. The red line corresponds to the COP of a Danfoss hermetic compressor (MBP/HBP, R404a/R507, type FR 6CL, condensing temperature 45 ℃). A star (*) denotes that the temperatures are identical to the condensing/evaporation temperature of the refrigerant.*

According to Fig. 9 a magnetic refrigerator operating with frequencies up to 10 Hz becomes competitive to the conventional machine at magnetic flux densities beyond 1.5 Tesla. For the total volume of the device the limit is not so restrictive (see Fig. 8). A small volume requires a high frequency. It is seen in Fig.'s 8 and 9 that this has also an influence on the efficiency. Figures 11 and 12 show the total mass and total volume depending on different magnetic flux densities.

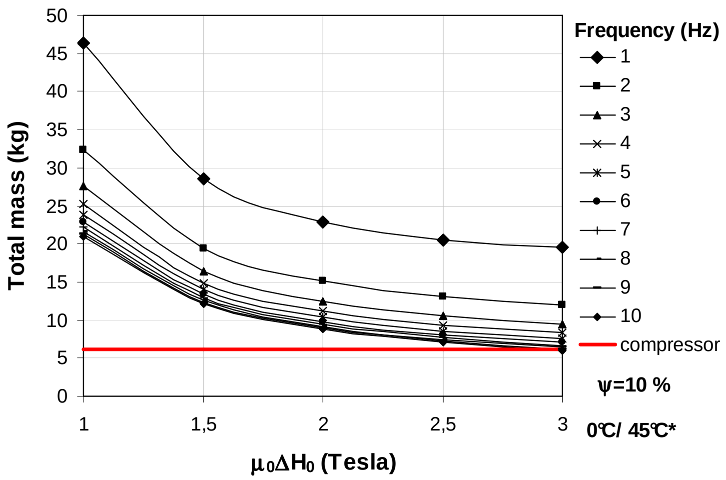


Figure 11: *The total mass of a 50 W refrigerator as a function of the magnetic flux density. The data are shown for numerous rotation frequencies of operation. The red line corresponds to the total mass of a Danfoss hermetic compressor (MBP/ HBP, R404a/R507, type FR 6CL, condensing temperature 45 ℃).. A star (*) denotes that the temperatures are identical to the condensing/evaporation temperature of the refrigerant.*

In Fig. 11 one sees that the total mass of a magnetic refrigerator approaches the one of a hermetic compressor in the case that the magnetic flux density is approximately 3 Tesla and the frequency is high. Because at present 3 Tesla is the maximal realizable field strength for an economic magnetic refrigerator with permanent magnets, a reduction of the total mass can be easier obtained by an increase of the volume fraction of the magnetocaloric material. This is shown in Appendix 1. Studying this appendix one experiences that increasing the volume fraction to 30% substantially reduces the mass and the volume.

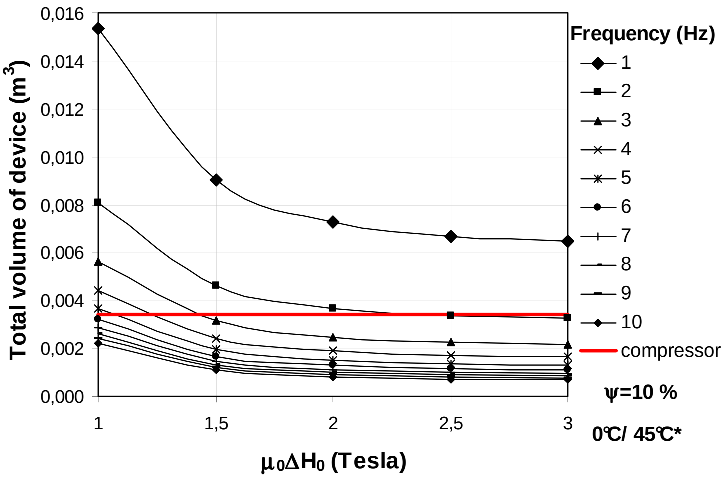


Figure 12: *The total volume of a 50 W refrigerator as a function of the magnetic flux density. The data are shown for numerous rotation frequencies of operation. The red line shows the approximate volume of a hermetic compressor device. A star (*) denotes that the temperatures are identical to the condensing, respectively to the evaporation temperature of the refrigerant.*

To obtain a small total volume of the device is not a so large challenge as to reduce the total mass. This can clearly be seen from Figure 12. Very compact devices are obtained with 30 % package degree, frequencies beyond 10 Hz and magnetic flux densities of 2 Tesla or above.

5.3 Central cooling systems

5.3.1 Introduction

The world production in 2003 of compressors for air conditioning and refrigeration (centrifugal, screw, scroll, reciprocating and the rotary type with two cylinders) was 22 millions and 18 millions, rspectively [18]. The world market estimated for both is approximately 3 billion US$ per year. Conventional central cooling systems, vapour compression and sorptive chillers (usually hot water and gas absorption chillers, rarely adsorption and steam driven absorption chillers) are found in practical applications. Figure 13 shows an example of a centrifugal chiller with a large volume flow and a small temperature span.

Figure 13: *Top picture: A typical centrifugal chiller (www.carrier.com) of large size. These chillers are usually used for large cooling powers (large refrigerant volume flow and low pressure ratio). The nominal cooling capacity may occur in a wide range. Beside electric energy, also other kinds of sources may be used, e.g. gas or steam turbine driven compressor chillers.*

Bottom on the left: Air cooled Carrier liquid screw compressor chiller. Right: The McQuay water cooled liquid screw compressor chiller.

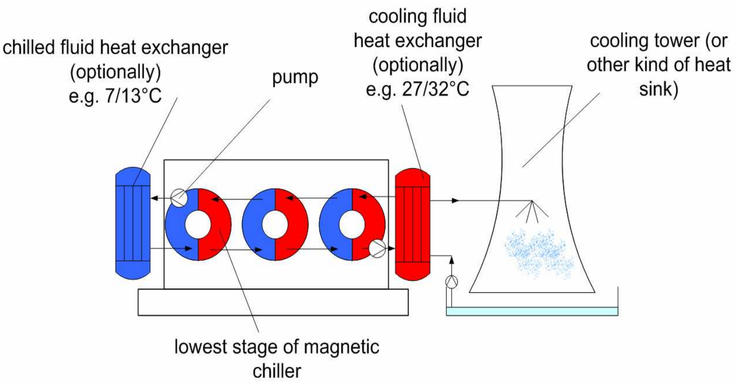


Figure 14: *An example of the three-stage magnetic chiller unit is shown. For a typical water/water or brine/brine conventional compressor chiller the cooling water temperatures for the supply and return circuits are usually 27/32°C and the chilled water temperatures of the supply and return circuits are 7/13°C. This technology may present a serious alternative to central cooling systems, especially in larger systems. Such are e.g. district cooling systems.*

In a magnetic central chiller, especially when operating with water/water or brine/brine, the operating conditions are very favourable for an application of the magnetic refrigeration technology. Additionally it has to be emphasized that for large scale units of central cooling systems other machines than magnetic refrigerators based on permanent magnets may also be applied, e.g. such with superconducting magnet coils. The cooling system for the superconducting coils - which preferably should be performed by high temperature superconductors - may be used for several coils. These coils provide the magnetic field sources for a large number of chiller units. The higher the required cooling power is, the lower the relative costs of such a system will be. Such systems, in general, may show also a much better compactness, especially when compared to magnetic refrigerators with permanent magnets. Furthermore, the use of superconducting coils permits to work with only a single stage magnetic chiller. This results, because the magnetocaloric effect is much larger when the magnetic field strength is higher. Note that the maximal magnetic field strength of superconducting magnets is much higher than the one of permanent magnets.

A central cooling plant - realized with the magnetic cooling technology - permits a one-loop or a two-loop system. In a single-loop system of a magnetic refrigerator the working fluid (liquid or another conventional secondary liquid refrigerant) may be directly transferred to the outer system. The disadvantages are the regulation/control of such a system as well as the required pressure. On the other hand an advantage is the higher efficiency that can be reached, because of a lack of further intermediate heat exchangers, which are necessary in the case of a two-loop system.

There exist many different possibilities to integrate the magnetic refrigeration technology into central unit systems. This includes, for example, also a kind of decentralized cooling system, where a central unit (central cooling system) causes a pre-cooling and then local magnetic cooling devices are responsible for a further cooling. Such a method could be applied, if further cooling is required, e.g. for the cooling of ceiling panels or fan coils, etc.

Another solution is a hybrid system where a compressor chiller takes over a central pre-cooling and - depending on the requirements of end-use coolers - magnetic cooling units are mounted and operated for the final conditioning. Such a kind of system is not analyzed here.

Magnetic central chillers (or industrial refrigerators) may be mounted in a large number of applications. Such are for instance:

- central cooling and/or air-conditioning systems in buildings or in marine transport
- central cooling units for district cooling
- central refrigeration system in warehouses (storage) or in marine transport
- central refrigeration system in food production processes.

The above list of applications slightly differs in temperature levels of heat source and heat sink. Based on this, the analysis comprises different kinds of central chillers.

Here we start with the most common application in buildings. The first analysis was based on two different central chillers with heat rejection using a water (brine) sink and in the other case air as the heat sink medium. Furthermore, we will evaluate here a large scale water cooled liquid chiller, which could be applied also in district cooling systems.

5.3.2 Air cooled liquid chillers

Figures 15 to 18 show results for the air cooled liquid chillers with a cooling power of 500 kW. Because this kind of chillers does not have a sufficient power in order to apply superconducting coils, the analysis was focused on systems with only permanent magnets as magnetic sources. Superconducting refrigeration machines are only feasible in large scale applications. The high cost of the superconducting magnets can only be accepted, if the system is large and these additional costs relatively unimportant. In the case of water/water (brine/brine) chillers in the supply tubes the temperature level on the cooling side of the water cooling loop usually varies from 5 to 10℃. On the other hand the temperature is 10 to 18℃ in the return tubes with flu id arriving from the heat source. The temperature level of the heat rejection loop usually varies between 18 to 35℃. For the air cooled condensers (e.g. air/water or air/brine chillers) the temperature of air varies between 25 to 45℃. The *COP* of the last is usually approximately 30% lower than the one of a brine/brine chiller, especially in the case when the power consumption of the air fans is included in the calculation of this characteristic efficiency number.

Figure 15 shows the coefficient of performance (*COP)* and Figure 16 the exergy efficiency of a magnetic central refrigeration system with air as heat sink medium.

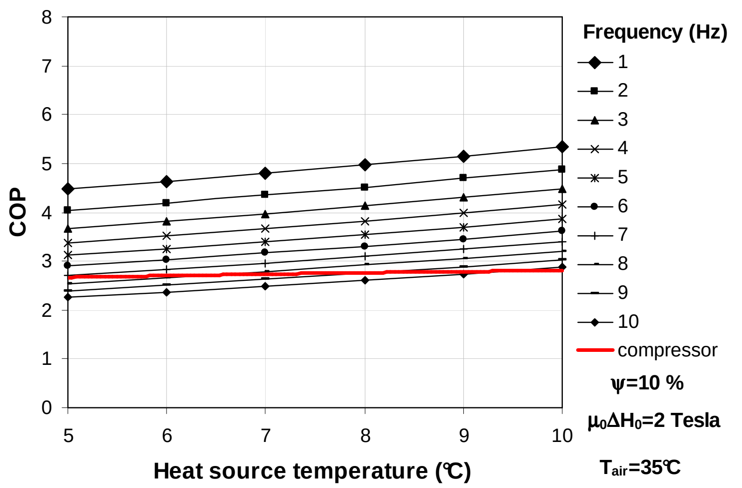


Figure 15: *The COP of an air/water (brine) magnetic chiller unit is shown. This quantity is presented depending on the frequency of the operation of the machine and the temperature of the heat source. Furthermore, the graphic contains typical values of COP's of screw compressor chillers operating under the same conditions (Carrier 30 GK).*

Notify that magnet-based machines with a magnetic flux density of 2 Tesla enable much higher *COP*'s than the conventional devices. This means that in such cases the frequency of operation could be beyond 10 Hz. This would positively influence the compactness of a device. Figure 16 shows the exergy efficiency of a central magnetic chiller and its comparison with that of a conventional one. The comparison shows the high exergy efficiency of magnetic chillers.

