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Central Magnetic Cooling and Refrigeration Machines (Chiller) and their Assessment

A feasibility study

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Swiss Federal Office of Energy, SFOE
Research Programme Electricity Technologies and Applications
CH-3003 Berne
www.bfe.admin.ch

Project performance:
University of Applied Sciences of Western Switzerland
HEIG-VD
Route de Cheseaux 1
CH-1401 Yverdon-les Bains
www.heig-vd.ch

Authors:
Prof. Dr. Peter W. Egolf, HEIG-VD, peter.egolf@heig-vd.ch
Assist.-Prof. Dr. Andrej Kitanovski, University of Ljubljana, andrej.kitanovski@fs.uni-lj.si
Cyrill Gonin, HEIG-VD, cyrill.gonin@heig-vd.ch

SFOE Leader of Division: Dr. Michael Moser
SFOE Leader of Programme: Roland Brüniger
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Zusammenfassung

Dieser Bericht stellt eine ausführliche thermodynamische und oekonomische Analyse von Anwendungen von rotativen magnetischen Kältemaschinen („Chillern“) dar. In magnetischen Chillern können zwei verschiedene magnetische Feldquellen effizient eingesetzt werden. Die Studie befasst sich mit magnetischen Chillern die auf Permanent-Magneten und auf supraleitenden Magneten beruhen.

Ein numerisch unterstützter Entwurf wurde mit einer Permanent-Magnet-Konfiguration mit verschiedenen magnetischen Feldliniendichten durchgeführt. Spezielle Anstrengungen wurden gemacht um einen optimalen „Design“ der magnetokalorischen Strukturen zu erhalten. Zuerst wurden diese als wellenförmige Strukturen vorausgesetzt. Verschiedenste Resultate der Konstruktion und Betriebsweisen der magnetischen Chiller führten/führen zu wichtigen Informationen für weitere Forschungs- und Entwicklungsarbeiten. Die thermodynamische Analyse zeigt, dass rotative magnetische Chiller bessere Wirkungsgrade erzielen können als konventionelle mit Kompressoren. Dies wurde schon in einer früheren Publikation aufgezeigt. Die Resultate dieses Berichtes sind basiert auf realen Entwürfen von magnetischen Rotations-Chillern. Es wird gezeigt, dass rotative magnetische Chiller, basierend auf Permanent-Magneten, einen modularen Aufbau mit mehreren Einheiten in einer Serienschaltung verlangen. Dies präsentiert eine Grenze für die Grösse eines Chillers, welche durch die Grösse der Magnetkonfiguration bestimmt wird. Chiller, basierend auf Permanent-Magneten, können dadurch Leistungen zwischen einigen kW und etwa 200 kW erbringen. Höhere Leistungen und tiefere Kosten können erzielt werden durch die Anwendung von neuen zukunftsgerichteten magnetokalorischen Technologien (siehe unten).

Rotative magnetische Chiller führen zu höheren Kosten als diese von äquivalenten Kompressor-Kälte-Anlagen. Dies ist vor allem evident, wenn man Applikationen mit einem 20 % - Äthanol/Wasser-Fluid studiert. Um den Wirkungsgrad und damit die Leistung eines magnetischen Chillers zu steigern und die Kosten zu senken, können andere Typen von Flüssigkeiten eingesetzt werden. Applikationen mit metallischen Fluiden (z.B. solchen basierend auf In und Ga) erhöhen die Kühlkapazität mehr als eine Grössenordnung verglichen mit Äthanol/Wasser bei vergleichbarer Effizienz eines Chillers. Wegen des hohen Preises von solchen Flüssigkeiten, ist der Preis eines Kernteils eines rotativen magnetischen Chillers etwa zweimal höher als derjenige eines äquivalenten kompressor-basierten Chillers. Falls man aber die Betrachtung auf alle Teile einer solchen Kältemaschine ausdehnt, so ist die Differenz der Kosten zwischen einem magnetischen Chiller und einem konventionellen vergleichsweise klein. Auch die Charakteristik des Wärmetransports hat einen grossen Einfluss auf die Kosten einer Maschine. Das ist der Grund, dass diese Studie nicht von luftgekühlten Chillern handelt. Luftgekühlte Chiller sind beim jetzigen Stand der Entwicklung der magnetischen Kältetechnik noch nicht bereit für eine Markteinführung im Gebäudesektor. Trotzdem zeigen sie ein interessantes Potential für einige Industriezweige.

Supraleitende magnetische Chiller sind nur machbar in gross-skaligen Anwendungen von über 1 MW Kälteleistung. Die Kosten eines solchen Apparates werden als kleiner veranschlagt, als jene einer konventionellen Kompressor-Maschine. Der Wirkungsgrad wäre höher. Solche Kältemaschinen sollten ernsthaft in Erwägung gezogen werden für eine zukünftige Markteinführung. Die Entwicklung von supraleitenden magnetischen Chillern würde Investitionen und Aktivitäten in Forschung und Entwicklung auf einer grösseren Skala verlangen.

Zum Schluss enthält dieser Bericht auch einige neue Ideen für die magnetische Kältetechnik, welche über den gegenwärtigen Stand der Kenntnisse hinausgeht. Diese beinhalten ein Potential für weitere Kostenreduktionen und Erhöhungen von Wirkungsgraden.

Schlüsselwörter: magnetische Kältetechnik, Magnetokalorik, magnetischer Chiller, Energieeffizienz.

Abstract

This report presents a comprehensive thermodynamic and economic analysis of applications of rotary magnetic chillers. In a magnetic chiller two types of magnetic field sources can be efficiently applied. The study deals with magnetic chillers based on permanent magnets and superconducting magnets, respectively.

A numerical design has been performed for permanent magnet assemblies with different magnetic flux densities. Special efforts have been made to obtain an optimal design of magnetocaloric porous structures. These were first considered to have the form of a periodic wavy structure. Numerous results on the design and operating characteristics of magnetic chillers led/lead to important information for further research and development. The thermodynamic analysis shows that rotary magnetic chillers can overcome efficiencies of conventional compressor chillers. This was already reported in a previous publication. The results of this report are based on real designs of rotary magnetic chillers. It is shown that rotary magnetic chillers, based on permanent magnets, require a modular design of several units in a connected series. This presents a limit given by the size of the permanent magnet assembly. Chillers based on permanent magnets can, therefore, provide a cooling power in the range from a few kW to 200 kW. Higher power and lower costs can be obtained by new future magnetocaloric technologies (see section below).

Rotary magnetic chillers lead to higher costs than those of an equivalent compressor system. This becomes obvious for applications with a 20% ethanol-water fluid. In order to increase the efficiency and the power of a magnetic chiller, as well as to reduce costs, other types of heat transfer fluids may be applied. Applications with liquid metals (e.g. based on In and Ga elements) increase the cooling power for more than one order compared to solutions with ethanol-water for an equal efficiency of the device. Because of the very high price of such liquids, the core part of the rotary magnetic chiller leads to costs that are approximately two times higher than those of an equivalent compressor. However, taking into account all the devices and elements of the cooling system, the difference in costs between the magnetic cooling system and the conventional compressor cooling system is small. Also heat transfer characteristics have a strong influence on the cost of a device. This is the reason why this study does not deal with air-cooled chillers. Air-cooled chillers are at the present stage of development of the magnetic refrigeration technology not (yet) feasible for a market application in buildings. However, they show a large potential in some industrial refrigeration markets.

Superconducting magnetic chillers are feasible only in large-scale applications that go beyond 1 MW of the cooling power. The cost of such a machine is smaller than that of an equivalent compressor chiller. Its efficiency will be higher. Such systems should be seriously taken into consideration for future market applications. Superconducting magnetic refrigeration would require large future research activities on a broader scale.

This report briefly describes new ideas for magnetic refrigeration technologies, which go beyond the state of the art. They show potential for a substantial cost reduction and further improvements of the efficiency.

Keywords: magnetic refrigeration, magnetocaloric's, magnetic chiller, energy efficiency.

Résumé

Ce rapport présente une analyse thermodynamique et économique complète sur des refroidisseurs magnétiques rotatifs. Dans ce type d'applications, deux genres de sources magnétiques peuvent être efficacement employées. La présente étude porte sur des refroidisseurs magnétiques dont les sources emploient des aimants permanents ou des supraconducteurs.

Des designs numériques ont été élaborés pour des sources magnétiques à aimants permanents dont les flux d'induction varient. Une attention particulière a été apportée aux structures magnétocaloriques poreuses, dans le but d'en optimiser les effets. Celles-ci furent d'abord étudiées sous forme de structures périodes alvéolées. De nombreux résultats sur des conceptions et des caractéristiques de fonctionnement de refroidisseurs magnétiques conduisent ont conduit à d'importantes informations en vue de recherche et de développements futurs. L'analyse thermodynamique a montré que les refroidisseurs magnétiques rotatifs peuvent surpasser les rendements des refroidisseurs classiques à compression. Ces conclusions ont déjà été soutenues lors d'une précédente publication. Les résultats de ce rapport sont basés sur des conceptions réelles de refroidisseurs magnétiques rotatifs. Il a été montré que les refroidisseurs magnétiques rotatifs, basés sur des aimants permanents, requièrent une conception modulaire de plusieurs unités connectées en série. Cela introduit une limite donnée par la taille de l'assemblage magnétique. Les refroidisseurs basés sur l'emploi d'aimants permanents peuvent, le cas échéant, produire une puissance de refroidissement de l'ordre de quelques kW à 200 kW. Des puissances plus étendues, ainsi que des coûts plus restreints pourront être obtenus par de nouvelles technologies magnétocaloriques, (voir section ci-dessous).

Les refroidisseurs magnétiques rotatifs conduisent à des coûts plus prohibitifs que les systèmes à compression, à puissance équivalente. Cela devient évident pour les applications avec un fluide à 20% d'éthanol-eau. Afin d'accroître l'efficacité et la puissance d'un refroidisseur magnétique, ainsi que d'en réduire les coûts, d'autres types de fluides de transfert de chaleur peuvent être appliqués. Des applications avec des métaux liquides (p. ex. basés sur les éléments In et Ga) augmentent la puissance de refroidissement d'un ordre supérieur à un, comparées aux solutions éthanol-eau et pour une efficacité égale de l'appareil. En raison du prix très élevé de tels liquides, la partie centrale du réfrigérateur magnétique rotatif entraîne des coûts deux fois supérieurs à ceux d'un compresseur équivalent. Toutefois, en tenant compte de l'intégralité des composants et éléments du système de refroidissement, la différence de coûts entre un système magnétique et un compresseur classique est faible. Aussi, les caractéristiques de transfert de chaleur ont une forte influence sur le coût d'un appareil. C'est la raison pour laquelle cette étude ne traite pas de refroidisseur par air. Ce type de refroidisseurs sont actuellement à l'étape de développement et ne sont pas (encore) réalisables pour le marché de l'habitation. Cependant, ils montrent un grand potentiel dans certains marchés de la réfrigération industrielle.

Des refroidisseurs à aimants supraconducteurs sont réalisables que dans des applications à grande échelle, pour des puissances de refroidissement qui avoisinent 1 MW. Le coût d'une telle machine est inférieur à celui d'un refroidisseur à compression équivalent. Son efficacité sera plus élevée. De tels systèmes devraient être sérieusement pris en considération pour de futures applications commerciales. La réfrigération magnétique à supraconducteurs nécessiterait d'importants travaux de recherche sur une échelle plus large.

Ce rapport décrit brièvement les nouvelles idées sur des technologies de réfrigération magnétique, qui vont au-delà de l'état de l'art. Elles montrent un potentiel pour une réduction considérable des coûts et une amélioration de l'efficacité.

Mots clefs: réfrigération magnétique, magnétocaloriques, refroidisseur magnétique, efficacité énergétique.

Objectives of the project

By the discovery of the „giant magnetocaloric effect“ magnetic refrigeration obtained a large momentum. One may easily show that the low number of publications published in international journals before the discovery of Gschneidner and Pecharsky in the year 1996 suddenly started to grow exponentially. The number of patents in this domain increases as well and up-to-present approximately 40 prototypes have been built world-wide [1].

Three studies performed for SFOE concerning the feasibility of the three technologies, namely magnetic heat pumping, magnetic refrigeration and magnetic energy conversion have caused a large interest in the related community of scientists and industrial representatives.

Specially the study *“Application of Magnetic Refrigeration and its Assessment: A Feasibility Study”* [2] has caused a large attention among refrigeration engineers. This study had the objective to evaluate all possible refrigeration technologies for their potential to apply magnetic refrigeration as a substitute technology. It was shown that chillers for air conditioning of buildings and the cooling of products in process techniques, in the case that the second application does not require a too low temperature, as for example 5 °C, are ideal applications.

Therefore, the objective of this succeeding project is – on the basis of the previous more general study – to focus specially on the chiller technology. Based on this study the possibility is given to spend financial resources for research and development more optimally directed to an ideal application. Researchers have the hope that this evaluation will lead to a following project, which should include the building of a first prototype with a support by industry. Relations to such companies have been taken up and are at present in a favourable state.

The expected results of this project are listed below:

1) „Review“ of the chiller technology (air cooling, evaporative cooling, water cooling)
2) List of advantages and disadvantages of the single technologies with relating to the size of the systems
3) Comparison with other more conventional refrigeration technologies
4) List and an extensive description of possible applications
5) Technical characterisation of the devices
6) Proposal of a suitable magnetic and regenerative prototype for each application
7) Numerical modelling with simplifications of machines, mentioned under point 6
8) Numerical energy consumption determinations
9) Estimations of costs of devices by taking the competence of refrigeration companies into consideration
10) Comparisons (compare points 8 and 9) of the new system with the conventional technology
11) Proposal for further work
12) Search for an ideal industrial partner
13) Working out all the demanded end-of-year, intermediate and final research reports.

Evaluation methods

For the purpose of this feasibility study, special methods were developed for the evaluation of efficiencies, geometries and the economics of magnetic refrigerators. The following works led to the development of these unique studies or methods:

- Study of magnetocaloric material properties (La (Fe,Si,H))
- Study, design and numerical simulation of the permanent magnet assemblies
- Study, numerical simulations and economic evaluation on superconducting magnets
- 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
- Development of a 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 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 effect 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
9) Energy losses in superconducting magnet systems.

There exist two main types of magnetic refrigerators: a rotary and the reciprocating. The first is in most cases based on the rotation of the magnetocaloric material through the variable magnetic field. In certain cases, the magnets rotate instead of the magnetocaloric material. The reciprocating type is based on the reciprocate movement of the magnetocaloric material in and out of a magnetic field. Also in this case, the magnets may move instead of the magnetocaloric material. Regarding the operation characteristics, rotary machines operate with higher frequencies of operation. Since in this case the magnetocaloric material continuously rotates, there are no losses accompanied with the mass inertia and related acceleration and deceleration. The two types of devices differ also in their thermodynamic cycle. Rotary machines have usually an open thermodynamic cycle, whereas reciprocate machines apply a closed thermodynamic cycle. Above mentioned reasons led the authors of this report to focus only on rotary magnetic chillers.

The calculation of the behaviour of liquid rotary magnetic chillers was based on the follow in the simulation processing parameters: the chilled liquid supply temperature to the outer system being 7 °C and the exit temperature of the cooling fluid coming in from the magnetic chiller being assumed to be 32 °C. In the simulation process the temperature of the returning chilled fluid and the supply temperature of the cooling fluid were varied. In a first approach 20 % ethanol/water solution was chosen as working fluid. In the second approach, 20% ethanol water was replaced by the liquid metal Galinstan [3].

The procedure started with the design of the magnet assembly and then led over to numerous simulations of magnetic field line distributions. The maximum diameter of the magnet assembly was fixed to be 40 cm. This was decided in order to avoid too large occupied spaces and costs caused by a production of large-size permanent magnets. The magnets are designed in such a manner that they magnetize two symmetric regions of a coaxial ring (gap). The ring consists of two small soft permeable iron coaxial cylinders with a thickness of about 2 mm each. These serve as the housing of the magnetocaloric porous structure and together present the rotating part of the machine. Between the cylinders a magnetocaloric material is positioned in form of a fine periodic wavy structure. Simulations for such structures were made for both heat transfer fluids, the 20% ethanol-water and the liquid metal Galinstan. They were also made for two types of rotary magnetic chillers. Magnetic chillers with permanent magnet assemblies and those equipped with superconducting magnets. At the present stage of developments on magnetocaloric materials their mechanical properties restrict the geometry and the related design possibilities. Additional design and simulations were performed. The structure of the magnetocaloric material was considered to be performed by micro-tubes (for the fluid flow), embedded in grains of magnetocaloric material of different sizes.

Accomplished work and achieved results

1. Overview of existing cooling technologies and the application of magnetic chillers

The final report of the SFOE study *"Application of Magnetic Refrigeration and its Assessment"* [2] shows different possible applications of magnetic chillers. There, a table with a list of the most feasible technologies is presented. Additional research activities led the authors of this report to further restrictions. These are given by the economics of a device. Namely, conventional air cooled chillers require a large temperature span, because of occuring large irreversible heat transfer losses. In order to achieve efficiencies higher than those of conventional machines, magnetic air cooled chillers require a large mass of magnets. A large mass of magnets is required for both, the high magnetic flux density and the magnetization of a larger amount of magnetocaloric material (due to the larger temperature span). A high magnetic flux density leads to an increase of the power density of the magnetocaloric material. Then this compensates irreversible heat transfer losses. However, for the same magnetized space, the mass of magnets increases approximately by a quadratic power law with the increase of magnetic flux density. Existing permanent magnet materials are very expensive. Because of this, air cooled magnetic chillers – despite of a possible high efficiency – lead to a too high cost. One must conclude that they are at present not feasible for an application in buildings. However they may be cost effective in some industry sectors. In order to evaluate on most feasible technologies, this report only deals with magnetic chillers applying liquids.

1.1. Central cooling and air conditioning systems

There exists a certain interest and some activities in the industry of central chillers or HVAC systems in the field of the magnetic refrigeration technology. However, compared to activities in other domains of refrigeration (which e.g. regard small compressor units), the industry of central chiller systems seem to be more rigid. The only R&D activities that are held at institutes worldwide in the domain of magnetic cooling or air-conditioning in buildings and houses are to our best knowledge performed by the HEIG-VD (SIT) group. This is also due to the continous support of the Swiss Federal Office of Energy.

In conventional central cooling systems two main technologies are mostly applied. These are vapor compression (reciprocate, screw, turbo-compressors) and sorption (usually hot water and gas absorption chillers, rarely adsorption and steam driven absorption chillers). Heat rejection to the ambient is in most cases combined with an additional cooling via cooling towers. The efficiency of water cooled chillers is much higher than that of air-cooled chillers.

Figure 1: *Left: A typical centrifugal chiller (Carrier) of a large size. These chillers are usually applied for a large cooling power (large refrigerant volume flow and low pressure ratio). The nominal cooling capacity may be kept in a wide range of operating characteristics. Right: The McQuay water cooled liquid screw compressor chiller.*

Operating conditions of liquid/liquid central chillers are favorable for the application of the magnetic refrigeration technology. This is due to the small temperature span between the heat sink and source. A conventional liquid/liquid compressor chiller operates with the temperature of the cooling fluid of 27/32 °C (return and supply fluid temperatures to and from e.g. the cooling tower). The chilled fluid temperatures are usually 7/13 °C (supply to e.g. fan coils and return to evaporator). Considering magnetic refrigeration, the following chiller technologies have the highest potential for a market penetration at an earlier stage:

- **central magnetic chillers ($< 200\ kW_C$)**

In series connected modular assembly of magnetic chiller units. Application of permanent magnets.

- **decentralized magnetic chillers ($<200\ kW_C$)**

Single or in series connected modular assembly of magnetic chiller units. Application of permanent magnets. Possible combination with the conventional chiller technology. The last enables smaller temperature spans between the heat source and sink. Notify that there are not many examples of such configurations in practice where a central chiller serves as pre-cooler for dislocated smaller chiller units.

- **large central magnetic chillers (e.g. > 1 MW)**

Application of superconducting magnets. Possible application in district cooling systems or other central cooling systems. In district cooling systems central chillers operate with a lower temperature of the chilled fluid than this is the case in a central chiller unit in a building.

1.1. Secondary units

These units serve for the utilization of the cooling energy. Because a magnetic chiller is restricted to rather smaller temperature spans, this also affects the selection of a secondary unit. Most appropriate technologies that may be applied in such cases are:

- Ceiling panel radiant cooling

The temperature of the heat source in the panel radiant cooling depends on the building air characteristics. These are the air temperature and the relative air humidity. Therefore, the temperature of the chilled liquid is rather high, e.g. from 10-16 °C. Small temperature differences between the heat source and the heat sink lead to a high Coefficient Of Performance (*COP*).

- Fan coil cooling

Fan coils are mostly applied in central or split cooling systems. These elements apply forced air convection over the surface of the integrated heat exchanger. They are usually floor mounted, ceiling mounted or wall mounted units. Their lowest temperature level is about 4 °C (usually 7 °C). The temperature difference between the inlet and outlet of the fluid is usually 4-7 K. Fan coils are manufactured for applications with two or four connections (e.g. two for heating and two for cooling).

- Air conditioning

Air conditioning systems comprise cooling, heating, humidification, dehumidification, filtering, heat recovery or heat regeneration of the air. The chilled fluid temperature level is higher than in an application with fan coils, and similar or higher than the temperature level in a cooling ceiling application. Applications of the magnetic cooling technology in air conditioning may appear in a cold production or in other types of air treatment.

2. Rotary magnetic liquid chillers with wavy structures

2.1. Design and simulations of permanent magnet assemblies

A basic design concept for the magnet assembly was made for the purpose of this study (see Fig. 2). Three different magnet assemblies – with the same outer diameter, namely 40 cm – were designed. These provide magnetic flux densities of 1 T, 1.5 T and 2 T, respectively (see Fig.'s 2a-c). The magnetic field occurs in two symmetric regions of a coaxial ring. The ring is positioned into the magnet assembly. The dimension of the coaxial ring is shown in Fig.'s 2a-c. It denotes only a part, where the magnetocaloric structure – with a certain volume fraction – is contained. These figures also show the (rough approximation to reality) 2-d magnetic simulation results resulting from an application of a finite element analysis.

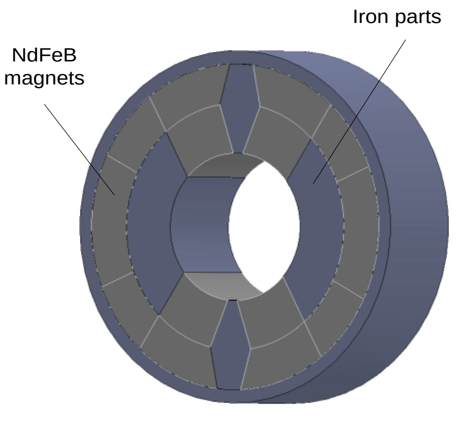


__Figure 2:__ The design of the magnet assembly for a magnetic chiller is presented. To obtain a clear presentation, the inner core part (made of soft iron) and the magnetocaloric structure of the ring are not shown.

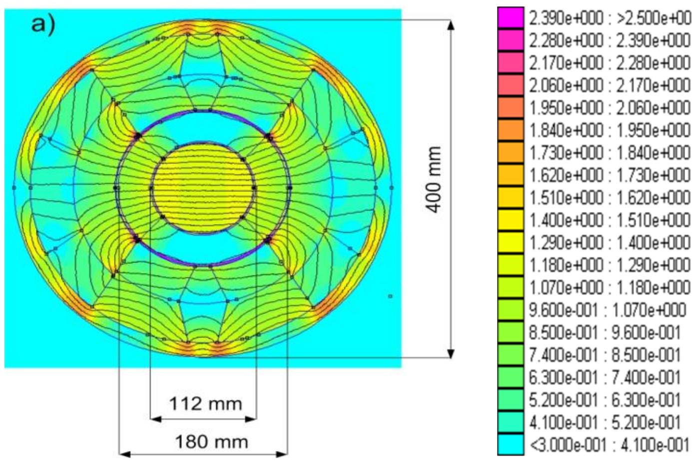


__Figure 3a:__ The results of magnetic simulations with a finite element analysis (1 T magnet assembly) are shown. A large gap enables a large amount of magnetocaloric material to be located in it.

Numerous simulations were performed (simultaneously related changes in design were done) so that final designs for magnet assemblies with the already mentioned 1 T, 1.5 T and 2 T magnetic flux density were obtained. Notice that the magnet assemblies are not completely optimized. It is seen in Fig.'s 2a-c that higher magnetic flux densities require smaller gaps or smaller coaxial rings, respectively. A smaller gap contains less magnetocaloric material, and this naturally influences the power of the machine. On the other hand, a higher magnetic flux density leads to a higher power density of the magnetocaloric material. It is therefore expected that the optimum results for solutions with magnetic fields between 1 to 2 T occur. This is valid for the structure and magnetocaloric properties taken into account.