As for household refrigerators, also the central chillers mass and volume play an important role, especially when being placed into buildings with limited space. Figures 17 and 18 show the total mass and total volume of a magnetic chiller and its comparison with a conventional one.

The total mass of a magnetic central chiller may be expected to be much larger than that of a conventional chiller. However, one should note that the data in Figure 17 is based on a 10 % volume fraction magnetocaloric material porous wheel. This of course leads to a high total volume of a device. When applying for instance 30 % of volume fraction, the total volume of a magnetic chiller is very close to the one of a conventional one. More comprehensive data may be found in Appendix 1.

Important information is shown in Figures 19 to 23. These show the characteristics of a magnetic chiller depending on the air (heat sink) temperature at different magnetic flux densities.

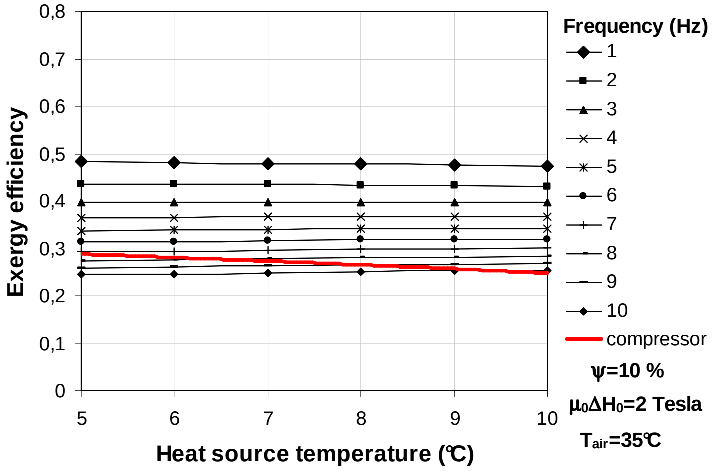


Figure 16: *The exergy efficiency of an air/water (brine) magnetic chiller unit is shown. This quantity is presented depending on the frequency of the operation of the machine and the temperature of heat source. Furthermore, the graphic contains typical values of COP's of screw compressor chillers operating under the same conditions (Carrier 30 GK)).*

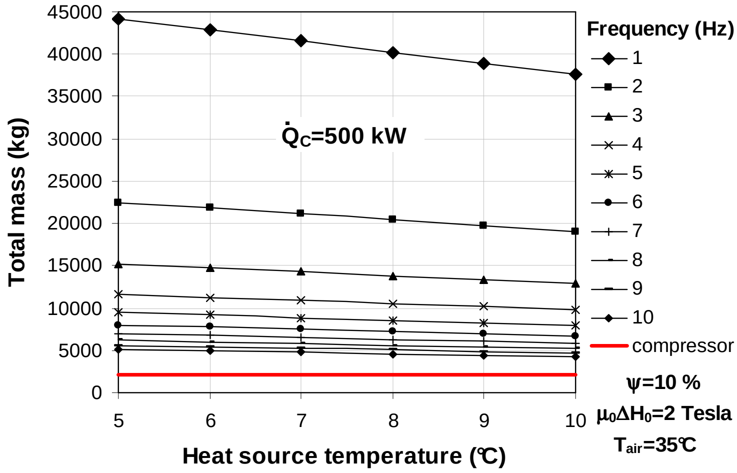


Figure 17: *The total mass of a 500 kW air/water (brine) magnetic chiller unit is shown. This quantity is presented depending on the frequency of the operation of the machine and the temperature of heat source. Furthermore, the graphic contains typical values of mass of screw compressors (without condenser and evaporator) operating under the same conditions (Carrier 30 GK).*

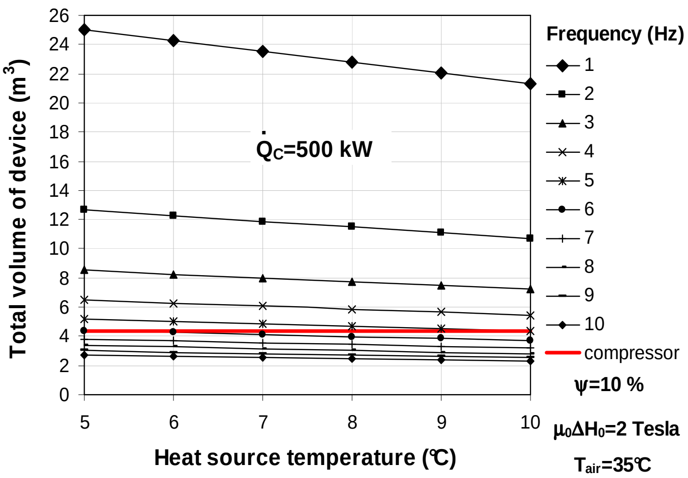


Figure 18: *The total volume of a 500 kW air/water (brine) magnetic chiller unit is shown. This quantity is presented depending on the frequency of the operation of the machine and the temperature of heat source. Furthermore, the graphic contains typical values of volume of screw compressors (without condenser and evaporator) operating under the same conditions (Carrier 30 GK).*

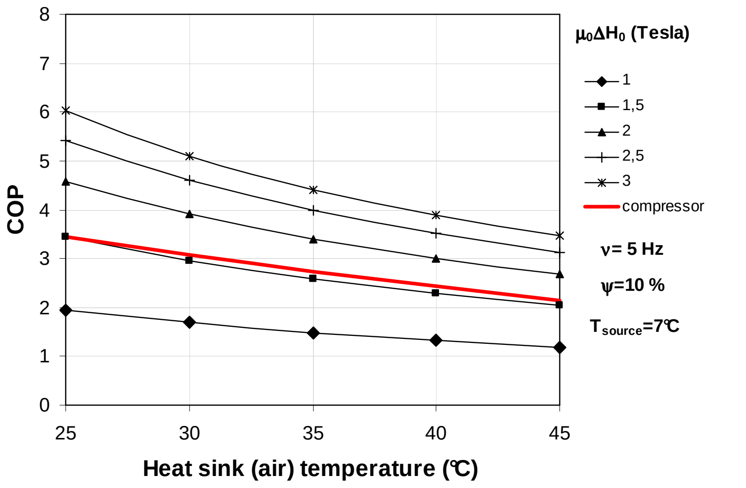


Figure 19: *The COP of an air/water (brine) magnetic chiller unit is shown. This quantity is presented depending on the magnetic flux density and the temperature of the heat sink (air). Furthermore, the graphic contains typical values of COP's of screw compressor chillers operating under the same conditions (Carrier 30 GK).*

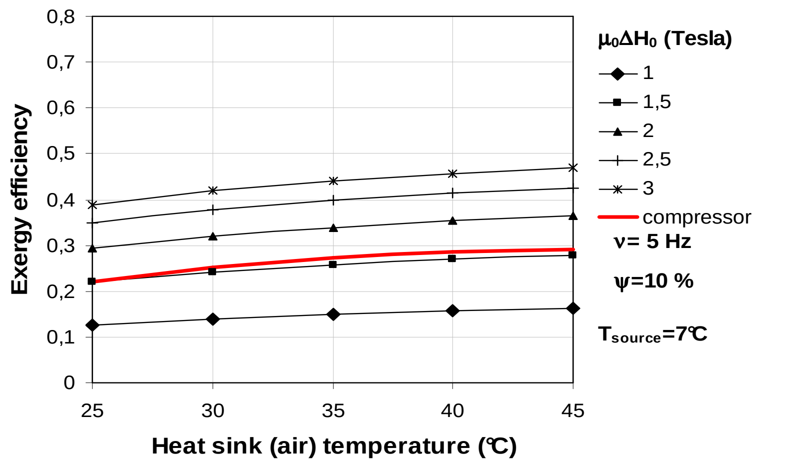


Figure 20: *The exergy efficiency of an air/water (brine) magnetic chiller unit is shown. This quantity is presented depending on the magnetic flux density and the temperature of the heat sink (air). Furthermore, the graphic contains typical values of exergy efficiencies of screw compressor chillers operating under the same conditions (Carrier 30 GK).*

Based on results shown in Figure 19, the magnetic flux density should be higher than 1.5 Tesla. Increasing the temperature of the heat sink negatively influences the advantages of magnetic cooling-devices. They operate best at small temperature spans between the heat source and the heat sink. Similar results are found in Figure 20, which shows the exergy efficiency. Applying magnetic flux densities of up to 3 Tesla does not allow a magnet based machine mass to compete with the low mass of a conventional chiller, which is much smaller (see Figure 21). However, in Appendix 1 it is shown that the mass of a magnet based chiller - by increasing the volume fraction of the magnetocaloric material porous structure - may be substantially reduced leading to an interesting measure.

When magnetic flux densities higher than 1.5 Tesla are applied, the total volume of the magnet based chiller is smaller than the one of a conventional compressor chiller. Considering the total mass, much better results may be achieved by increasing the volume fraction of the porous magnetocaloric structure (see Appendix 1).

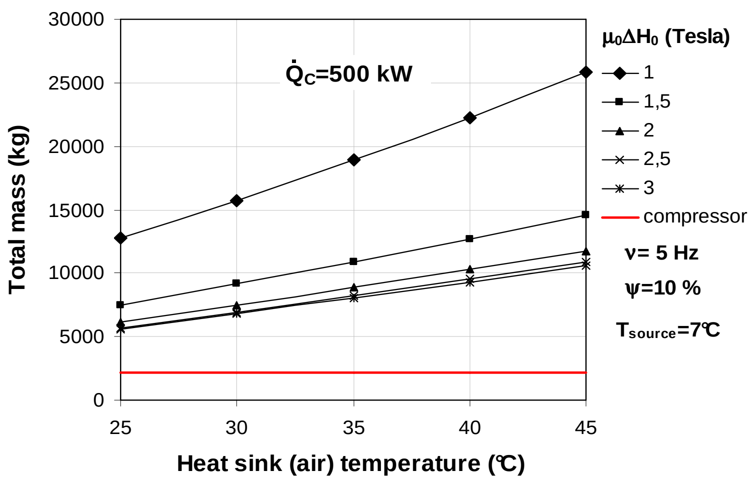


***Figure 21:** The total mass of a 500 kW air/water (brine) magnetic chiller unit is shown. This quantity is presented depending on the magnetic flux density and the temperature of the heat sink (air). Furthermore, the graphic contains typical values of the masses of screw compressors (without condenser and evaporator) operating under the same conditions (Carrier 30 GK).*

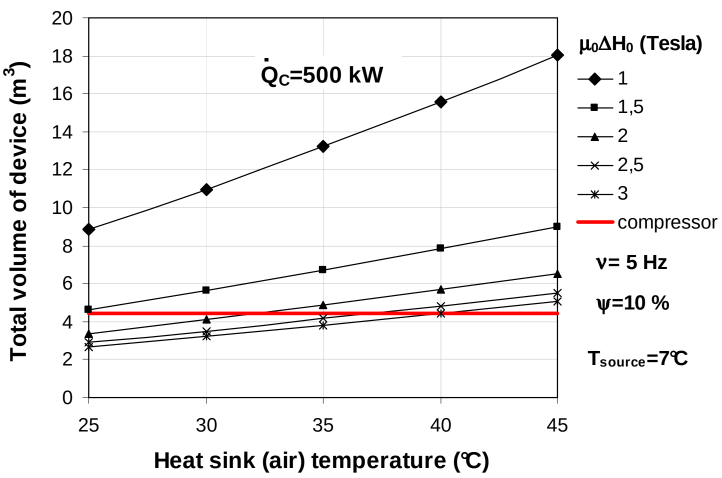


***Figure 22:** The total volume of a 500 kW air/water (brine) magnetic chiller unit is shown. This quantity is presented depending on the magnetic flux density and the temperature of heat sink (air). Furthermore, the graphic contains typical values of volumes of screw compressors (without condenser and evaporator) operating under the same conditions (Carrier 30 GK).*

5.3.2 Water cooled liquid chillers

In this section three different types of water cooled liquid chillers are presented. The first presents a large scale chiller, which may be used in district cooling systems and large scale cooling or air conditioning in buildings or for instance in marine transport (e.g. cruisers). Another example is a smaller scale water cooled liquid chiller, which is most common in commercial applications. Another very important domain of central cooling systems are industrial refrigerators, which may be applied in numerous different domains. Because of the diversity of applications, the mass and volume were not analyzed. A simple conclusion may be that for large scale applications of a few MW superconducting magnets will lead to more compact and less heavy devices as they occur in conventional refrigeration technology domains.