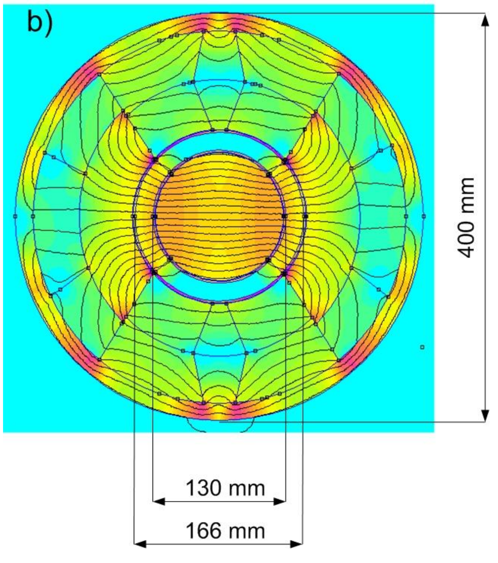


Figure 3b: *The results of magnetic simulations with finite element analysis (1.5 T magnet assembly) are shown. The legend of Fig. 3a is also valid for this figure.*

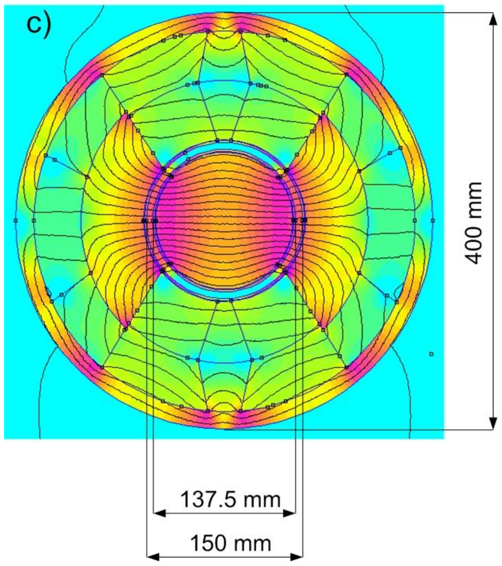


Figure 3c: *The results of magnetic simulations with finite element analysis (2 T magnet assembly) are shown. The legend of Fig. 3a is also valid for this figure.*

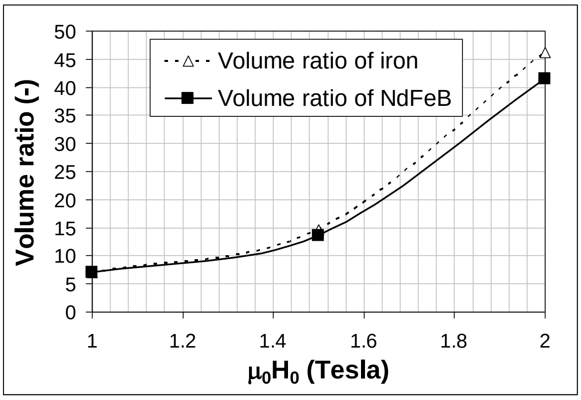


Figure 4: *The volume ratio between the volume of magnets or soft iron and the volume of the magnetized region for different magnetic flux densities are shown.*

Any substantial change of the heat transfer surface, heat transfer coefficient, heat diffusion rate and the fluid properties may lead to slightly different results. In a previous SFOE study [2], it is stated that the magnetic flux density should be as high as possible. Regardless the results shown in this report, this remains true especially in cases when the magnetocaloric structure cannot be shaped as desired. High magnetic flux densities and related energy densities compensate larger irreversible losses due to a not perfect structure.

Instructive information is contained in Fig. 4. It shows the volume ratio between the volume of the magnet material (NdFeB) and the volume of the magnetized region for different magnetic flux densities. It also presents the volume ratio between the volume of the soft iron and the volume of the magnetized region. Notice that both, namely the magnets volume and the volume of the soft iron, add up together to give the total volume of the magnet assembly. Fig. 4 clearly demonstrates the sudden large growth of the volume of a magnet assembly when the magnetic flux density is higher than 1.4 T. This is directly related to the cost of the magnet assembly and consequently the cost of the magnetic chiller. Despite of these results, further analyses are required in order to evaluate how much cooling power for different operating conditions for different magnet assemblies may be obtained.

2.2. Design, thermodynamic, economic characteristics

Iterative calculations have been made with an own developed numerical tool to determine the thermodynamic and fluid dynamic related characteristics. Additionally two commercial software's to calculate the 2-d (first approximation) and 3-d (final calculation) magnetic field line distributions were applied. In this study – contrary to other previous feasibility studies, where pure gadolinium was the magnetocaloric material – for modelling purposes the thermodynamic properties of La(Fe,Si,H) (see in Ref.'s [4] - [6]) were chosen. It was assumed that layering leads to 80 % of the maximum magnetocaloric effect of these materials.

2.2.1. First results

The analysis was performed for three different magnet assemblies that are presented in Fig.'s 3a-c. Based on this, information on the coaxial ring is given. The coaxial ring is filled with a wavy structure produced with magnetocaloric material. This material has a thickness of 0.1 mm. The magnetocaloric properties of the group of magnetocaloric materials La (Fe, Si,H) were taken into consideration. It is assumed that the group of materials is layered in the direction of the temperature directional derivative. This direction is the axial direction in the cylinder and also the downstream direction of the fluid flow. It is assumed that the layering of magnetocaloric materials leads to a cooling capacity of 80 % of the maximum one occurring at Curie temperature. Different volume fractions of the magnetocaloric material were considered, namely 30%, 45% and 60%, respectively. Since the front surface of the coaxial ring (which is filled with magnetocaloric structured material) is given by numerical simulations, the variation of the volume fraction at constant thickness led to different hydraulic diameters and different heat transfer surfaces. These substantially influence the characteristics of the pressure drop and heat transfer. The parameters were varied in all cases in such a manner that the *COP* was always kept at the value of 5.5 (exergy efficiency about 45 %). Fig.'s 5-7 show the results of the analysis for different parameters. Red pointers in these figures denote a selected optimal value that will be applied in a more comprehensive future analysis. In Fig.'s 5-7 magnetic flux densities of 1, 1.5 and 2 T correspond to the magnet assemblies in Fig.'s. 3a-c. It may be observed that the volume fraction of the magnetocaloric material drastically influences the cooling power of a device. This is also true for the magnetic flux density and the length of the magnet assembly.

The target was a *COP* value of 5.5 and this was the value kept fixed in all calculations (the *COP*=5.5 corresponds to the operation characteristics of a turbo-compressor chiller for the given temperature levels). Design and operation parameters could then only be varied in subspaces so that the predefined *COP* was guaranteed. The goal of the analysis was to find an optimal magnetic flux density (magnet assembly), optimal length of the magnet assembly and other optimal operation parameters. Furthermore, the pressure loss for the optimal case should not exceed 100 kPa. High pressure losses cause problems associated with seals and internal fluid leakage. All these applied methods led to a selection of magnet assemblies, which represent the lowest magnet's mass per cooling power.

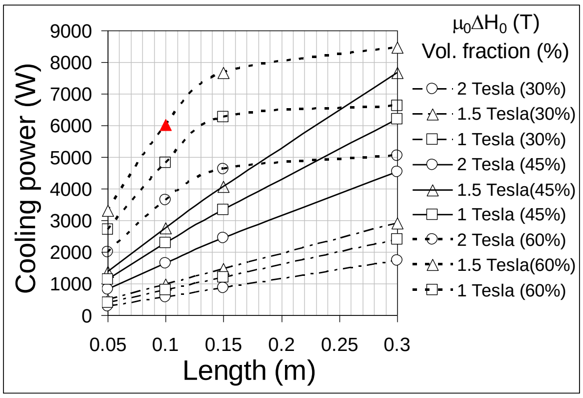


Figure 5: *The cooling power of the rotary magnetic chiller depending on the length of the magnetocaloric ring (magnet respectively), magnetic flux density and volume fraction of the magnetocaloric material are presented in this figure.*

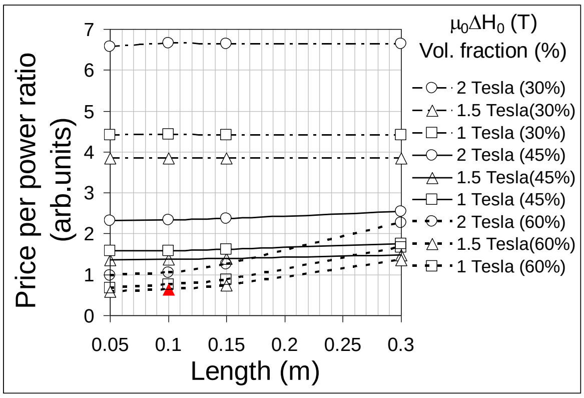


Figure 6: *The price per power ratio of a magnet assembly for different lengths, different magnetic flux densities and different volume fractions are presented in this figure. The ratio gives an important basis for further economic evaluations.*

According to Fig. 5 the increased volume fraction leads to a higher cooling power. However, one observes that for a volume fraction of 60 % the relation between the cooling power and the length of the magnet assembly (coaxial ring respectively) substantially differ from those at lower volume fractions. The reason is a smaller hydraulic diameter, which at higher fractions strongly influences the pressure drop and its related losses. This is more drastic for longer magnet assemblies, whereas for smaller lengths, e.g. up to 15 cm, all the volume fractions lead to approximately the same tendency of the *COP* dependence on the length. The magnetic field strength does not have a so strong influence on the cooling power as an increased volume fraction does. This fact should be seriously considered when designing a magnetic chiller. However, there exists also an optimal volume fraction. Since it strongly depends on the design and dimensions of the structure (which may differ from the wavy structure), the analysis was not focused on this detail too much. Fig. 6 shows the price per power ratio for different design and operating conditions.

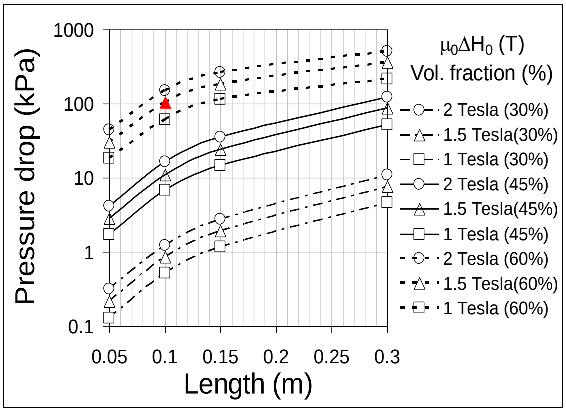


Figure 7: *The pressure drop for different lengths of magnet assemblies, different magnetic flux densities and different volume fractions of the magnetocaloric material are shown. Higher volume fractions (of about 60%) lead, especially for longer magnet assemblies, to very high pressure losses. Such cannot be accepted in a realistic machine design. This is why the red pointer is located at 100 kPa. It denotes a criterion for the selection of an optimal magnetic chiller. This selection is related also to Fig.'s. 3a-c and 5.*

The price per power ratio presents the ratio of the total mass of magnet material and soft iron (magnet assembly) per cooling power versus the ratio of the total mass of magnets and soft iron per cooling power of the reference unit. The reference unit was defined to have a *COP*=5.5 at a magnetic field strength of 1 T, 60 % volume fraction, and a cooling power of 1 kW. The ratio in Fig. 6 gives important information on optimal values that a particular magnet assembly can obtain at the same efficiency. The price per power ratio for the selected optimal point (see red pointer in Fig. 6), which corresponds to 60% volume fraction and a magnetic field of 1.5 T and a length of the wheel of *L*=10 cm, and the magnet assembly of 2 T magnetic field, for the same volume fraction and length, substantially differ. The 1.5 T magnet assembly presents approximately 50 % lower cost compared to the one with a magnet assembly reaching 2 T. It is shown that machines with lower volume fractions, of e.g. 30 %, lead to substantially higher costs than those with higher volume fractions. The minimal ratio is not obtained for highest magnetic flux densities of 2 T (the 2 T magnetic field leads to higher costs even when compared to an applied field of 1 T), but rather for values of about 1.5 T. More detailed analyses have shown that the minimal costs will require magnetic flux densities slightly lower than 1.5 T. Similar as in the case shown in Fig. 6, the dependence of the price per power ratio is more sensitive to the length of the magnet assembly at higher volume fraction than at lower one's. Fig. 6 shows pressure losses for different design and operation conditions.

The results of first analyses presented in this subchapter show the complexity of performing an optimal design of magnetic chillers, which depend on many parameters. Therefore, certain simplifications were made in order to avoid a full sixteen parameter optimization procedure. By choosing the pressure loss of 100 kPa at a volume fraction of 60 % and a length of the magnet assembly of 10 cm, the price per power ratio comes out almost at a minimum among all the results shown in Fig.'s 5-7. The cooling power of the selected rotary magnetic chiller is 6 kW with a *COP*=5.5 and the exergy efficiency is approximately 45 %. The selected magnetic flux density is 1.5 T. Shorter magnet assemblies show smaller cooling power. Short magnet assemblies may cause the problem of a magnetic flux leakage into the surrounding space of the magnet assembly. Because the selected power of 6 kW presents the maximum for one unit (for the predefined efficiency), a higher cooling power may be achieved by a modular assembly of numerous chiller units. However, it is expected that the limit of such a modular construction would be at about 200 kW of cooling power. The reason for this is the price per cooling power, which for conventional chillers substantially decreases with the cooling power of one unit. Unfortunately, this is not the case with the modular design of the rotary magnetic chillers, except for certain auxiliary parts.

2.2.2. Extended analyses

Further investigation focuses on magnetic chillers which apply permanent magnet assemblies with magnetic flux densities of 1.5 Tesla (the magnet assembly and its available "gap" space is shown in Fig. 3b). Further restriction has been made for the length of the magnet assembly (also length of the magnetocaloric material's structure). This was taken to be L=10 cm. The volume fraction of the magnetocaloric material was varied between 30-60 %. The thickness of the magnetocaloric material's structure was varied between s=0.1-0.4 mm. In first calculations the 20 % ethanol-water solution was considered as working fluid. However, a small cooling power with such a fluid led the authors to investigate on other applications with liquids. A very interesting and promising application is the use of liquid metals as heat transfer fluids. However, most of these liquids are highly toxic and reactive (e.g. Mercury, NaK). This led to a selection of the liquid metal Galinstan [3]. Galinstan is a family of eutectic alloys of gallium, indium, and tin, which are liquid at room temperature, typically freezing at -19 °C. Due to the low toxicity and low reactivity of its component metals, it finds use as a replacement for many applications that previously employed toxic liquid mercury or reactive NaK (sodium-potassium alloy). Its density is 6440 kg m^{-3}, the melting point is -19 °C, the dynamic viscosity 2.4 mPas (at 20 °C) and the thermal conductivity is 15.5 W $m^{-1}K^{-1}$ [3].