Figures 23 and 24 show the *COP* and exergy efficiency of magnetic chillers depending on the frequency of operation and of the magnetic flux density. Note that the magnetic flux density overcomes the highest possible obtainable value with permanent magnet assemblies. For such magnetic flux densities the meaning is that superconducting magnets are applied.

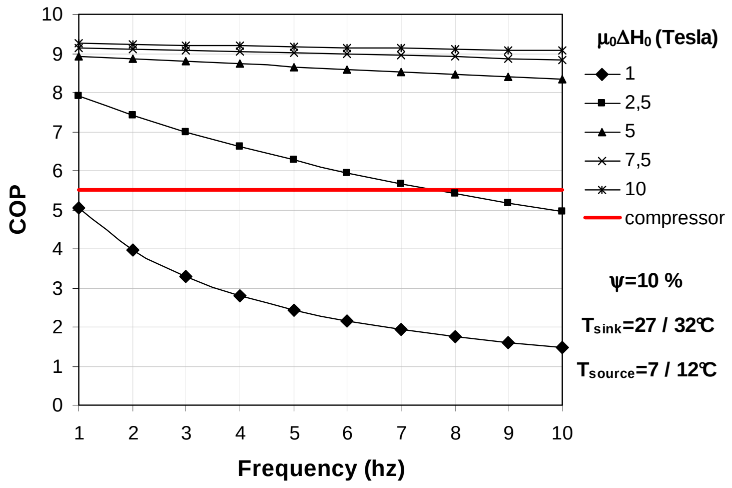


Figure 23: *The COP of a water/water (brine/brine) magnetic chiller unit is shown. This quantity is presented depending on the magnetic flux density and the frequency of operation. Furthermore, the graphic contains typical values of COP's of centrifugal compressor chillers operating under the same conditions (Carrier XR/ XRT).*

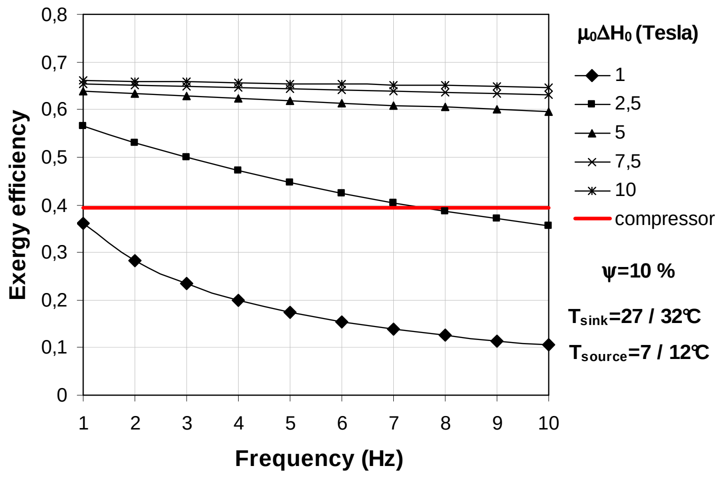


Figure 24: *The exergy efficiency of a water/water (brine/brine) magnetic chiller unit is shown. This quantity is presented depending on the magnetic flux density and the frequency of operation. Furthermore, the graphic contains typical values of exergy efficiencies of centrifugal compressor chillers operating under the same conditions (Carrier XR/ XRT).*

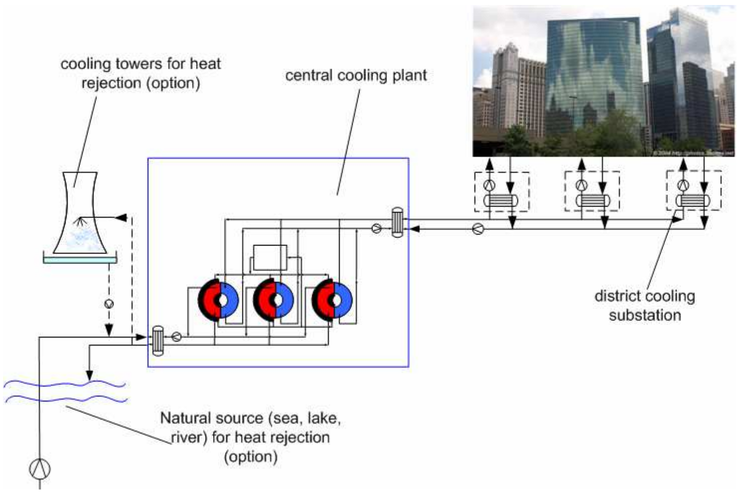
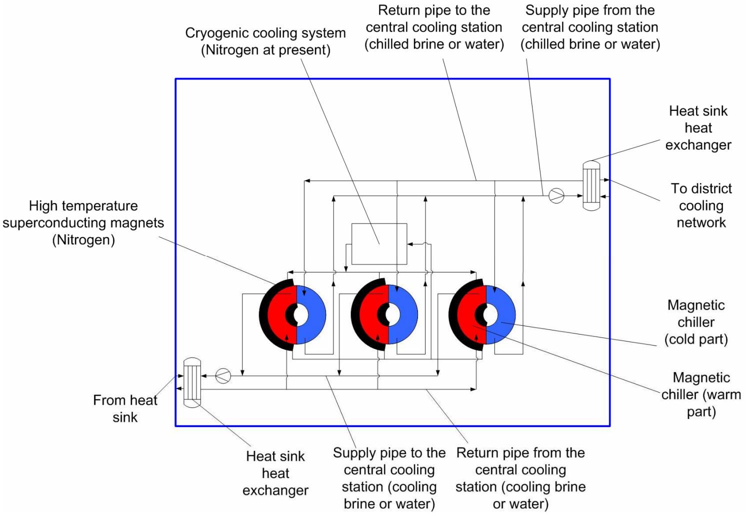


Figure 25: *An example of a district cooling system applying superconducting magnetic chiller units. District cooling systems enable large scale applications. Such systems operate usually with the conventional gas compressor technology or in some cases combine them with absorption chillers (especially in a combination with the cogeneration plant: "polygeneration" or "trigeneration"). A district cooling system allows a more efficient utilization of cold areas (compare the COP of the window mounted air conditioner to the large*



scale water cooled turbo-compressor), as well as a better monitored or utilized consumption. Despite the losses due to the transport and additional costs of the infrastructure, the relative costs of cold produced by such systems are competitive to partial solutions.

For the large scale chillers operating at conditions - as given in Fig.'s. 23 and 24 - the magnetic flux density should be approximately 1.5 Tesla or slightly higher depending on the frequency of operation of the machine. On the other hand, lower frequencies lead to larger devices and higher masses. Because many different types of liquid chillers exist, the analysis of the total mass and volume comprises a comparison of these quantities with those of sorption chillers. Data of sorption chillers were evaluated considering data sets of the Carrier company on hot water absorption chillers, one stage steam driven absorption chillers, two stage steam driven absorption chillers and two stage direct gas driven absorption chillers. Figures 26 and 27 show the total mass and total volume of a large-scale magnetic refrigerator operating with permanent magnets. Our finding is that the application of superconducting magnets will lead to the lowest possible mass and volume among all large-scale applications.

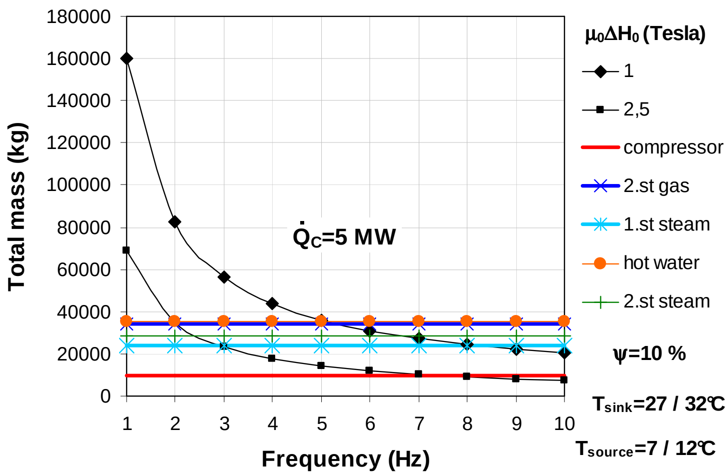


Figure 26: *The total mass of a water/water (brine/ brine) magnetic chiller unit is shown. This quantity is presented depending on the magnetic flux density and the frequency of operation. Furthermore, the graphic contains typical values of masses of centrifugal compressor chillers and different sorption chillers operating under the same conditions (Carrier).*

The total mass of a magnetic large-scale central chiller may be as high as the one of a compressor, if the frequency of operation is in the area of 10 Hz and the magnetic flux density approximately 2.5 Tesla. This size of magnetic flux density does not even require machines with superconducting coils. For absorption chillers it is known that they have a larger mass and volume, e.g. as it may be seen in Figure 27.

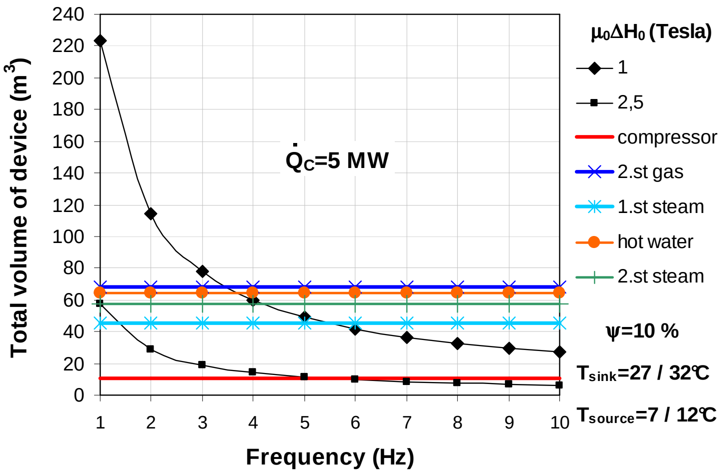


Figure 27: *The total volume of a water/water (brine/brine) magnetic chiller unit is shown. This quantity is presented in a dependence on the magnetic flux density and the frequency of operation. Furthermore, the graphic contains typical values of volumes of centrifugal compressor chillers and different sorption chillers operating under the same conditions (Carrier).*

The analysis evaluating air cooled liquid chillers was also applied to water cooled apparatuses. The identical power of 500 kW was taken into consideration in order to compare the resulting volumes and masses with those resulting for the conventional technology. Figures 28 and 29 show the *COP* and exergy efficiency of the water cooled magnetic refrigerator based on an operation with permanent magnets.