Figures 8, 12 and 16 show results of the thermodynamic analysis performed for the rotary magnetic chiller. The chiller consists of a magnetocaloric material with 30 %, 45 % and 60 % volume fraction, respectively. The heat transfer liquid is the 20 % ethanol-water solution. Figures 10, 14 and 18 show results of the thermodynamic analysis, where the liquid metal Galinstan was considered to be the heat transfer fluid. Simultaneously the economic evaluation was performed for the same parameters as shown in the thermodynamic analysis. Figures 9, 13, and 17 show results of the thermodynamic analysis for magnetic chillers with 20 % ethanol-water and 30 %, 45 % and 60 % volume fraction, respectively. Results of the economic analysis for magnetic chillers with the liquid metal Galinstan are shown in Fig.'s. 11, 15 and 19 for 30 %, 45 % and 60 % volume fraction, respectively.

The results of the thermodynamic analyses indicate a large influence of the volume fraction and the thickness of the structure on both, the cooling power and the *COP*. This is much more drastic for the application with the 20 % ethanol-water fluid. The magnetic chiller can overcome the efficiency of an equivalent conventional compressor chiller. This is true for all cases with the 20 % ethanol-water (Figs 8, 12 and 16) as well as the cases applying the liquid metal Galinstan (Figs. 10, 14 and 18). High coefficient of the performance requires small frequency of operation as well as a smaller thickness of the structure. However, the optimal thickness for applications with the liquid metal Galinstan is not necessarily also the smallest one. An increased volume fraction or a decreased thickness of the structure increases the heat transfer surface, but reduces the hydraulic diameter. The latter negatively influences the viscous losses, which are related to the power consumption. In cases with the 20 % ethanol-water the influence of the thickness does not increase the pressure loss so drastically. When the liquid metal Galinstan is applied, the best *COP* values are not obtained for the smallest thickness of the structure. This can be seen in results for volume fractions of 45 % and 60 % (see Fig.'s. 14 and 18). On the other hand, the cooling power is highest for smallest thicknesses and highest volume fractions. This is valid for all the considered cases and both liquids. One should note that volume fractions of 60 % should be taken as the upper limit. Higher volume fractions than 60 % lead to too high viscous losses for both considered liquids.

As may be seen from results in Fig.'s. 8-18, the application of liquid metal substantially increases the cooling power of a device. This can be up to an order larger compared to the case where 20 % ethanol-water is applied. The results show excellent heat transfer characteristics of the liquid metal. These lead to small heat transfer irreversible losses and thus positively affect the *COP* value. The red line in Fig.'s. 8-18 present the *COP* of a turbo-compressor chiller for the same operating conditions (7 °C chilled fluid, 27 °C cooling fluid). Fig.'s. 10, 14 and 18 show that devices, which apply liquid metals, can operate with a frequency of operation that is much higher than when using a conventional secondary refrigerant. Such a secondary refrigerant is also the 20 % ethanol-water solution.

The economic analysis was based on the results obtained in the thermodynamic analysis. Since a single unit of a chiller is rather small, one has to consider those connected in parallel into a module leading to a higher cooling power (up to 200 kW for the assembly of several units). Figures 9, 13 and 17 show a comparison between the specific costs of the core part of rotary magnetic chillers and conventional compressor-based machines. In this case, the heat transfer fluid is considered to be a 20 % ethanol-water solution. The core part of the conventional chiller consists of the motor drive, compressor, armatures and the refrigerant. In this case, the evaporator and the condenser are considered as external units. In the case of the magnetic chiller, its core part consists of the permanent magnet assembly, magnetocaloric material's structure, motor, heat transfer fluid, and other armatures (without external heat exchangers). While the cost of the 20 % ethanol-water can be neglected, this is not the case for the liquid metal Galinstan. Its price is approximately 5 k€ / liter. This value is considered in the economic analysis. However, the price corresponds to rather small amounts (e.g. 10 liters) and not a mass of hundreds or thousands of liters. In the last case, one may consider the relative cost of such a fluid to be less than 2-3 k€/liter. The specific costs are shown in Fig.'s. 9, 13 and 17. The data correspond to diagrams shown in Fig.'s. 8, 12 and 16, respectively. A similar analysis was performed for the case when liquid metal Galinstan is applied as heat transfer fluid. The results of an economic analysis are shown in Fig.'s. 11, 15 and 19. Data in these figures correspond to thermodynamic characteristics shown in Fig.'s. 10, 14 and 18, respectively.

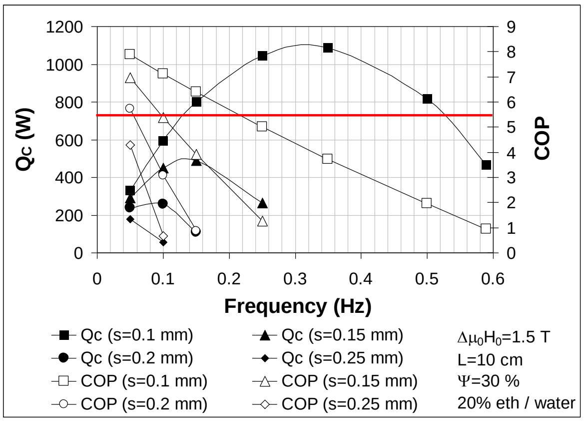


Figure 8: *The cooling power and the COP of rotary magnetic chillers depending on the frequency of operation and the thickness of the wavy structure for the working liquid 20 % eth.-water (30 % vol. fraction).*

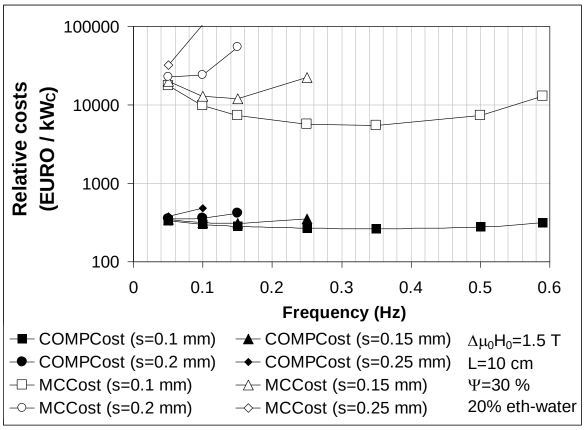


Figure 9: *The specific cost per cooling power for magnetic chillers with permanent magnets and for conventional compressor chillers (30 % vol. fraction, cooling power 0-1 kW, 20 % eth.-water).*

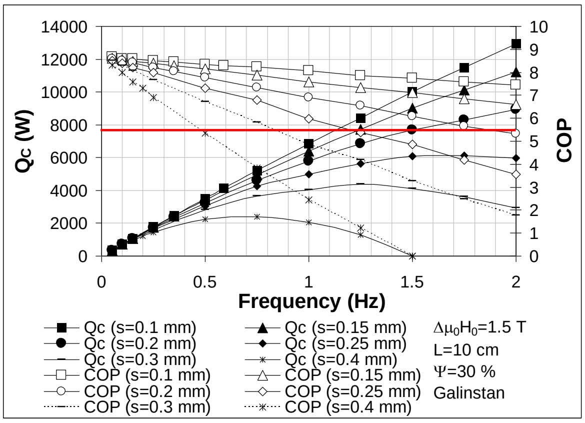


Figure 10: *The cooling power and the COP of rotary magnetic chillers depending on the frequency of operation and the thickness of the wavy structure for the working liquid Galinstan (30 % vol. fraction).*

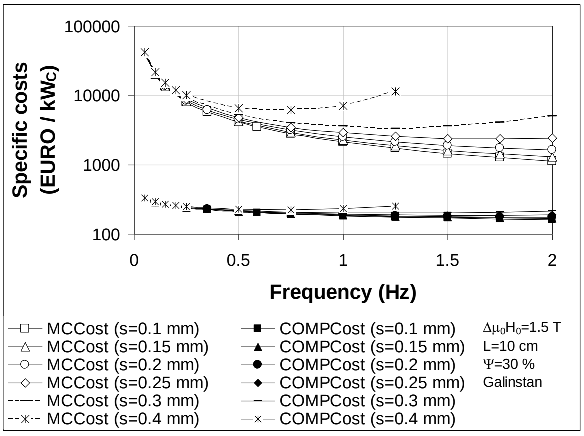


Figure 11: *The specific cost per cooling power for magnetic chillers with permanent magnets and liquid metal Galinstan and for conventional compressor chillers (30 % vol. fraction, cooling power 0-12 kW).*

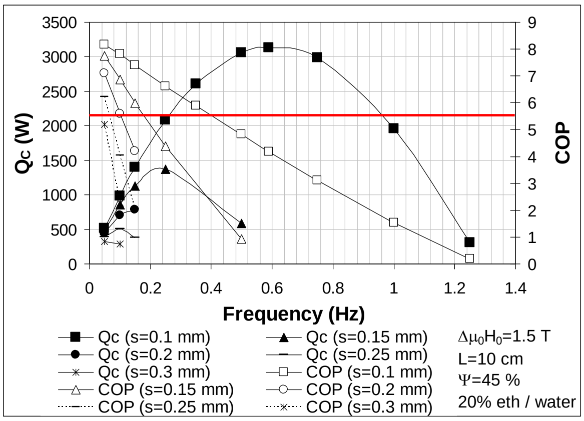


Figure 12: *The cooling power and the COP of rotary magnetic chillers depending on the frequency of operation and the thickness of the wavy structure for the working liquid 20 % eth.-water (45 % volume fraction).*

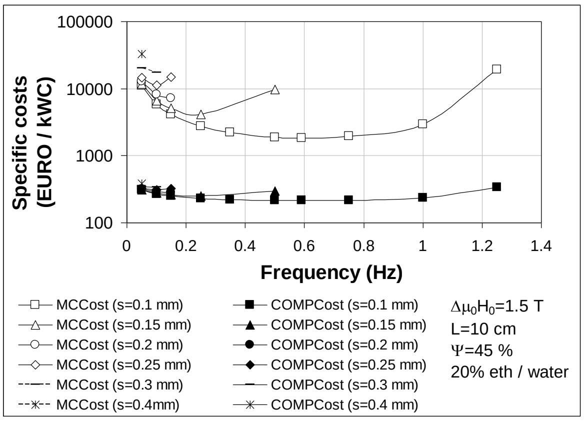


Figure 13: *The specific cost per cooling power for magnetic chillers with permanent magnets and conventional compressor chillers (45 % volume fraction, cooling power 0-3 kW, 20 % eth.-water).*

The specific cost of the rotary magnetic chiller is for all evaluated cases higher than the corresponding specific cost of the compressor chiller. The difference is generally most drastic for small volume fractions of magnetocaloric material and a large thickness of the magnetocaloric structure. The first influences the magnet's mass per magnetized space. The second influences the heat transfer characteristics and by this the irreversible losses. The lowest cost ratio for the case of 20 % ethanol-water (between the rotary magnetic chiller and the conventional compressor chiller) is approximately twenty (twenty times more expensive) if 30 % volume fraction are chosen (see Fig. 11). The ratio drops substantially when the volume fraction is increased to 45 % (see Fig. 13). In this case, its minimal value is approximately 8.5. If the volume fraction is further increased, e.g. up to 60%, then the minimum cost ratio is about 4.5 (compare with Fig.17). In the case of 20 % ethanol-water all the minimal values of the cost ratio occur at the smallest thickness of the wavy structure *(s*=0.1 mm).