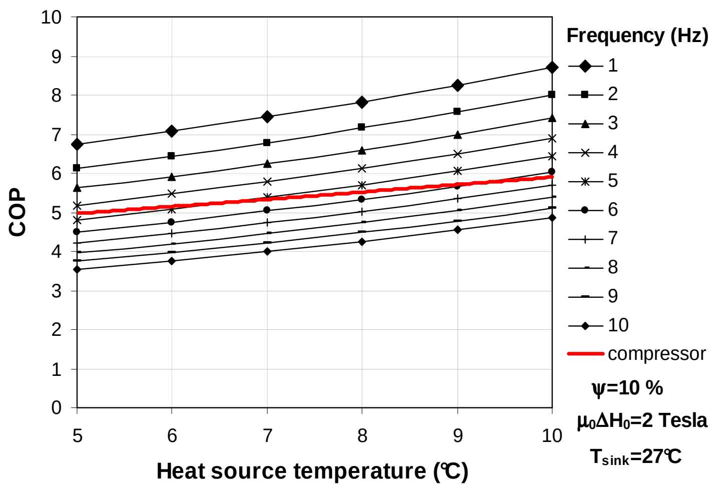


Figure 28: *The COP of a water/water (brine/brine) magnetic chiller unit is shown. This quantity is presented depending on the heat source temperature (water) and the frequency of operation. Furthermore, the graphic contains typical values of COP's of screw compressor chiller operating under the same conditions (Mc Quay, WHS 140 AW, R134a).*

To get a high *COP* of magnetic refrigerators with a magnetic flux density of 2 Tesla requires rather low frequencies of operation. However, increasing the volume fraction from 10 to 30% (see Appendix 1) will not only reduce the mass and volume, but also will increase the efficiency, because a high specific cooling power of the magnetocaloric material induces only small relative losses. Figure 29 shows the exergy efficiency for the same conditions. The mass and volume of the 500 kW water cooled magnetic chiller are shown in Figures 30 and 31. The mass of a magnet-based chiller is quite close to that of a conventional one, because the temperature difference between heat source and heat sink (see the parameters in the diagrams) is quite small.

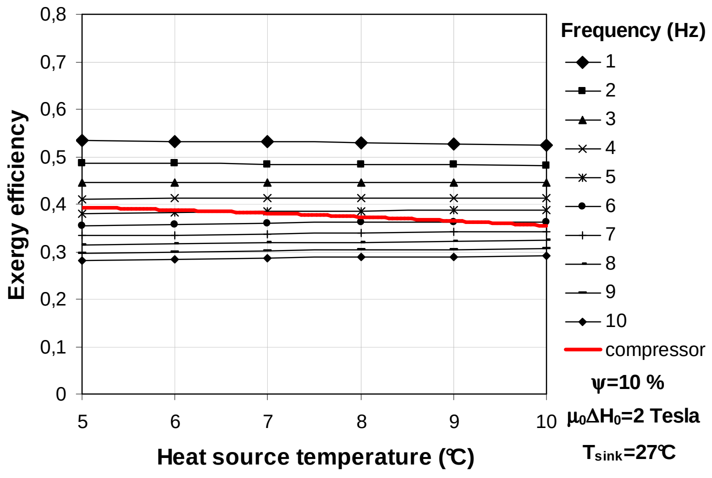


Figure 29: *The exergy efficiency of a water/water (brine/brine) magnetic chiller unit is shown. This quantity is presented depending on the heat source temperature (water) and the frequency of operation. Furthermore, the graphic contains typical values of the exergy efficiency of screw compressor chillers operating under the same conditions (McQuay, WHS 140 AW, R134a).*

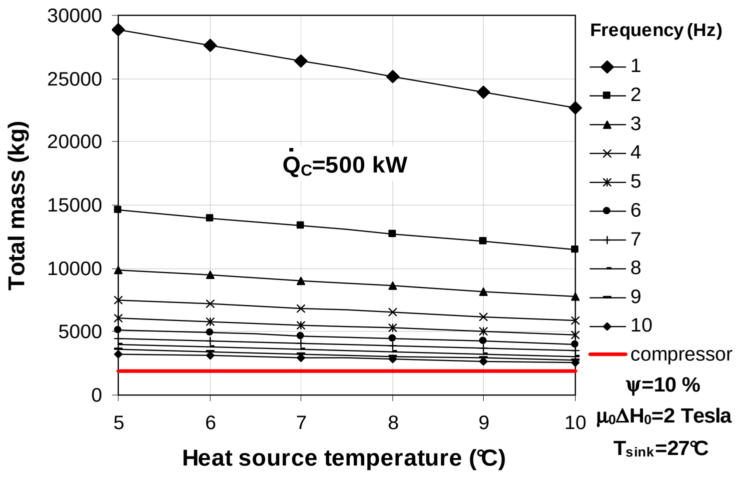


Figure 30: *The total mass of a water/water (brine/brine) magnetic chiller unit is shown. This quantity is presented depending on the heat source temperature (water) and the frequency of operation. Furthermore, the graphic contains typical values of the total mass of a screw compressor chiller operating under the same conditions (McQuay, WHS 140 AW, R134a).*

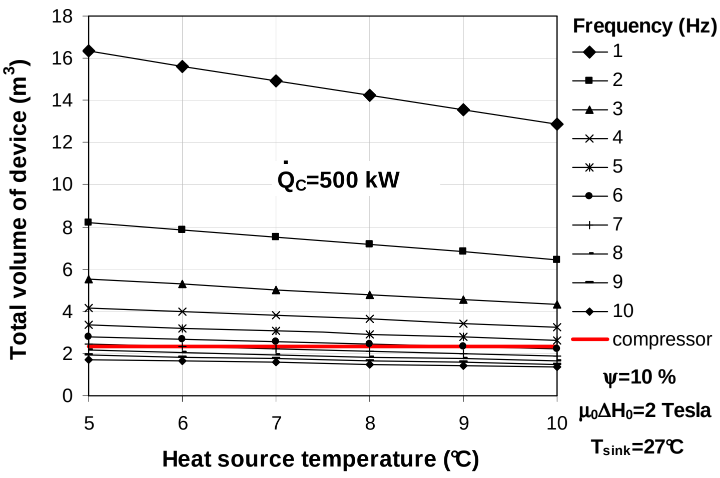


Figure 31: *The total volume of a water/water (brine/brine) magnetic chiller unit is shown. This quantity is presented depending on the heat source temperature (water) and the frequency of operation. Furthermore, the graphic contains typical values of the total volume of a screw compressor chiller operating under the same conditions (McQuay, WHS 140 AW, R134a).*

Key quantities of the medium-scale water cooled magnetic chiller are given with a dependence on the heat sink temperature (water) for different magnetic flux densities. These are only valid for cases where permanent magnets apply. Figures 32-35 show the corresponding characteristics.

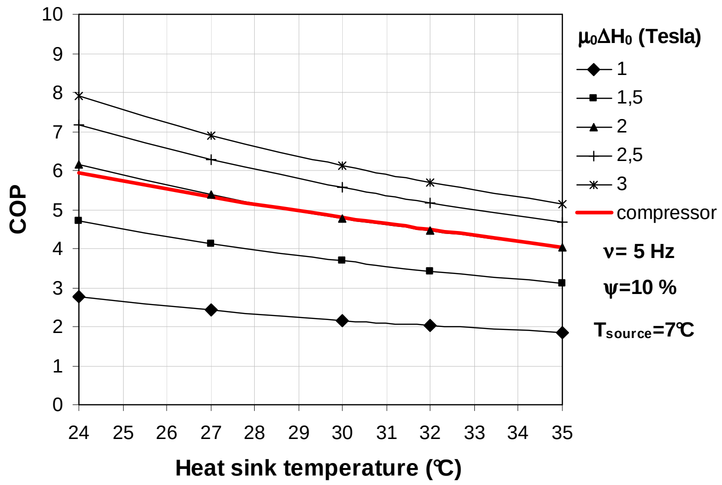


Figure 32: *The COP of a water/water (brine/brine) magnetic chiller unit is shown. This quantity is presented depending on the heat sink temperature (water) and the magnetic flux density. Furthermore, the graphic contains typical values of COP's of screw compressor chiller operating under the same conditions (McQuay, WHS 140 AW, R134a).*

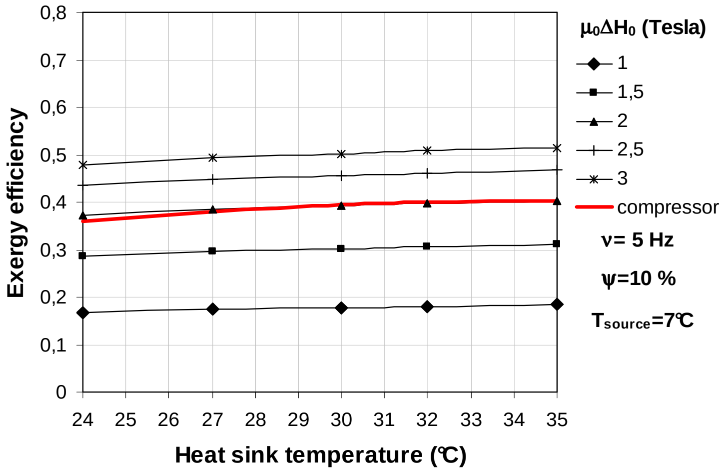


Figure 33: *The exergy efficiency of a water/water (brine/brine) magnetic chiller unit is shown. This quantity is presented depending on the heat sink temperature (water) and the magnetic flux density. Furthermore, the graphic contains typical values of exergy efficiencies of a screw compressor chiller operating under the same conditions (McQuay, WHS 140 AW, R134a).*

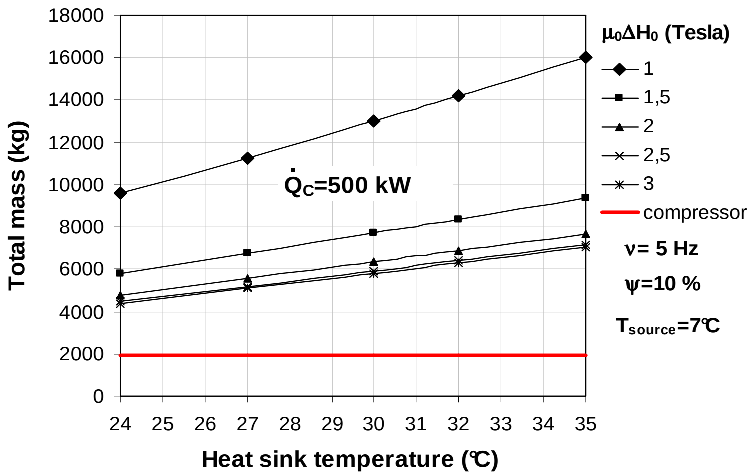


Figure 34: *The total mass of a water/water (brine/ brine) magnetic chiller unit is shown. This quantity is presented depending on the heat source temperature (water) and the frequency of operation. Furthermore, the graphic contains typical values of the total mass of a screw compressor chiller operating under the same conditions (McQuay, WHS 140 AW, R134a).*

According to Figures 32 and 33 the conventional compressor technology may be beaten by magnetic refrigeration, if the magnetic flux density is close or above 2 Tesla. Lower frequencies of operation permit to obtain higher efficiencies. However, low frequencies lead to small cooling powers and require a too large mass and volume of a machine. A smart improvement is obtained by increasing the volume fraction of the magnetocaloric porous material. The results of such an increase can be seen in Appendix 1. Figures 34 and 35 show the total mass and the total volume of a magnetic water-cooled chiller of 500 kW and the comparison of these values with the corresponding quantities of the conventional chiller. From these figures it is obvious that magnetic refrigerators will be heavier, but at least they are also compacter than the conventional chillers.

5.3.3 Large scale refrigeration units

The analysis comprises also the evaluation of large scale industrial refrigeration units, which are implemented e.g. in food preparation, production and storage. The target markets are mainly on land utilities and the marine transport. For the purpose of comparison, the data of conventional Ammonia screw compressors manufactured by the company Mycom were taken into consideration. It was assumed that magnet-based refrigerators would have to be operated with superconducting magnets, especially because of the large temperature spans between the heat source and the heat sink.

Figure 35: *The Screw compressor (V-Series) filled by the refrigerant R717 (Ammonia), manufactured by the Mycom company (see on internet: http://www.mycomkl.com.my). Such compressors show very low temperatures of evaporation, suitable for deep freezing applications as well as for various other applications with high evaporation temperatures (e.g. up to 5℃).*

Figures 36 and 37 show the *COP* and exergy efficiency of an industrial magnetic refrigerator and its comparison with the conventional counterpart. Because of a large temperature span between the heat source and the heat sink temperature, to obtain a reasonable *COP*, a magnetic flux density of 5 Tesla or even a higher value is required. This demands for superconducting magnets. However, the application of such magnet systems requires also large-scale applications in order to minimize the energy losses due to the special cryogenic cooling system. Furthermore, it is important to reduce the ratio of the cost of such special equipment to the total cost of the system. For large scale applications one can assume that the total mass and the total volume of a magnetic industrial refrigerator would be smaller than the mass and volume of a conventional gas compression/expansion refrigerator.

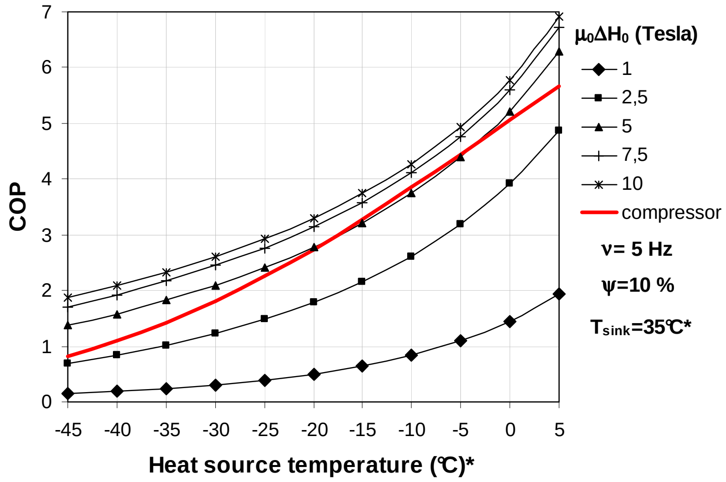


Figure 36: *The COP of an industrial magnetic refrigerator depending on the heat source temperature and the magnetic flux density. Furthermore, the graphic contains typical values of COP's of the Mycom screw compressor refrigerator operating at same conditions. A star (*) denotes that the temperatures are identical to the condensing, respectively to the evaporation temperature of the refrigerant.*

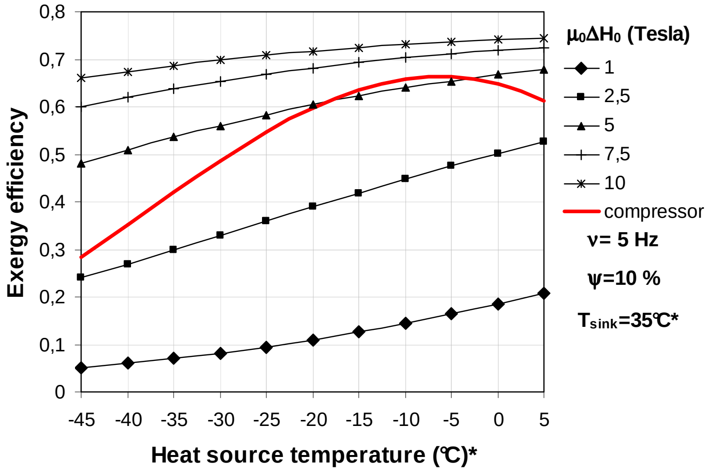


Figure 37: *The exergy efficiency of an industrial magnetic refrigerator depending on the heat source temperature and the magnetic flux density. Furthermore, the graphic contains typical values of the exergy efficiency of the Mycom screw compressor refrigerator operating at the same conditions. A star (*) denotes that the temperatures are identical to the condensing, respectively to the evaporation temperature of the refrigerant.*

5.4 Room air conditioners

The world production of gas compressors in 2003 for room air conditioners and dehumidifiers was 70 million units (rotary type, one cylinder, reciprocating, scroll) [18]. The average annual growth is estimated to be 10%. This is worrying, because of the increase of the related electricity consumption and the impact of refrigerants on the environment by global warming. It is well known that the installation and operation of room air-conditioning units should be as much as possible avoided. These systems have a large and uncontrolled energy consumption, which may be drastically reduced by an installation of central cooling systems or even more by the design and building of modern district cooling systems. An alternative technology like magnetic air-conditioning could bring benefits by lowering the power consumption and reducing the use of environmentally harmful refrigerants. Direct systems - e.g. a magnetic air conditioner with air as working fluid - at the present stage of the development of the magnetic cooling technology is not recommended, even if the design of a magnetic air-conditioner would not differ much from that of a conventional device.

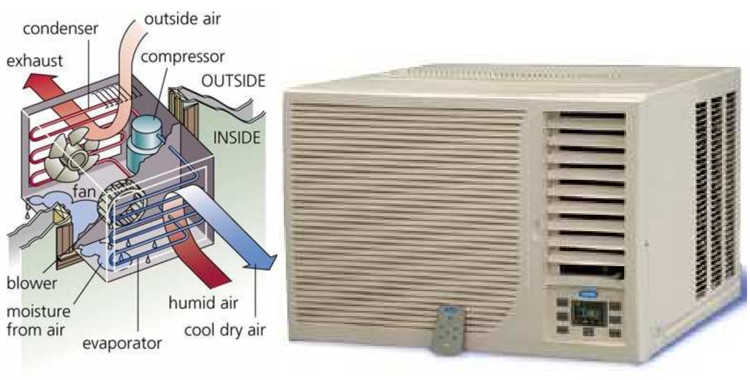


Figure 38: *A typical window mounted air conditioner is shown. Its cooling power usually does not exceed 3 kW. The heat rejection unit (condenser) is mounted outside of the building (see picture on the left). Some room air conditioners also cool additional fresh air and distribute it into desired room areas (www.carrier.com, www.daviddarling.info).*

The analysis was made in order to compare operation conditions of magnetic air conditioners with those of the conventional systems containing hermetic compressors. Figures 39 and 40 show the *COP* and the exergy efficiency of such equipment. Because the data available on hermetic compressors is given as a function of the evaporation and condensation temperature, the analysis does not comprise external heat exchange.

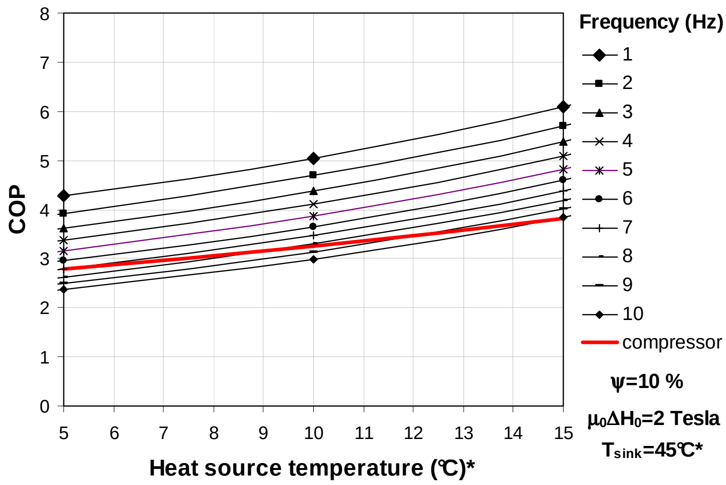


Figure 39: *The COP of a magnetic air-conditioner as a function of the heat source temperature and the frequency of operation for a magnetic flux density change of 2 Tesla is shown. The red line corresponds to the COP of a Danfoss hermetic compressor (MBP/HBP, R 407 c, type SC15DL, with a condensing temperature of 45℃).*

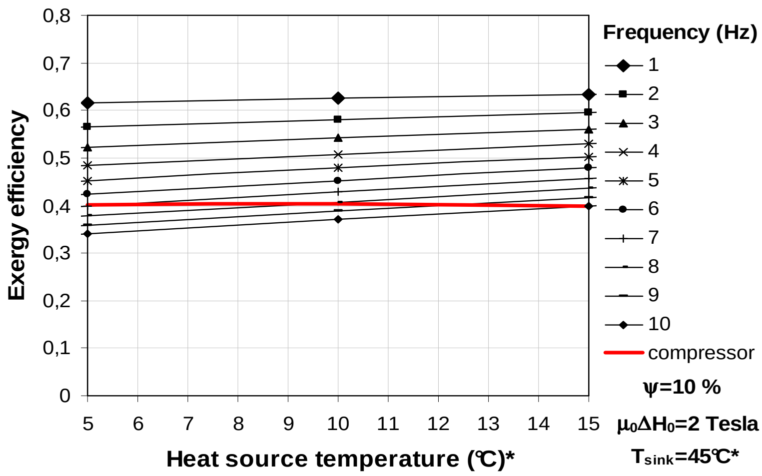


Figure 40: *The exergy efficiency of a magnetic air-conditioner as a function of the heat source temperature and the frequency of operation for a magnetic flux density change of exactly 2 Tesla is shown. The red line corresponds to the exergy efficiency of a Danfoss hermetic compressor (MBP/HBP, R407c, type SC15DL, with a condensing temperature of 45℃).*

According to Figures 39 and 40, the magnetic air conditioners are feasible at magnetic flux densities of 2 Tesla, even when they are operating with high frequencies. The advantage of the magnetic cooling technology becomes more important when the temperature of the heat source increases. The influence of increasing the volume fraction is shown in Appendix 1. Here we continue with the *COP* and exergy efficiency depending on different magnetic flux densities at fixed temperatures of operation (see Figures 41 and 42).