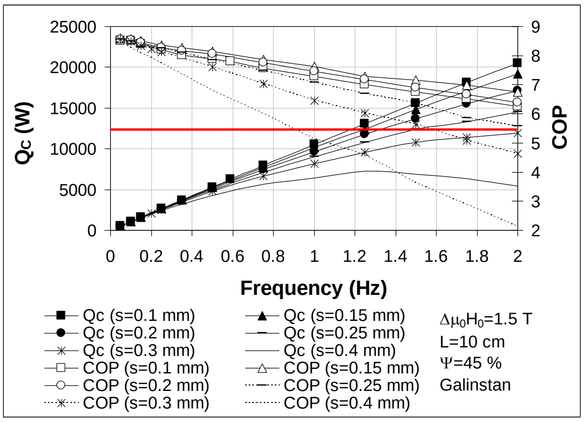


Figure 14: *The cooling power and the COP of rotary magnetic chillers depending on the frequency of operation and the thickness of the wavy structure. The data are obtained for liquid Galinstan (45 % vol. fraction).*

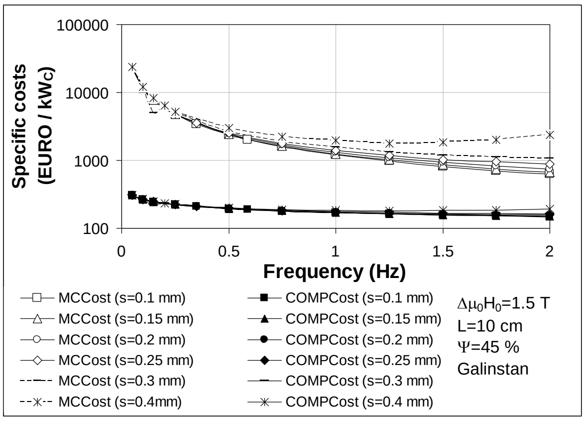


Figure 15: *The specific cost per cooling power for magnetic chillers with permanent magnets and liquid metal Galinstan and for the conventional compressor chillers (45 % vol. fraction, cooling power 0-20 kW).*

Other values of the cost ratio are obtained in cases applying Galinstan. In this particular case, the 30 % volume fraction leads to a minimum cost ratio of 3.5 for a *COP*=5.5. This value cannot be seen in Fig. 11, because the data in that figure is obtained according to the results of the thermodynamic analysis shown in Figure 10. Similar minimum cost ratios are obtained for 45 % (cost ratio 3 and *COP*=5.5) and 60 % (cost ratio 3.3 and *COP*=5.5) of volume fraction.

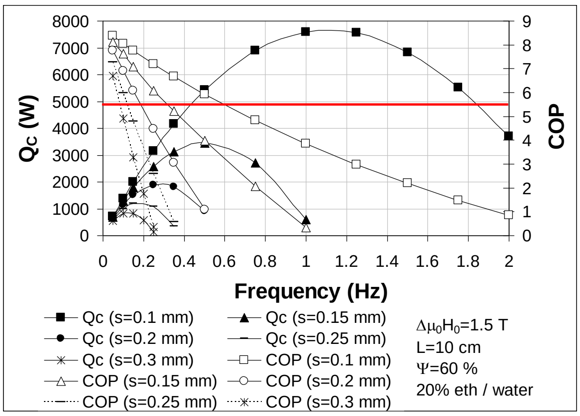


Figure 16: *The cooling power and the COP of rotary magnetic chillers depending on the frequency of operation and the thickness of the wavy structure for the working liquid 20 % eth.-water (60 % vol. fraction).*

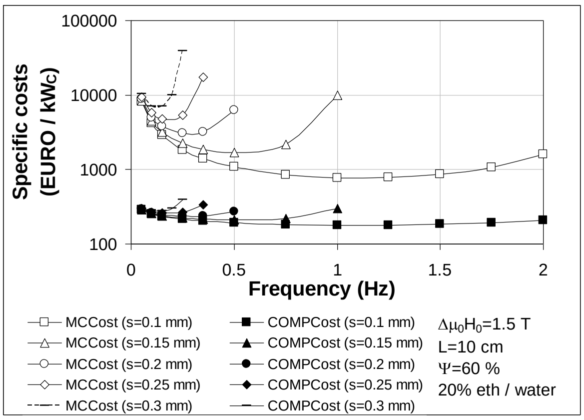


Figure 17: *The specific cost per cooling power for magnetic chillers with permanent magnets and conventional compressor chillers (60 % vol. fraction, cooling power 0-8 kW, 20 % eth.-water).*

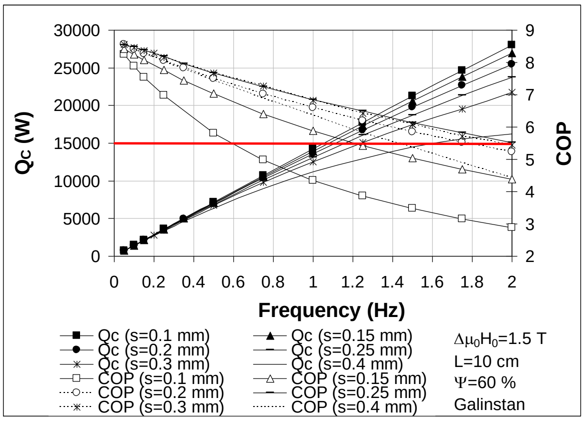


Figure 18: *The cooling power and the COP of rotary magnetic chillers depending on the frequency of operation and the thickness of the wavy structure obtained for Galinstan (60 % vol. fraction).*

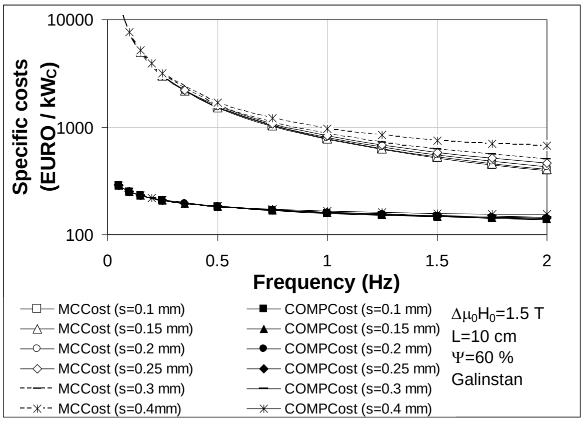


Figure 19: *The specific cost per cooling power for magnetic chillers with permanent magnets Galinstan and the conventional compressor chillers (60 % vol. fraction, cooling power 0-30 kW).*

2.2.3. Economic analysis for operation at a COP=5.5

This subchapter reports on the results of the economic analysis for rotary magnetic chillers with a *COP* of 5.5. The analysis was performed for different volume fractions and thicknesses of the magnetocaloric structure. These evaluations were pereformed for both fluids, namely the 20 % ethanol-water and the liquid metal Galinstan. Fig. 20 shows the cost ratio between the rotary magnetic chiller and the conventional compressor chiller. Fig. 21 shows corresponding frequencies of operation. As may be seen in Fig. 20, the best values of cost ratios are obtained for volume fractions of 60 % and with a thickness of the structure of 0.1 mm. The smaller the thickness of the structure is, the smaller is the difference in the cost ratio between the cases with 45 % and 60 % volumetric fraction. The minimum value of the cost ratio resulting in Fig. 20 is 5.15 (COP=5.5). Other results are obtained for Galinstan. Fig. 22 shows the cost ratio between the rotary magnetic chiller and the conventional compressor chiller.

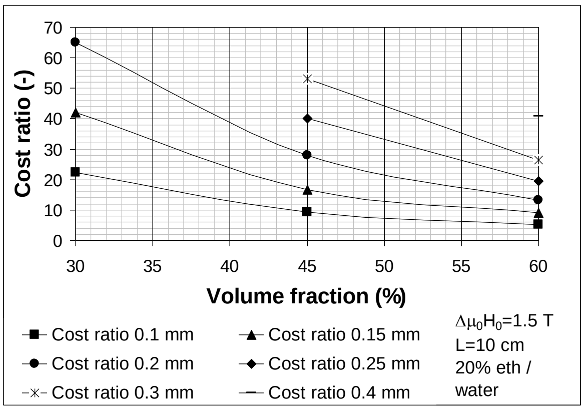


Figure 20: *Cost ratio between the rotary magnetic chillers and the conventional compressor chillers (20 % eth-water, COP_{MC}=5.5, cooling power for an assembly of several units up to 200 kW).*

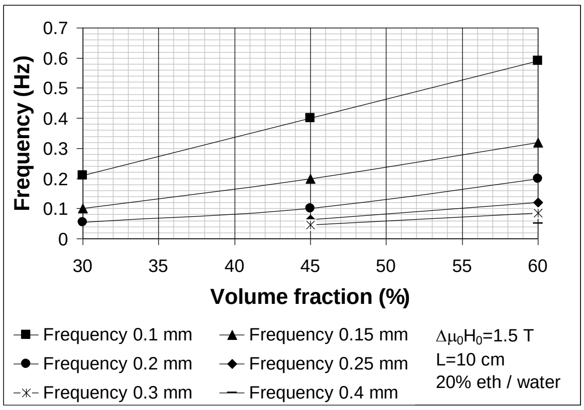


Figure 21: *The frequency of operation, which corresponds to data shown in Figure 20. (20 % eth-water, COP_{MC}=5.5, cooling power for an assembly of several units up to 200 kW).*

The minimum cost ratio in the case of Galinstan is not obtained for 60 % of volume fraction. The cost ratio (3.06 at a *COP*=5.5) in this case corresponds to a thickness of the structure of 0.15 mm and a volume fraction of 45 %. Volume fractions above 45 % negatively influence the cost ratio. The reason for this are substantially increased viscous losses. In order to keep the *COP*=5.5, the viscous losses need to be reduced. This may be done by a reduction of the frequency of operation (smaller power), what also leads to a smaller mass flow (and consequently to smaller viscous losses). Fig. 23 shows the frequency of operation related to data in Fig. 22.

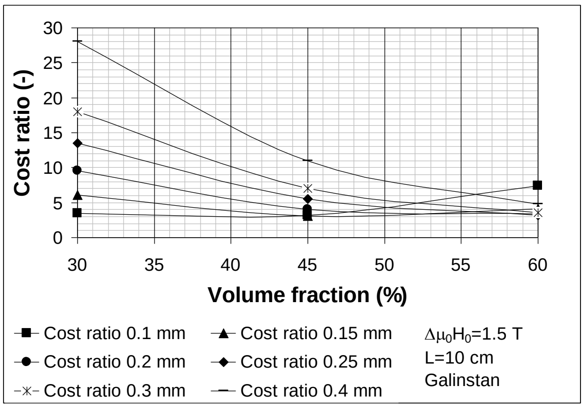


Figure 22: *Cost ratio between the rotary magnetic chillers and the conventional compressor chillers (liquid metal Galinstan, COP_{MC}=5.5, cooling power for an assembly of several units up to 200 kW).*

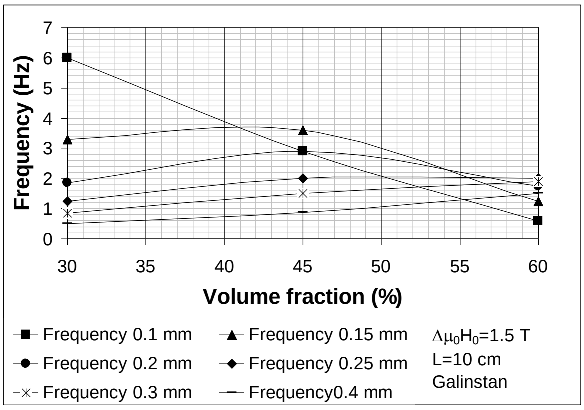


Figure 23: *The frequency of operation, which corresponds to data shown in Fig. 22. (*liquid metal Galinstan*, COP_{MC}=5.5, cooling power for an assembly of several units up to 200 kW).*

2.2.4. Potentials of cost reduction

The potential cost reduction for rotary magnetic chillers, based on permanent magnets, cannot be related to a potential decrease in prices of permanent magnet materials. Such estimations can be made only in the case that a cheaper substitute of NdFeB magnets is found. At present prices of NdFeB magnets increase, especially because of the increased market demand on permanent magnet motors and related technologies (strong influence on demand will be given by the further development of electric cars, wind turbines, etc.). The permanent magnet assembly is the major cost contributor in the rotary magnetic chiller. The magnet assembly presents about 85-90 % of the total cost. This occurs when only the core part of the chiller is evaluated (e.g. magnet assembly, motor, magnetocaloric material and armatures), and when cheap magnetocaloric material, e.g. La based compounds are taken into consideration. However, in the case of an application with Galinstan, the cost contributions of the magnet assembly and the liquid metal Galinstan are similar and are between 35-45 % for each, depending on the geometry and the specific operation conditions.

The designs of magnet assemblies considered in this study were not absolutely optimized. One may assume that a 15 % reduction in mass of magnets still could be possible. The thermodynamic cycle considered is a Brayton regenerative thermodynamic cycle. In the case of more efficient cycles (e.g. Stirling, Ericsson, Carnot-like, Rankine-like), the mass of the permanent magnet can be further reduced, e.g. for 10-15 %. The price of Galinstan was obtained for rather small amounts. A mass production of such liquids could lead to at least 50 % reduction in price. The evaluation on the possible future cost ratio was made for the above given assumptions. The cost ratio presents the ratio in specific costs (€/kW_C) between the core part of the rotary magnetic chiller and the core part of an equivalent compressor chiller. The analysis shows that an optimized core part of the magnetic chiller, based on the 20 % ethanol-water solution would be approximately 3-4 times more expensive than the core part of the conventional chiller. Both would require external heat exchangers (evaporator and condenser in the case of the compressor chiller) and eventually a cooling tower. Therefore the relative difference in costs for both cooling systems would be less than 2:1 (higher value for magnetic cooling system, lower for compressor cooling system). In the case with the application of Galinstan, the optimized core part of the rotary magnetic chiller is approximately 2 times more expensive than the compressor part of the conventional chiller. Therefore the relative difference in costs for both cooling systems would be less than 1.5:1 (higher for magnetic cooling system, lower for compressor cooling system). Based on these results the following conclusion can be made. The rotary magnetic chiller, based on permanent magnets and with a wavy porous structure of the magnetocaloric material, will hardly reach the low cost of an equivalent compressor chiller. However, the compressor is not the only part of the cooling system. When two cooling systems are compared, the difference in cost between both are expected not to be very large. Especially when external heat exchangers (or condenser, evaporator) are taken into account, as well as the cooling tower. Other features should be taken into account as well. The operation with the rotary magnetic chiller is silent, without vibrations, more efficient and environmentally friendly because of its harmless solid refrigerants. Furthermore, other cost reductions are still possible. But these require new technology concepts. Some of those are briefly presented at the end of this report.