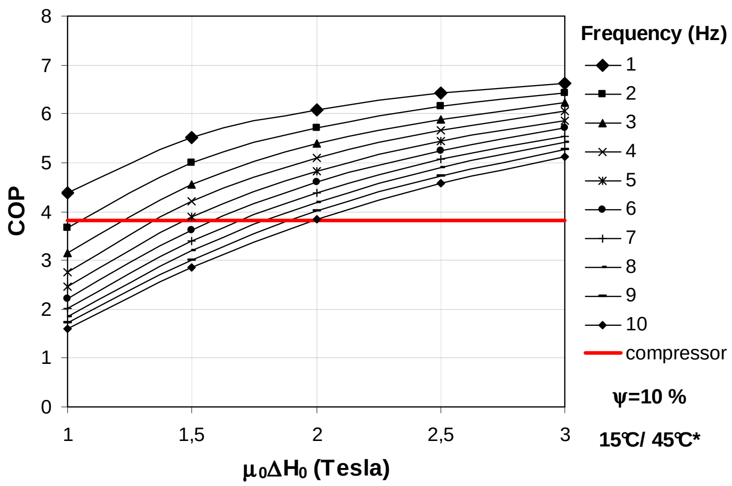


Figure 41: *The COP of a magnetic air conditioner as a function of the magnetic flux density and the frequency of operation for fixed temperatures of heat source and heat sink. The red line corresponds to the COP of a Danfoss hermetic compressors (MBP/ HBP, R407c, type SC15 DL, with a condensing temperature of 45℃).*

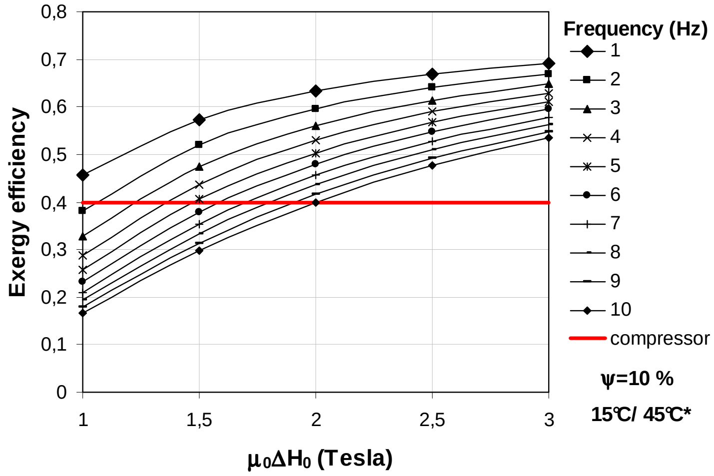


Figure 42: *The exergy efficiency of a magnetic air conditioner as a function of the magnetic flux density and the frequency of operation for fixed temperatures of the heat source and heat sink. The red line corresponds to the exergy efficiency of a Danfoss hermetic compressor (MBP/HBP, R407c, type SC15DL, with a condensing temperature of 45℃).*

A magnetic flux density of 1.5 Tesla is sufficient so that a magnet based air conditioner can beat the conventional one. But this limit is not constant; it depends also on the frequency, which furthermore influences the total mass and the total volume of the device. The results of machines with a volume fraction of 30 % magnetocaloric material show even more promising results (see Appendix 1). Figures 43 and 44 show the total mass and total volume of a device with a 10% volume fraction of magnetocaloric material content.

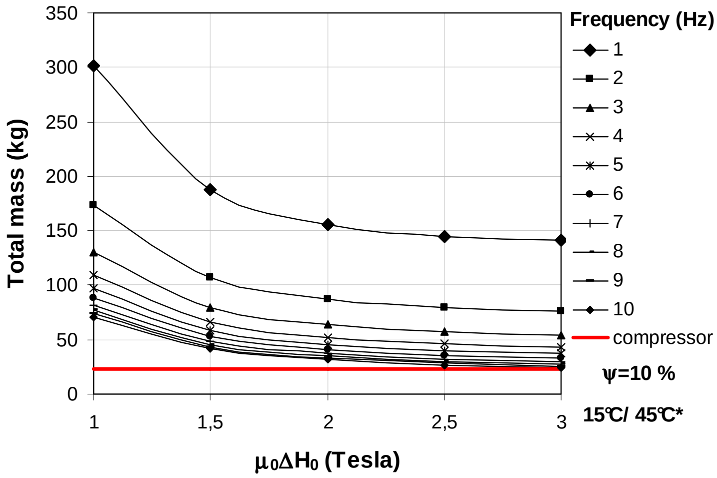


Figure 43: *The total mass of a 2 kW magnetic air conditioner as a function of the magnetic flux density and the frequency of operation for fixed temperatures of the heat source and heat sink. The red line corresponds to the COP of a Danfoss hermetic compressor (MBP/HBP, R407c, type SC15 DL, with a condensing temperature of 45℃).*

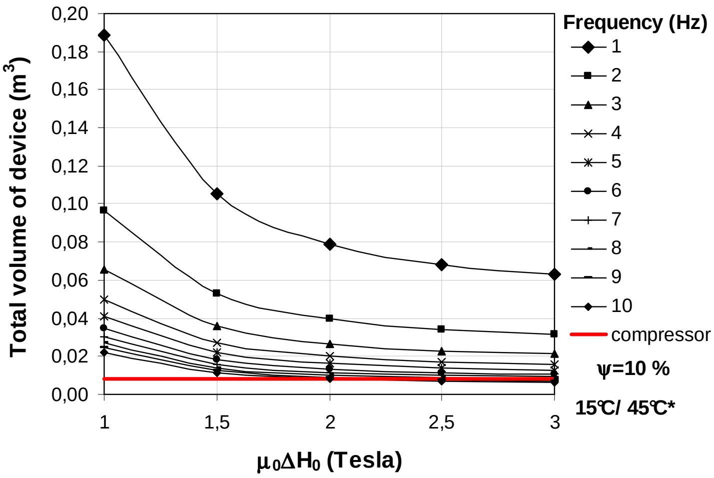


Figure 44: *The total volume of a 2 kW magnetic air conditioner as a function of the magnetic flux density and the frequency of operation for fixed temperatures of the heat source and heat sink. The red line corresponds to the total volume of a Danfoss hermetic compressor (MBP/HBP, R407c, type SC15DL, with a condensing temperature of 45 ℃).*

Figure 45 shows an example of an implementation of the magnetic cooling technology in a room air conditioning apparatus. A large number of different possible solutions exist and should be more deeply studied in order to bring benefits not only to the efficiency, but also to the weight and compactness of the devices. The potential of this technology is enormous. Air conditioning presents also one of the best applications, because cooling in moderate climate zones (e.g. Central Europe) does not show large temperature spans between the heat source and the heat sink.

Furthermore, in air conditioners forced convection of the air occurs on both sides - namely at the heat source and at the heat sink. This is a big advantage, because it lowers the necessary temperature difference between the temperature in the hot and the cold part of the magnetocaloric wheel. This advantage becomes evident in a comparison with household appliances were usually only free convection flows are realized. The temperature of the heat source, therefore, in a magnet-based air conditioner may be higher.

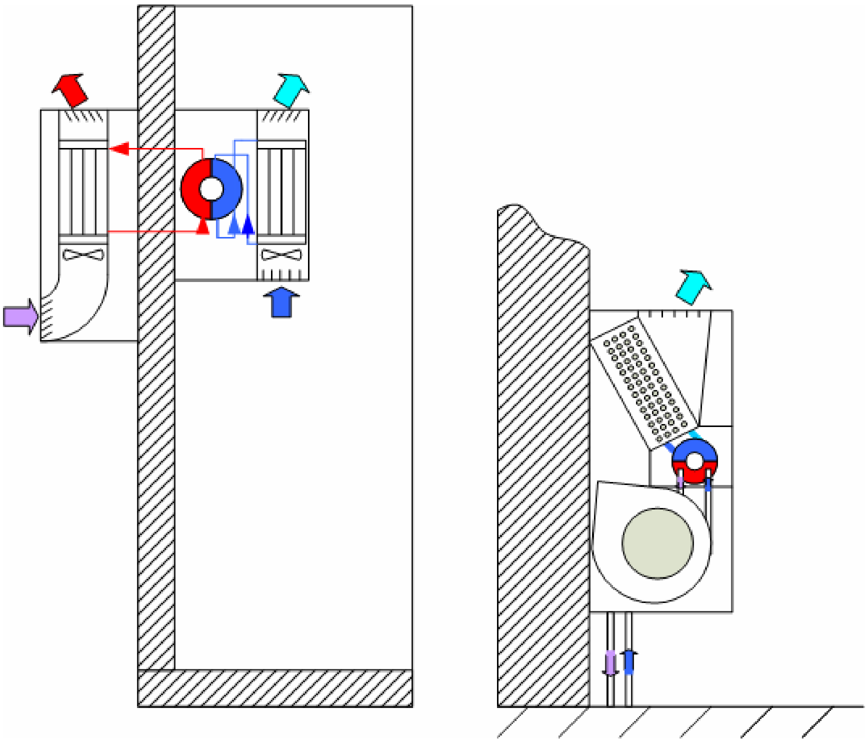


Figure 45: *A simple example of a wall or window mounted magnetic air conditioning unit (on the left) and a fan coil operating with the split system (on the right) is shown. In split systems a central magnetic cooling unit is responsible for the cooling task. It can be directly implemented into a fan coil equipment. Also in other devices - as e.g. cassettes, ceiling cooling apparatuses, etc. - magnetic cooling units can be inserted. If several such units are mounted and correctly connected, cascade or regeneration systems can be realized.*

5.5 Supermarket refrigeration applications

Supermarket applications may be divided into different areas, as living comfort, food storage, display cabinets (refrigerators and freezers) and the glass-door or chest-type refrigerators/freezers. Because the first two domains were already described in previous chapters, in this section we will primarily focus on display cabinets, which may exist in various sizes and show different solutions. Also glass door or chest-type refrigerators - because of their striking similarity to household refrigerators - must not be discussed anymore.

Most cabinets are vertical multi-deck cabinets for a display and a self-service retailing of packaged chilled food, fresh meat, fish and poultry. There are also the “delicatessen” or “serve over” cabinets for food, which normally is not packaged but cut and presented. Multi-deck cabinets have a refrigeration evaporator in the base, and this may be supplied either from a self-contained condensing unit or (in a larger installation) is connected by tubes to a central store cabinet refrigeration system. The evaporator coil is mounted in the lower part of the cabinet behind or under the display area, and fans blow cooled air from behind the shelves in a forward direction and also from the top front of the cabinet downward creating an air curtain. Warm air is returned through a grille at the base of the cabinet.

Modern multi-deck cabinets are designed to maintain food temperatures at 5ºC or below. The food temperature is not just depending on the cabinet type, it also depends on the manner of its management and utilization. A very tight or untidy cabinet loading can prevent a proper air circulation. High store temperatures or excessive radiant heating from light sources can lead to warm foodstuff. Good housekeeping allied to the use of night covers - when the store is closed - leads to best results. Cabinets are designed to maintain temperatures. That is the reason why they should not be loaded with warm foodstuff. To save energy in numerous countries, cabinets with doors have largely superseded open-front multi-deck cabinets. Such cabinets have severe disadvantages to the retailer, both in loading time and in customer resistance. Some open-fronted cabinets also incorporate shelves for display of non-chilled goods related to the chilled products on display. Serve-over display cabinets have food displayed on a base over which cold air flows, and normally they have a glass front. From behind this glass front the food is served. Air from a rear evaporator is gravity-fed or fan-assisted, but the more food in these cabinets is not wrapped in, excessive air speeds must be avoided to prevent dehydration and weight loss. For the same reason these cabinets are usually used for display only during sale is in progress, and other storage cabinets are used to store food overnight. A variation on the serve-over cabinet is the chilled ingredient display and store used in some catering establishments. These cabinets store refrigerated ingredients below the counter section, and cold air is blown across the underside of the display pans and keeps them cool. This is aided by a curtain of cool air blowing across the surface of the pans. This is just one example of the way in which display equipment can be designed to meet specific requirements.

In selecting a cabinet, the method of use, the standard of temperature control and the cost will be major factors. Ease of maintenance and cost of operation are also important. Beside the direct operation of primary refrigerants, one finds indirect systems in which the cabinets are cooled by cold liquids. Such are brines or glycol solutions, phase change slurries (e.g. ice slurry), hydrates, etc., which are cooled by a central plant.

The magnetic cooling technology may be performed in different manners, namely as centralized cooling (freezing) system or as a decentralized one. The choice of the working fluid depends on the temperature levels. Various fluids from brines to water may act as working fluids. In a very large supermarket the central cooling for the display cabinets and other kinds of cooling tasks (e.g. food storage and living comfort) may be combined. In such cases the application of a superconducting magnetic refrigerator seems feasible. Furthermore, the highest efficiency is obtained by a combined use of magnetic cooling and heating (magnetic heat pump). Note that cooling units have a heat rejection into the air-conditioned space, which is at 20-25℃. Figure 46 shows an example of a decentralized (local) magnetic refrigerator built into a display cabinet.

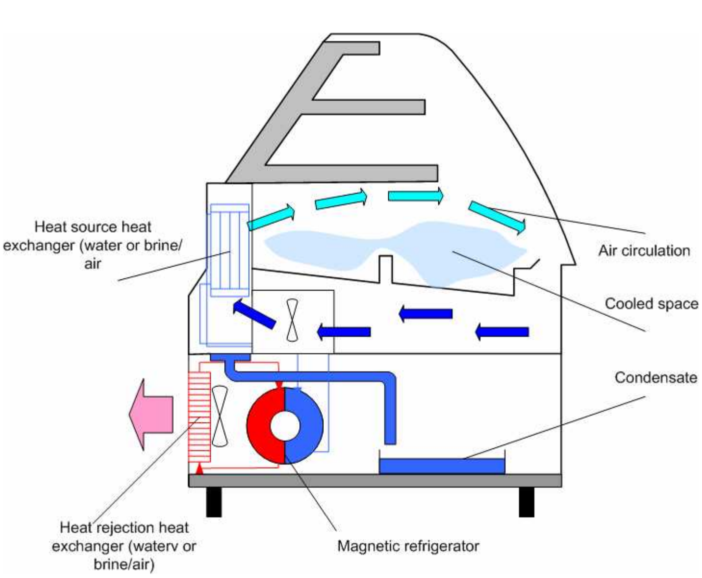


Figure 46: *Horizontal display cabinet cooled by a magnetic refrigerator unit. An advantage is the stable ambient temperature of a usually air-conditioned environment. This kind of application can be combined with different other solutions, e.g. with a central system. In this case a phase change slurry acting as a secondary refrigerant may be applied in a combination with magnetic cooling. The data on efficiency, mass and volume may be related to the Figures 5-12. This is the case, because the temperatures of evaporation and condensation are very similar to those in household appliances.*

6. CONCLUSIONS AND OUTLOOK

This final report contains a list of conventional refrigeration systems, which may be successfully replaced by the magnetic cooling technology. By adapting and applying a method developed for heat pumps in another project - financed by the Swiss Federal Office of Energy/Bundesamt für Energie (BFE) (see Ref. [17]), the coefficent of performance (*COP*) values and exergy efficiencies of all these systems were calculated. This evaluation shows that some application domains are more ideal for a replacement of conventional by magnetic refrigerators than others. Four good examples - the household appliance without a freezing compartment, the central refrigeration or cooling unit, the room air conditioner, and the supermarket display cabinet (including the multideck) or glass door refrigerator - were chosen for a more detailed study and presentation.

Briefly one can say that applications with smaller temperature differences are much more favourable. This results from the limited adiabatic temperature difference of the magnetocaloric materials. The result then is that for high temperature differences numerous cascading or regeneration stages have to be taken into consideration. These lead to additional heat transfer losses so that the coefficient of performance is lower. Furthermore, the constraint to have the working domain around the Curie temperature of the magnetocaloric material makes systems with steady operation conditions more favourable. If for example the temperature of the heat source and sinks are wildly fluctuating, a well determined operation of a machine is not guaranteed. Please note that these two restrictions are valid for all kind of magnetic machines (i.e. magnetic heat pumps, magnetic refrigerators and magnetic “power conversion” machines).

The study reveals that for smaller magnetic fields high *COP* values are only possible, if the rotation frequency is low. That is due to the connection between the rotation frequency and the fluid velocity, given by a criterion to keep the carry-over leakages small. Only small fluid velocities lead to small pressure losses in the porous structures of the rotary wheels. To keep these velocities small the angular velocity and the frequency must also be low.

At higher magnetic fields the dependence on the rotational frequency is smaller. If the magnetic field strength is high, a lower number of stages is needed, what leads to lower irreversibilities. And even more, because of fewer stages, fewer rotors in series occur, and also the pressure drop loss is smaller. That explains why high fields are very interesting for the magnetic/magnetocaloric machine design. Furthermore, the increase of the volume fraction of the magnetocaloric porous structure has a high influence on all the machine characteristics. The reason is that in the same “gap” in the permanent magnet assembly, a higher concentration of magnetocaloric material leads to a higher specific power. Our analysis has shown that it is possible to increase the volume fraction without having the problem of higher pressure losses, if the structure is still allowing a good diffusion process of heat and also sufficient mass flow within the limits defined by the fluid carry-over leakage. An increase of the volume fraction improves the characteristics and leads to a large reduction of the specific losses. Note that there are upper limits for the volume fraction. One may state that 30% volume fraction is close to the optimal value. Furthermore, the Swiss team found solutions which enable theoretically very high frequencies of operation (beyond 10 Hz) without having the problem of an occurrence of a too large carry-over leakage. These solutions need now to be investigated also in first prototypes and later in practice. The mass and compactness of magnetic refrigeration and cooling devices is defined by the temperature levels and also strongly related to the magnetic flux density, frequency of operation and the volume fraction of the magnetocaloric porous structure. In this report it is shown that the volumes of the machines are reasonable small, but that the total masses of devices become rather large. However even the mass of a magnetic refrigerator may be reduced to that of a conventional machine with new approaches, which the Swiss team already studies. Furthermore, an application of high temperature superconducting magnets - most appropriate for large scale magnetic cooling units - presents an interesting solution of this green technology. Therefore, a special study related only to machines with superconducting magnets with large cooling powers would be a step forward for the commercialization of this kind of technology. Beside this, for usual smaller daily life applications the permanent magnet based systems are also very promising. At the present stage of development of the “new” magnetic refrigerator technology the approach with permanent magnets is more feasible to a short term industrialization.

Based on the analysis, which was worked out during this project, different results were obtained. A first is the detection of further possible improvements and modifications of magnetic cooling and refrigeration machines compared to existing ideas. Then a comparison between different applications was made in order to evaluate the most feasible technology. Table 1 shows a comparison of magnetic cooling machines with the analogous conventional refrigeration machines. In Table 1 the best suitable

Table 1: *A comparison of the magnetic cooling technology with the conventional one is presented. The gray areas present refrigeration domains, where the magnetic cooling technology would be most feasible. This table only contains the technical criteria. One marker denotes not as good as (√), two markers approximately equal (√√) and three markers better than in the conventional refrigeration technology.*

	COP	Exergy efficiency	Mass	Volume
Household freezing appliances	√√	√√	√	√√
Household refrigerators with freezers	√√	√√	√	√√
Household hybrid refrigerator with freezer	√√√	√√√	√	√√
Household refrigeration appliances	√√√	√√√	√	√√
Wine/beverage refrigerator	√√√	√√√	√	√√
Small medicine refrigeration appliances	√√√	√√√	√	√√
Small medicine freezing appliances	√√	√√	√	√√
Small medicine deep freezing appliances	√	√	√	√
Small medicine ultra low freezing appliances	√	√	√	√
Portable evaporative indoor unit	√√√	√√√	√	√√
Portable indoor cooling device	√√√	√√√	√	√√
Portable freezing and refrigerator boxes for household and medicine appliances	√	√	√	√
Window room air conditioners	√√√	√√√	√	√√
Magnetic split coolers/ air conditioners	√√√	√√√	√	√√
Water cooled chillers	√√√	√√√	√	√√
Air cooled chillers	√√	√√	√	√√
Large scale superconducting chillers	√√√	√√√	√√√	√√√
Water cooled industrial refrigerators	√√√	√√√	√	√√
Industrial large scale superconducting freezers	√√	√√	√√	√√
Industrial freezers	√	√	√	√
Industrial large scale superconducting refrigerators	√√√	√√√	√√√	√√√
Supermarket refrigeration display cabinets	√√√	√√√	√√	√√

Supermarket freezer display cabinets	√√	√√	√	√
Water cooled supermarket refrigeration and air conditioning	√√√	√√√	√√	√√
Air cooled supermarket refrigeration and air conditioning	√√	√√	√	√√
Land and air transport vehicle air conditioners or split systems	√	√	√	√
Land and air transport vehicle refrigerators	√	√	√	√
Land and air transport vehicle refrigerators	√	√	√	√
Land and air transport vehicle freezers	√	√	√	√
Large scale marine air-conditioning and refrigeration	√√√	√√√	√	√√
Large scale superconducting marine air conditioning and refrigeration	√√√	√√√	√√√	√√√
Large scale superconducting marine freezing	√√	√√	√√	√√

applications for magnetic refrigeration are presented in gray color. They would allow the easiest way of commercialization. The superconducting units will show the best efficiencies and will lead also to compact and light devices. On the other hand they are only adequate to an implementation in large scale systems. The same is the case for medium size or large scale water chillers. It must be stated that no prototype of a magnetic refrigerator exists yet in these domains, where numerous prototypes for household appliances are now in development. This would make it interesting to build a large scale machine with superconducting magnets. On the other hand it is more convenient to start a new development in creating smaller machines. If one is searching for a similar project without much concurrence yet, one could choose the supermarket display cabinet application.

An economic analysis at the present stage of development is quite difficult to be performed. The reason for that is that most of the parts of magnetic refrigerators or chillers consist of materials and shapes, which are not yet under mass production and are thus performed only as unique parts. The comparison between the magnetic refrigeration and compressor technology is even more difficult, because the last is a mature technology, which almost fully converged to its limits, especially when considering compactness (volume), mass, efficiency and cost. As shown previously, the markets of the conventional machines are enormous and this highly reduces the price of production for sales. But still, in Table 2 for all evaluated technologies a rough evaluation of the economics (investment costs and operation costs) is shown. For more sophisticated comparisons, a special economic analysis should be performed, which will be based on different scenarios, following the directions listed below:

- prediction on the development and mass production of magnetocaloric materials, including the possibility of improved properties
- prediction on the development and mass production of permanent magnet assemblies and materials, as well as superconducting magnet systems (for large scale systems), including the possibility of improved properties
- future view on development and mass production of magnetic refrigerators, including the possibility of improved characteristics
- view on future energy efficiency requirements and environmental restrictions

- active policies supporting new and better technologies and defending them toward conventional industry interests
- prediction on how industrialization will work out in certain market niches.

A further work could be a special economic analysis comprising also the technology foresight for different domains of magnetic cooling and refrigeration technologies. Magnetic supermarket refrigerators present a domain, where at the present stage a very fast industrialization process could be possible.

Because superconducting magnet based cooling and refrigeration systems could bring large improvements of the compactness, efficiency and cost, a feasibility study should be performed to prepare and start future Ra&D developments in this domain. It must be emphasized that as a result of this study, it follows that the magnetic flux density in such a system would require magnetic field strength of less than 10 Tesla. Beginning with a smaller scale machine would make the handling easier and still could also lead to a good demonstrator.