3. Rotary magnetic liquid chillers with micro-tubes

At present a feasible and also very promising solution involves the micro heat exchanger technology. Its production is a little more expensive than the creation of wavy-structure heat exchangers. This alternative method with micro tubes and its optimal application is presented in the following chapter. The idea and knowledge on such a design was developed in the BFE study: *“Magnetic heat pump with ground heat source”* [7].

Hydrogenated alloys containing Lanthanum are considered as one of the best magnetocaloric materials. For these at present only solutions with powders (particles) are feasible. One reason is a lack of experience on the resistance against cycling of the material for periodic processes of more than a thousand cycles. The envisaged wheel contains a space with a large number of micro tubes and a packed particle bed in their surroundings (Fig. 24). The outer and the inner diameter of the wheel are the same as given in previous chapters. To obtain high efficiencies, the packed bed must have the highest possible package degree. On the other hand the production must be reasonable and, therefore, only a limited number of particle sizes are feasible. To obtain a large package degree with a smaller number of particles, one immediately recognizes that the particle diameters of the different classes or generations must vary very much. More information on the structure with micro tubes may be obtained in Ref.’s [7, 8].

3.1. Thermodynamic and economic evaluation

Fig.’s 25 and 26 present the results of the thermodynamic and the economic analysis for rotary magnetic chillers, based on structures with micro tubes. The number of tubes was varied, as well as the internal tube diameter. The data in two figures presents best values for the cost ratio and the corresponding cooling power. Applications with liquid metals (despite of their high cost) present technically and economically a better choice than this is the case for the 20 % ethanol-water (see Fig.’s. 25 and 26). The available heat transfer surface of micro tubes is substantially smaller than this is the case for wavy structures. Since the thermal conductivity of Galinstan is approximately thirty times higher than that of water, the resulting high heat transfer coefficient compensates the occurring smaller heat transfer surfaces. The best cost ratio for solutions with the 20 % ethanol water is approximately 40, whereas for application with Galinstan, the cost ratio is close to 4 (an order smaller). A similar difference exists in the cooling power. In all cases with micro tubes the pressure losses are small. Therefore, information on pressure drops are not presented in this report. Also the frequency is very small, because a small heat transfer surface does not allow large power densities. It may also be seen from Fig.’s 25-26 that the optimal cooling power strongly depends on the number of the chosen tubes.

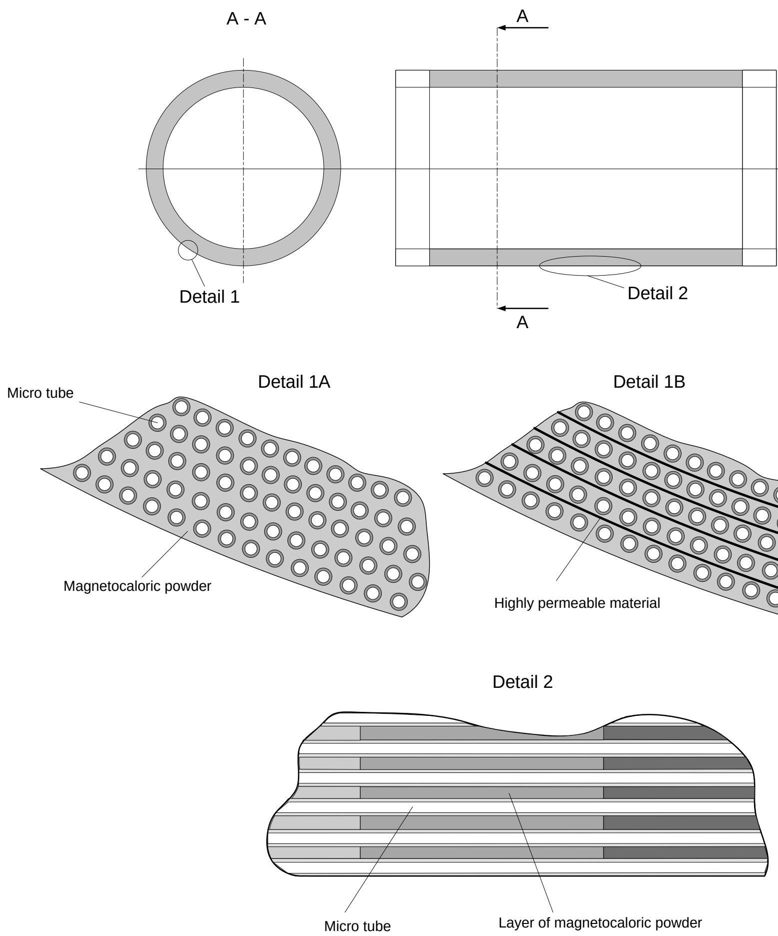


Figure 24: *The magnetocaloric structure of the wheel of a magnetic heat pump is shown (top figure and detail 1). It contains particles of two sizes, micro tubes and, in a special case, also concentric rings of high-permeable material (detail 2). This structure can be produced industrially in a rather simple manner. The micro channels allow obtaining a high surface to volume ratio [7].*

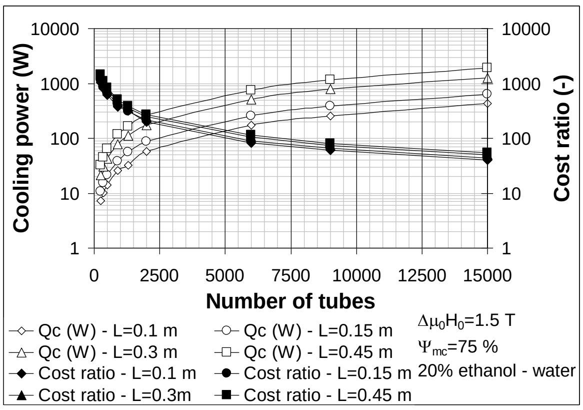


Figure 25: *The cooling power and the cost ratio between the rotary magnetic chillers and the conventional compressor chillers (20 % ethanol-water, COP_{MC}=5.5, internal tube diameter d_i=0.5 - 6 mm, depending on the number of tubes, tube thickness s=0.15 mm, volume fraction of magnetocaloric material being only 75 %. The total volume fraction varies with the number of tubes and their internal diameter).*

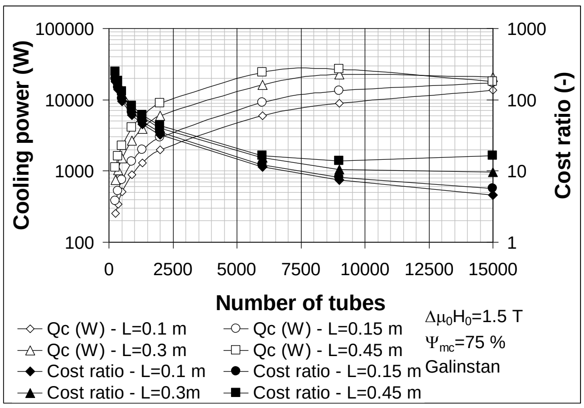


Figure 26: *The cooling power and the cost ratio between the rotary magnetic chillers and the conventional compressor chillers (liquid metal Galinstan, COP_{MC}=5.5, internal tube diameter d_i=0.5-6 mm, depending on the number of tubes, tube thickness s=0.15 mm, volume fraction of magnetocaloric material being only 75 %. The total volume fraction varies with number of tubes and their internal diameter).*

However, too large number of micro tubes require small inner tube diameters. Then the viscous losses start to influence the cooling power (the fixed value of the *COP* is again 5.5). Similar as in the case with wavy structures, smaller lengths of magnetocaloric porous structures lead to better thermodynamic and economic characteristics. Therefore, it is preferable to apply shorter magnetocaloric structures. However, one has to pay attention to the possible magnetic flux leakage. This requires a careful design of the magnet's assembly.

4. Superconducting magnetic chillers

Superconducting magnetic chillers were detected as a promising magnetic refrigeration technology, especially for large-scale cooling applications [2]. This chapter deals with the thermodynamic and economic analysis of such systems. The application of superconducting magnets enables high magnetic flux densities in the magnetized space. Consequently also the magnetocaloric effect is larger. However, the largest gradients of the magnetocaloric effect (e.g. adiabatic temperature change or isothermal entropy change versus the change of the magnetic flux density) are limited to rather lower magnetic fields, with flux densities up to about 3 T. Furthermore, a conventional chiller usually operates at low temperature spans of the chilled fluid (e.g. 7/13°C). This may be obtained, up to a certain magnetic field change (e.g. < 3 Tesla), by a regenerative Brayton cycle. Higher magnetic field changes lead to higher adiabatic temperature differences. Then other types of thermodynamic cycles are required. The evaluation in this report considers machines having a regenerative Brayton cycle. This was taken into consideration also for the thermodynamic and the economic evaluation of the superconducting magnetic chillers (with a magnetic flux density of 3 Tesla).

In this chapter the method for the price evaluation of the superconducting magnetic refrigeration system is described. Since there is no such evaluation found in the literature, the aim of the following study was to define simple models that can serve for a reasonable accurate economic analysis. The basis for such an evaluation was found in the domain of superconducting storage of electric energy (SMES). SMES systems store electric energy in the magnetized space of their system. Most of these devices apply toroidal and cylindrical solenoids. The maximal energy stored per volume at a certain magnetic field is calculated by simple mathematical relations. The existing literature gives information on costs of total superconducting systems per energy stored. This may be on the other hand referred to the magnetized space. With this information it is possible to define the cost of a superconducting magnet system for any kind of magnetic chiller. The model in our analysis does not deal with a special superconducting magnet structure. This should be adapted to a particular design of the magnetocaloric porous structure with its magnetized and demagnetized domains.

4.1. Definition of the maximal stored energy

The maximal energy stored in the magnetized space (gap) of the superconducting magnet needs to be first defined. The derivation for the specific magnetic work was based on Landau and Lifshitz, and was shown already in Ref. [8]. In the superconducting magnet, the magnetization increases the internal energy of the empty space, so Eq.(1) is shown with a positive sign. For the magnetized space in the superconducting magnet system the specific energy derivative equals to:

$$dw = \vec{H} \; d\vec{B} \qquad (1)$$

In the superconducting magnetic energy storage system (SMES), there is no material in the magnetized space, so Eq.(1) leads to the following form:

$$dw = \vec{H}_0 \ \mu_0 \, d\vec{H}_0 = \frac{\mu_0}{2} d\left(\vec{H}_0{}^2\right) = \frac{1}{2\mu_0} d\left(\vec{B}_0{}^2\right) \tag{2}$$

Now the empty magnetized space is considered to be a material with a linear magnetic characteristics. The change of the stored energy in a certain space is now defined. We assume an uniformly distributed magnetic flux density in the magnetized space:

$$dW = \frac{1}{2\mu_0} \int_V d\left(B_0{}^2\right) dV \tag{3}$$

The total derivatives can be dissolved by integration on the left and right-hand side. This is done by an assumption that the magnetic flux density is constant. Then Eq. (3) may be written as:

$$W = \frac{B_0{}^2}{2\mu_0} \cdot V \tag{4}$$

Figure 27 shows the maximal energy stored per volume of the magnetized space for different magnetic flux densities.

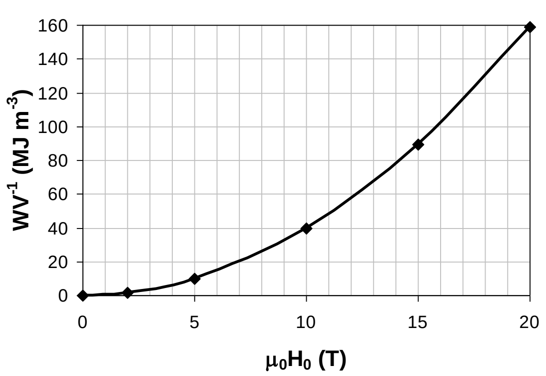


Figure 27: *The maximal energy stored per volume of the magnetized space in superconducting magnets. The quadratic relation of the magnetic flux density in Eq. (4) leads to the parabolic increase of the stored energy with the increase of magnetic flux density. The maximal energy in this case does not contain any losses that occur in the superconducting energy storage system; so it presents an ideal value.*

4.2. Definition of costs for superconducting magnet systems

The review of existing publications has shown, that there exist certain co-relations and definitions for costs of superconducting magnetic systems. However, there is a large difference between several models. Here we present a comparison of such models.

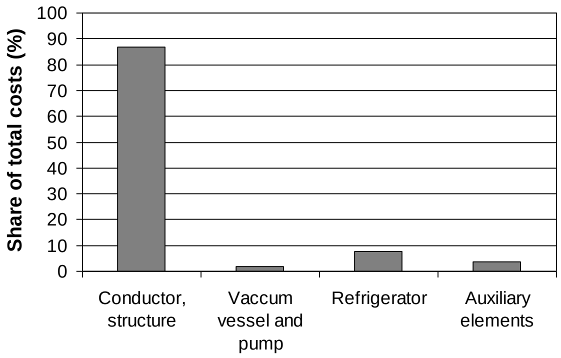
4.2.1. Cost analysis for superconducting magnet systems

In Ref. [9] the following cost breakdown for components in an SMES system is presented (see Fig. 28). Usually the cost ratios between different elements are listed for large units and applications of high temperature superconductors (HTS). Ref. [10] shows a comparison of different SMES systems with different magnetic flux densities and different magnetized space configuarations. The devices are assumed to have toroidal structures. Based on the results given in Ref. [10], a diagram was constructed. This is presented as Fig. 29. This figure shows the length of the superconducting wire per magnetized volume, depending on the magnetic flux density. The cost of the superconducting magnet and its structure presents the major contribution to the total cost in a superconducting magnet system (see also in Fig. 28). Then an approximation of the relative costs can be made by following Eq. 5. This was done for the same magnetized space depending on the magnetic flux density. The data in Fig. 28 was then applied, leading to the results shown in Fig. 30.

Based on the results shown in Fig. 30, the following expression was obtained for the cost ratio of the magnetized volume. Notify that Eq. (5) is not valid for magnetic flux densities below 1 Tesla.

$$CR = 0.0056297 \cdot B_0^{\,3} + 0.0083756 \cdot B_0^{\,2} + 0.0996051 \cdot B_0 - 0.0062344 \qquad (-) \qquad (5)$$

Eq. (5) is further applied to distinguish prices of superconducting magnet systems for different magnetic flux densities.



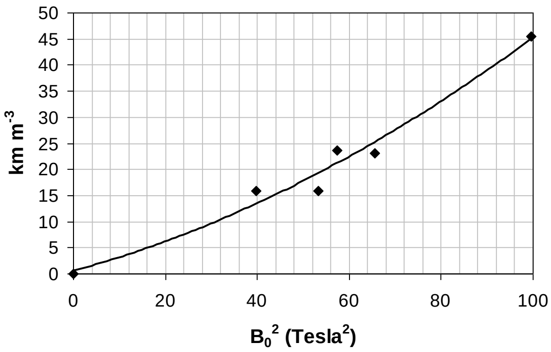


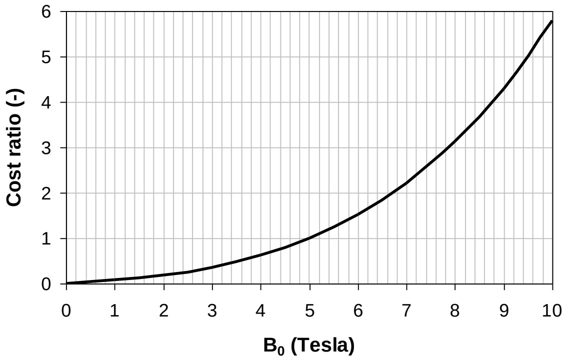
Figure 28: *The share of total costs for the SMES system after Ref. [9]. The superconducting magnet in this particular case has a toroidal structure for a storage of 535 MJ with the peak magnetic flux density of 8.1 T. According to Fig. 25, the majority of cost of the system relates to the superconducting magnet with wires and its structure. This is an important information for the further evaluation of superconducting systems.*

Figure 29: *The length (in kilometers per cubic meter) of the superconducting wire per magnetized volume depending on the magnetic flux density are shown. The data was obtained from Ref. [10]. The diagram demonstrates that for the same magnetized volume the increase of the magnetic flux density requires a much larger mass of the superconducting magnet. Similar results apply for permanent magnet assemblies.*

Fig. 31 shows the total cost of a superconducting magnetic energy storage system. The data were obtained from Ref.'s.[11-14]. Among all the available data, unfortunately the information about the magnetic flux density is given only in Ref. [5]. This are data for a 10 Tesla field and high temperature superconductors. Other information was not available for the applied magnetic field; also not on the type of superconductor. Based on Ref. [13], the following equation was applied for the cost estimation:

$$C = 0.535 \cdot 10^3 \cdot \left(W \cdot 10^{-6}\right)^{0.5} = 0.535 \cdot 10^3 \cdot \left(\frac{B_0^{\,2}}{2\,\mu_0} \cdot V \cdot 10^{-6}\right)^{0.5} \qquad \text{(kCHF)} \qquad (6)$$

where the stored energy W is in the unit Joule. The applied model, described by Eq. 6, leads to the highest cost shown in Fig. 31. The model based on Eq. (6) was taken into a further analysis, mainly because it leads to rather conservative values. Most SMES systems operate with magnetic flux densities between 2 to 10 Tesla.



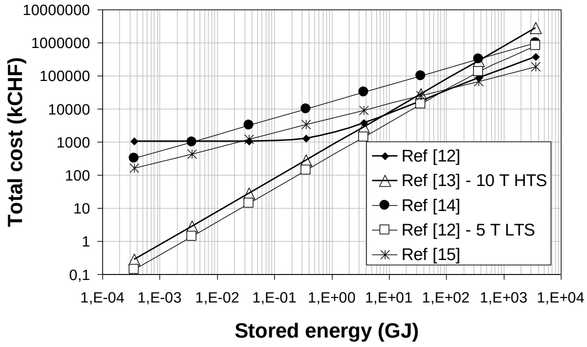


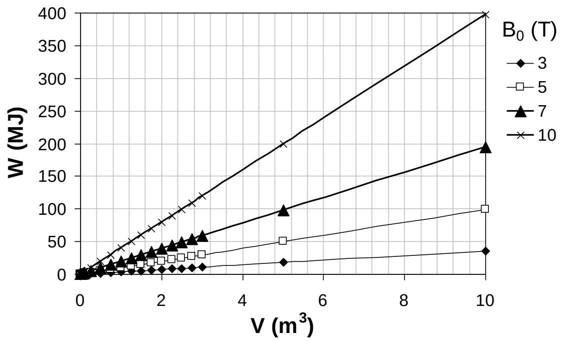
Figure 30: *The relative cost for the same magnetized space depending on the magnetic flux density. The cost ratio with the value 1 was fixed for the 5 T magnetic flux density. According to the results in the diagram, the 10 Tesla superconducting magnet system would present approximately a six time higher value. Furthermore, a higher magnetic flux density leads to an increased power density.*

Figure 31: *The total cost of superconducting magnetic energy storage systems depending on the stored energy are presented. A large difference between different models and data occurs. Data from Ref.'s [12,14 and 15] seem to be the most appropriate, especially for small energy storage systems. For large systems, with the storage capacity beyond 10 GJ, all the models and data present similar values.*

4.3. Application of two different approaches

4.3.1. First approach

In this first approach Eq.(6) is applied. Then it is possible to express the maximal stored energy as a function of the magnetized space and the magnetic flux density. Fig. 32 shows such a diagram. Eq.'s. (4 and 5) are then applied to define costs depending on the magnetized space for a given magnetic flux density. For the same magnetized space, a higher magnetic flux density leads to a higher cost (compare Fig.'s 33 and 34).



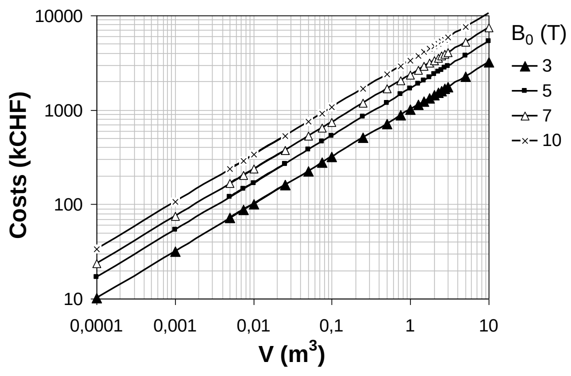


Figure 32: *The maximal stored energy depending on the magnetized space and magnetic flux density are shown. As may be noticed from the figure, an increase of the magnetic flux density leads to an enormous increase of the stored energy in the homogenously magnetized space.*

Figure 33: *Total cost of the superconducting magnet system depending on the magnetized volume and magnetic flux density are presented. Costs of systems for magnetized volumes below e.g. 1 dm^3 are too low. The possible error relates to the cryogenic refrigeration system, which is required for small-sized systems.*

For a fixed volume, this first approach leads to a linear relationship between the price and the magnetic flux density. But this is not in agreement with results shown in Fig. 30, where a nonlinear relation is shown. The nonlinear relationship is applied in the following second approach.

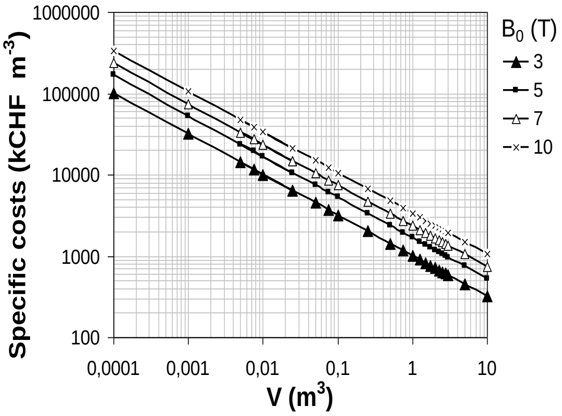


Figure 34: *The total specific cost of a superconducting magnet system depending on the magnetized volume and the magnetic flux density are presented in the figure on the left-hand side. As may be seen in this figure, small systems lead to much higher costs than those with larger magnetized spaces. This is why this kind of technology is mainly interesting for large scale applications in the MW domain.*

4.3.2. The second approach

The second approach keeps to the relation given by Eq. (4). In this case we assume that Eq. (6) corresponds to an average magnetic flux density of 5 T (because the data set applied in Eq. (6) was based on systems operating with magnetic field strength between 2 and 10 T). If the cost of the total system is known by applying Eq.(6), then for other magnetic flux densities, which differ from 5 T, Eq. (5) may be applied. This method leads to Eq.(7):

$$C = \left[0.535 \cdot 10^3 \cdot \left(W \cdot 10^{-6} \right)^{0.5} \right] \cdot CR \qquad \text{(kCHF)} \tag{7}$$

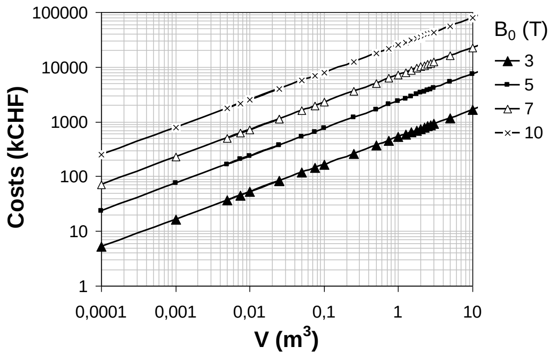


Figure 35: *Total cost of a superconducting magnet system depending on the magnetized volume and magnetic flux density are shown. Similar as in the first approach (Fig. 30), costs of systems for magnetized volumes below e.g. 1 dm^3 are too low. One may also observe larger variations of costs depending on the magnetic flux density.*

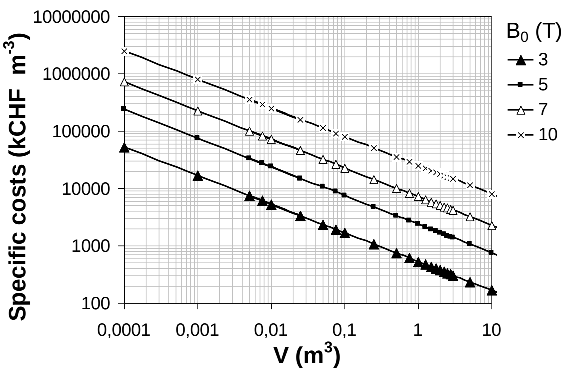


Figure 36: *Total specific costs of the superconducting magnet system depending on the magnetized volume and magnetic flux density are shown. As may be seen in this figure, small systems present much higher costs than those with larger magnetized spaces. This shows again why this kind of technology is interersting only for large-scale applications.*

Applying Eq. (4), Eq.(7) may be rearranged as follows:

$$C = \left[0.535 \cdot 10^3 \cdot \left(\frac{B_0{}^2}{2\,\mu_0} \cdot V \cdot 10^{-6} \right)^{0.5} \right] \cdot CR \qquad \text{(kCHF)} \tag{8}$$

Results obtained by the second approach are shown in Fig.'s 35 and 36. The two models of the first and the second approach are applied for a cost evaluation in the further analysis.

4.4. Definition of the power consumption for superconducting magnet systems

The total efficiency of the superconducting magnetic energy storage system is between 80 and 90 %. However, in superconducting generators an efficiency of up to 99 % may be observed [13]. Our search in the literature [12, 13, 15] has shown that the ratio of the electric power consumption (for cryo-cooling systems) versus the total generated or stored power varies from 0.005 to 0.05. The exergy efficiency of the cryo-cooler is very small, between 5 to 10 %. In the further analysis, the superconducting magnet system (together with its cryogenic system) was assumed to have an exergy efficiency of 95 %.