Table 2: *A comparison of the magnetic cooling technology with the conventional one is presented. The gray areas present refrigeration domains, where the magnetic cooling technology would be most feasible. This table contains the investment and operation/maintenance costs. The evaluation by three types of markers follows the same principle as the one in Table 1.*

	Investment costs	**Operation and maintenance costs**
Household freezing appliances	√	√√
Household refrigerators with freezers	√	√√
Household hybrid refrigerator with freezer	√	√√√
Household refrigeration appliances	√	√√√
Wine/beverage refrigerator	√	√√√
Small medicine refrigeration appliances	√	√√√
Small medicine freezing appliances	√	√√
Small medicine deep freezing appliances	√	√
Small medicine ultra low freezing appliances	√	√
Portable evaporative indoor unit	√	√√√
Portable indoor cooling device	√	√√√
Portable freezing and refrigerator boxes for household and medicine appliances	√	√
Window room air conditioners	√	√√√
Magnetic split coolers/ air conditioners	√	√√√
Water cooled chillers	√	√√√
Air cooled chillers	√	√√

Large scale superconducting chillers	√√√	√√√
Water cooled industrial refrigerators	√	√√√
Industrial large scale superconducting freezers	√√	√√
Industrial freezers	√	√
Industrial large scale superconducting refrigerators	√√√	√√√
Supermarket refrigeration display cabinets	√	√√√
Supermarket freezer display cabinets	√	√√
Water cooled supermarket refrigeration and air conditioning	√	√√√
Air cooled supermarket refrigeration and air conditioning	√	√√
Land and air transport vehicle air conditioners or split systems	√	√
Land and air transport vehicle refrigerators	√	√
Land and air transport vehicle refrigerators	√	√
Land and air transport vehicle freezers	√	√
Large scale marine air-conditioning and refrigeration	√	√√√
Large scale superconducting marine air conditioning and refrigeration	√√√	√√√
Large scale superconducting marine freezing	√√	√√

Based on this extensive study two proposals for further work is proposed:

1) The most interesting case to further investigate is the household refrigerator without a freezing compartment. The hotel mini bar refrigerator and the wine cooler can be seen as very similar applications. In an air-conditioned hotel room the temperature of the surrounding air of a refrigerator is very stable, which is a great advantage for the magnetic refrigeration technology. Also wine coolers may be located at places with stable air temperatures. Furthermore, the power is small reaching from 40 W up to 100 W energy consumption. Small machines are also favorable for a first building of a prototype.

2) At the second position large chiller units for systems with not to low temperatures were evaluated to be ideal. Because of the large size of such equipment a superconducting magnets array could become economic. With increasing size the cost of an auxiliary cooling device for the superconducting magnets will show a decreasing (relative) economic impact. But such a system should not be realized without performing in advance a serious technical and economic study to prove that this solution is interesting for a small to medium time range.

7. National collaboration

A project of the Gebert Rüf foundation with the title: “Magnetic cold production at room temperature” had the objective to give us the chance to immediately start with some work on the field. In this project a first “demonstrator” (a radial magnetic refrigerator) was designed and built. This machine was not optimized by numerical simulations and that’s why we call it “demonstrator” instead of “prototype”. HEIG-VD/TIS (TIS denotes the division Thermal Industrial Systems) obtained an additional financial support from the Swiss Federal Office of Energy for developing the demonstrator.

The Swiss Federal Office of Energy also finances a further study, in which potential applications of a magnetic “power production” system (inverse process) using magnetocaloric material will be listed. A corresponding annual report showing the results of that study is also available.

The County of Vaud intends to support the division HEIG-VD/SIT (Simulations of Thermal Systems) with priority. The Swiss Federal Office of Energy (R&D program on heat pumping technologies, co-generation and refrigeration of SFOE) together with the County of Vaud finances a project to build a magnetic heat pump prototype. Also for this activity an annual report 2007 is available.

A meeting to present magnetic refrigeration to experts from a Swiss company led to a collaboration to develop some other technology. At present HEIG-VD researchers are discussing and starting research and development projects with different European companies, which are building refrigeration machines.

8. International collaboration

Two main authors of this work are the President and the Vice-president of the Magnetic Cooling Working Party of the International Institute of Refrigeration (IIF/IIR) in Paris. Up to now this group has organized two “International Conferences on Magnetic Refrigeration at Room Temperature”: the first one in 2005 in Montreux, Switzerland, and the second one in 2007 in Portoroz, Slovenia (see Figure 47 and Ref. [19]). Both conferences were very successful and a large number of participants from Universities and different companies worldwide participated. The next - the “Third International Conference on Magnetic Refrigeration at Room Temperature” - will be organized by V.K. Pecharsky in spring 2009 in the USA. V.K. Pecharsky is professor at the IOWA State University (AMES Laboratory). The HEIG-VD/SIT group has created the web-site of the working party, which may be found under the address given in Ref. [20].

After the second conference the two pioneers on materials for room-temperature magnetic refrigeration, K A. Gschneidner Jr. [21] und Vitalij K. Pecharsky [22], travelled with the group from Yverdon to Switzerland. Karl Gschneidner held a well visited invited presentation at the University of Applied Sciences of Western Switzerland with the title: „Thirty years of near room temperature magnetic cooling“. Then successful discussions on future collaboration were performed. The two experts explained that they are open to discuss a delivery of high-quality magnetocaloric material for magneto-thermodynamic testing in prototypes to the HEIG-VD group.

Figure 47: *The participants of the above mentioned conference in 2007, briefly named THERMAG II (THERMAG is an abbreviation for thermodynamics and magnetism), in front of the famous Postojnska caves. We experience that these conferences are visited by approximately 150 interested scientists and industrial representatives from all over the world. These conferences are also the official meeting occasions of the working party. During the conference always a larger meeting is organized to discuss with the members of the IIR working party the next two years activities.*

A result of the former conference Thermag I, which took place in 2005 in Montreux, is a Special Issue of the International Journal of Refrigeration on Magnetic Cooling (see Ref. [23]). It contains selected and improved conference articles.

In summer 2006 the division HEIG-VD/SIT had the excellent opportunity to benefit from the visit of Professor R. Rosensweig, who is a pioneer in the domain of ferrohydrodynamics. The collaboration with R. Rosensweig focuses mainly on the domain of the theory of magneto-thermodynamics and magnetic refrigeration as well as on the field of magnetocaloric slurries. In October 2007 P.W. Egolf produced together with him the 20th Informatory Note of the International Institute of Refrigeration (see Ref. [24]). R. Rosensweig is the well-known author of the standard text book „Ferrohydrodynamics“ [25]).

Our work on magnetic heating and cooling as well as a first “demonstrator“ were presented as results of a model project of a Swiss University of Applied Sciences in Switzerland at Swissnex in San Francisco [26].

In 2007 HEIG-VD - with the initiative of the division SIT - has signed a collaboration agreement with the deputy rector of Lomonosov State University in Moscow. A strong collaboration is under development with the well known specialist for magnetism, Prof. Alexander M. Tishin [27], who is also the author of a wide-spread standard text book on magnetocaloric materials and systems (see Ref. [28]).

The group SIT also collaborates with the University of Ljubljana. Two authors of this report are members of the commission for the Slovenian thesis of PhD student Alen Sarlah.

A further collaboration agreement has recently been signed with BASF (Future Technologies). This large German chemical company intends to start to produce magnetocaloric materials in large quantities. Such an action would tremendously support the production of magnetocaloric machines.

Acknowledgements

The authors are grateful to the Swiss Federal Office of Energy for financial support of their work. We also thank Felix Frey and Roland Brüniger for their scientific and administrative support. Furthermore, we are grateful to R. Rosensweig for his valuable contributions to our theoretical work on the field of magnetic refrigeration and complex fluids.

References

[1] E. Warburg, **Magnetische Untersuchungen über einige Wirkungen der Koerzitivkraft**. Ann. Phys. **13,** 141 –164, 1881.

[2] N. Tesla, **Pyromagneto-electric generator**, US patent 428,057, May 18, 1890.

[3] T.A. Edison, **Pyromagnetic generator**, US patent 476,983, June 14, 1892.

[4] P. Weiss, A. Piccard, **Sur un nouveau phénomene magnétocalorique**, Compt. Rend. Ac. Sc., **166**, 352, 1918.

[5] P. Debye, **Einige Bemerkungen zur Magnetisierung bei tiefer Temperatur**, Ann Phys. **81**, 1154 –1160, 1926.

[6] W.F. Giauque, **A proposed method of producing temperatures considerably below 1° absolute** . J. Amer. Chem. Soc. **49**, 1864 –1870, 1927.

[7] W.F. Giauque, D.P. MacDougall, **Attainment of temperatures below 1° absolute by dem agnetization of $Gd_2(SO_4)_3 \cdot 8H_2O$**, Phys. Rev. Lett. **43**(9), 768, 1933.

[8] G.V. Brown, **Magnetic heat pumping**, US Patent 4.069.028, 1978 (filed in Nov. 1976).

[9] G.V. Brown, **Magnetic heat pumping near room temperature**, J. Appl. Phys. **47**, 3673 –3680, 1976.

[10] C.B. Zimm, A. Sternberg , A.G. Jastrab, A.M. Boeder, L.M. Lawton, J.J. Chell, **Rotating bed magnetic refrigeration apparatus**, US Patent 6.526.759.4, 2003 (filed in Aug.2001).

[11] K.A. Gschneidner, V.K. Pecharsky, **30 Years of near room temperature magnetic cooling**, Second International Conference on Magnetic Refrigeration at Room Temperature, Portoroz, Slovenia, 2007.

[12]. Egolf P.W., Sari O., Kitanovski A., and Gendre F. (Editors), **Proceedings of the First International Conference on Magnetic Refrigeration at Room Temperature**, Montreux, Switzerland, 27-30 September 2005.

[13]. Rosensweig R.E., Gonin C., Kitanovski A. and Egolf P.W., **Magneto-Thermodynamics' Charts of Gadolinium for Magnetic Refrigeration** (in preparation).

[14]. Gschneidner K.A. Jr, Pecharsky V.K. and Tsokol A.O., **Recent Developments in Magnetocaloric Materials**, Institute of Physics Publishing, Rep. Prog. Phys. **68**, pp. 1479-1539, 2005.

[15]. Brück E., **Developments in Magnetocaloric Refrigeration**, *Topical Review J Phys. D: Appl. Phys*. **38**, pp. R381-R391, 2005.

[16] Kitanovski A. and Egolf P.W., **Thermodynamics of Magnetic Refrigeration**, *Int. J. Refr.* **29**, pp. 3-21 (2006).

[17] P.W. Egolf, F. Gendre, A. Kitanovski, O. Sari, 2006, **Machbarkeitsstudie für magnetische Wärmepumpen: Anwendungen in der Schweiz**, Schlussbericht des Projektes zuhanden des Bundesamtes für Energie Nr. 100873 / 151017, 1- 67.

[18] **World ACR compressors: rapid growth and shift towards regional hubs**, Press release 24/04, BSRIA Limited, 2004.

[19] http://www.thermag2007.si/ (November 2007).

[20] http://www.mcwp.ch/ (November 2007).

[21] http://www.metcer.ameslab.gov/people/gschneidner.html (November 2007).

[22] http://www.metcer.ameslab.gov/people/pecharsky.html (November 2007).

[23] H. Auracher, P.W. Egolf (Editors), **Magnetic Refrigeration at Room Temperature***,* Special Issue of the Int. J. Refr. **29** (8), 2006.

[24] P.W. Egolf, R.E. Rosensweig, **Magnetic refrigeration at room temperature,** 20th Informatory Note on Refrigeration Technologies of the Institute of Refrigeration, Paris, 1-8, October 2007.

[25] R.E. Rosensweig, **Ferrohydrodynamics**, Cambridge University Press, New York, 1985; reprinted with updates by Dover Publications, Inc. Mineola, New York, 1997.

[26] http://www.swissnexsanfrancisco.org/ (November 2007).

[27] http://ferro.phys.msu.su/eng/staff/tishin.html (November 2007).

[28] A.M. Tishin, Y.I. Spichkin, **The Magnetocaloric Effect and its Applications**, Series in Condensed Matter Physics, Institute of Physics, Publishing Ltd, 2003.