4.5. Thermodynamic and economic analysis for superconducting magnetic chillers

The thermodynamic analysis considers the magnetocaloric material to also be the wavy structure with a volume fraction of 30 %. It was assumed that the wavy structure forms a coaxial ring with different lengths. The outer ring diameter in this case was fixed to D=2.28 m and the inner ring diameter was assumed to be d=2 m. The dimensions of the ring do not represent a real design feature. They may be very much different for other designs. Much more important is the volume that the structure occupies and the length of the structure. The last affects the fluid dynamic and the thermodynamic behaviour. A magnetic flux density of 3 T was considered to be homogeneously distributed in two 90° symmetric regions of the magnetocaloric ring. This is an equal concept as described in previous chapters which deal with permanent magnets. The thermodynamic cycle was taken to be a regenerative Brayton cycle. Higher magnetic flux densities (larger adiabatic temperature changes) > 3 T, especially in chillers, require other types of thermodynamic cycles. The heat transfer fluid was considered to be a 20 % ethanol-water. For this fluid, due to the higher magnetic flux density, higher volume fractions (> 30 %) lead to too high power densities.

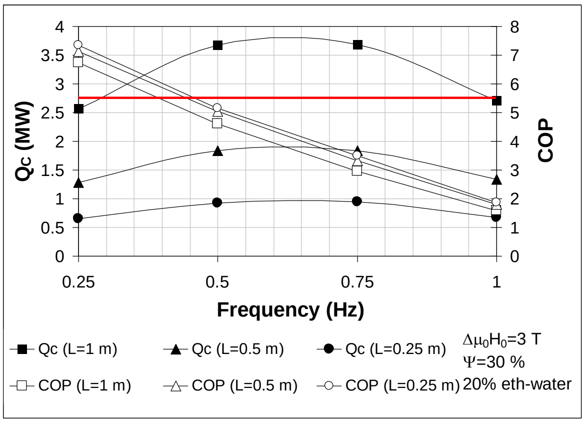


Figure 37: *The cooling power and the COP of the rotary superconducting magnetic chillers depending on the frequency of operation and the length of the wavy structure (working liquid 20 % ethanol-water, 30 % of volume fraction) are shown above.*

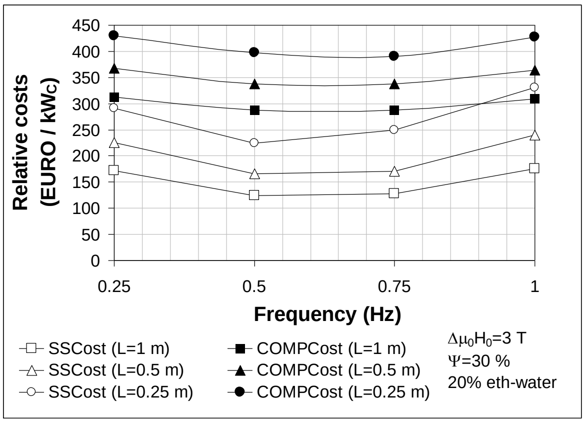


Figure 38: *Specific costs of superconducting magnetic chillers depending on the frequency of operation and the length of the wavy structure (working liquid 20 % ethanol-water, 30 % of volume fraction) are presented in this figure.*

The mass flow of the fluid needs to be substantially increased in order to efficiently evacuate heat, as well as to keep the required temperature levels. This leads to too high pressure losses at high volume fractions. Fig. 37 shows the cooling power and the *COP* for different lengths of a coaxial porous magnetocaloric structure. The thickness of the wavy structure was assumed to be s=0.1 mm. The frequency of operation needs to be low in order to keep the efficiency higher than that of an equivalent turbo-compressor chiller (red line in Fig. 37). When the magnetocaloric material has a low magnetocaloric effect, the frequency of operation may be substantially increased (since it relates to the power density). Fig. 38 shows a comparison of specific costs between conventional compressor chillers and superconducting chillers. It is based on the results presented in Fig. 37. In the case of superconducting chillers, external heat exchangers (in analogy with the evaporator and the condenser) were not taken into account. As may be seen in Fig. 37, the superconducting magnetic chillers show a large potential for future large-scale cooling applications. This is strongly dependent on the size of the system. It may be seen that superconducting chillers should be designed for cooling powers around or above 1 MW.

5. Future magnetocaloric technologies

All the at present studied solutions of magnetic refrigeration at room temperature (for a complete review see Ref. [1]) have serious limits, especially in the frequency of operating the refrigerator. To overcome this situation, the authors have published some new innovative ideas (see Ref. [17]). Some basic aspects from this work are also repeated here.

In order to reduce the cost of a magnetocaloric device, its specific power must be increased. An efficient possibility to do so is to increase the frequency of operation of a machine. The frequency of cycling a magnetocaloric material in a machine may be different from the frequency of operation of that machine. For example in a rotary machine, the magnetocaloric material may cross alternatively numerous (n=1, 2,…) magnetization and demagnetization sections, when the core part of the machine turns only once around its axis. Then one has n times more thermodynamic cycles than cycles of rotation. It is reported that the highest frequency of operation is 5 Hz [17]. However, most machines operate at much lower frequencies. The major technical reasons for low frequencies are:

- The limited manufacturability and stability of magnetocaloric materials:
  - Limits of the size of the heat transfer surface
  - Limits of its shape
  - Limits of heat diffusion through the magnetocaloric material
  - Increases of the magnetic field “gap”
  - Pulverisation of magnetocaloric material due to the mechanical cycling of the material
- Limited heat transfer rates
- Limited fluid properties (too high thermal capacity of the fluid, low thermal conductivity, too high viscosity, etc.)
- Limitations given by fluid flow switching armatures (strongly limits the frequency of a thermodynamic cycle and may cause “dead volumes”)
- Limitations given by the design and characteristics of moving parts; e.g. magnetocaloric material, magnets, seals, bearings, valves, etc.
- Limitations given by the precision obtained in building parts of the machine
- Limitations given by flow channels (e.g. uneven flow among parallel fluid stream lines in regenerators).

More comprehensive information and more details may be obtained in Ref. [18].

A requirement for low costs usually implies compact machines with simple design, small number of moving parts and a small mass. In addition, this demands high power densities (power per mass or volume unit).

Because of this reason, we have studied power densities of different possible magnetocaloric machine types. For this purpose, several analyses were performed (see Ref [18]). The results obtained are very instructive. The main results are summarized in a diagram showing these power densities (see Fig. 39).

In all cases presented in Fig. 39 it was assumed that the efficiencies of the magnetocaloric devices are higher than those of the analogue conventional devices. In several studies for the Swiss Federal Office of Energy model predictions confirm this assumption (see Ref. [2] for magnetic refrigeration, Ref. [18] for magnetic heating, and Ref. [19] for magnetic energy conversion). In the presented diagram, the letters A) to E) denote the following conventional, respectively new magnetocaloric technologies:

A) Reciprocate and rotary machines with gases as working fluids
B) Reciprocate and rotary machines with water (and maybe some additives)
C) Reciprocate and rotary machines with liquid metals (proposed by authors in the Refs. [7, 17])
D) Static machines that apply magnetocaloric slurries (new-old idea, Ref [17])
E) Solid-state static magnetocaloric devices (new idea presented in Ref [17]).

The power density of the different methods applying magnetocaloric materials are increasing in the order of the presentation in the above list. One has to be aware that at present practically all investigations are located in the domain A) or B) with the minimum power densities. But still, even these machines have a good potential to enter some refrigeration markets. Research and developments on systems belonging from to C) to E) are future work. Our main prediction is that the interaction of solid state physics applications with the magnetic/magnetocaloric heating and cooling technology will lead to more innovative and more efficient machines, which will show even higher potentials to be serious concurrents to conventional compression/expansion refrigeration devices.

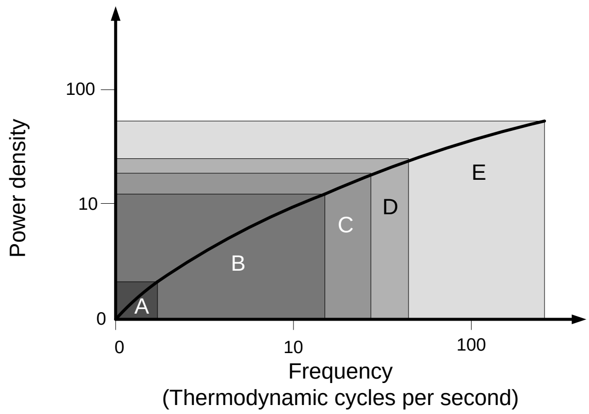


Figure 39: *Predicted power densities of magnetocaloric devices (the power density is presented in arbitrary units), after Ref. [17].*

6. A rough design of a magnetic chiller

Based on this study the project team proposes to continue with a building of a smaller prototype (see also conclusions of this report). The presented analysis could not have been performed without already having a rough idea of how a magnetic chiller would be designed. For this purpose numerous different designs were performed. A solution that at present seems very promising is presented in this chapter.

Fig. 40 shows a cut-view of a rotary magnetic liquid chiller unit with micro tubes, surrounded by magnetocaloric grains. In order to increase the effective conductivity of magnetocaloric particles, these may be mixed with non-permeable metal having a good thermal conductivity and low eutectic point, e.g. Zinc or a similar metal. The longitudinal heat conduction through such a structure should be prevented. Fig. 41 shows the coaxial ring consisting of micro tubes and of magnetocaloric grains. The magnetocaloric material is layered in the direction of the fluid flow (temperature directional derivative). In Fig. 42 (underneath) the magnet assembly is shown. Brown-coloured parts present soft permeable iron, whereas other parts present the NdFeB magnets. In Fig. 43 the whole unit of a magnetic chiller is shown. Modular designs enable connections of such modules in series or in parallel.

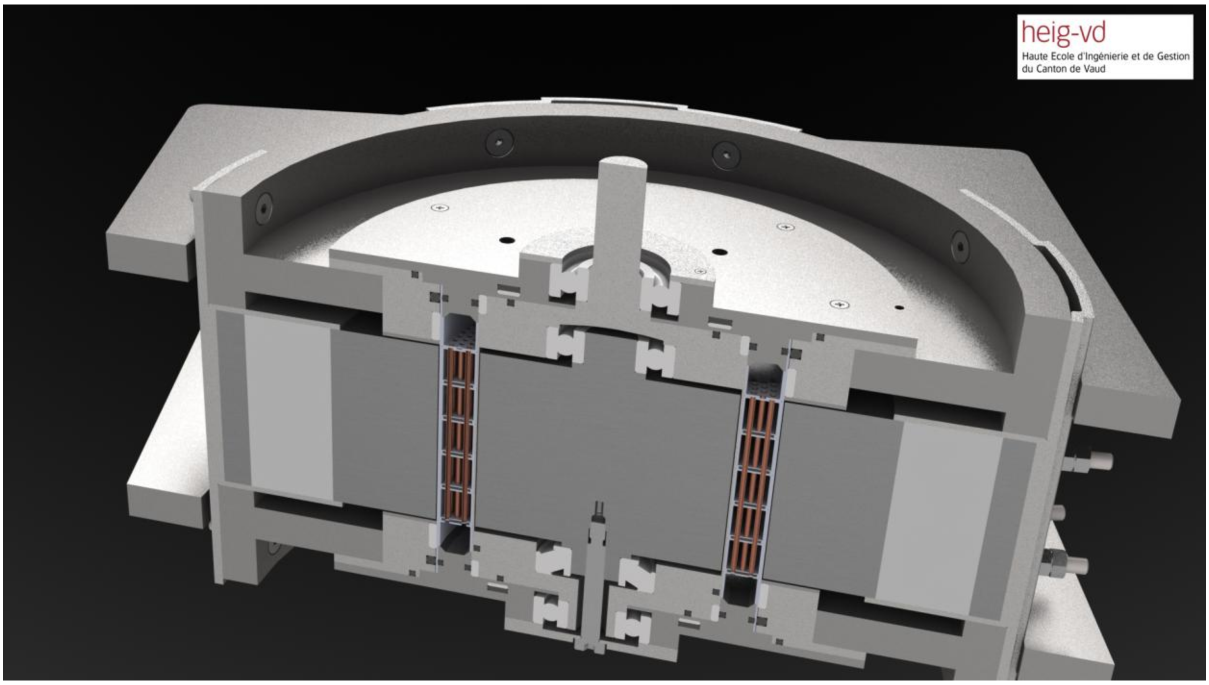


Figure 40:*. The cut-view of one unit of a magnetic chiller is shown. In this particular case micro tubes are applied. They are surrounded by magnetocaloric material particles. Magnetocaloric material is layered in the downstream direction paralle to the fluid flow. The only part which rotates is the coaxial ring, which is positioned between two static parts of the magnet assembly. The coaxial ring consists of micro tubes, magnetocaloric material and fluid separators, which also serve for the rigidity of the structure as well as to prevent heat conduction in the axial direction through the magnetocaloric material.*

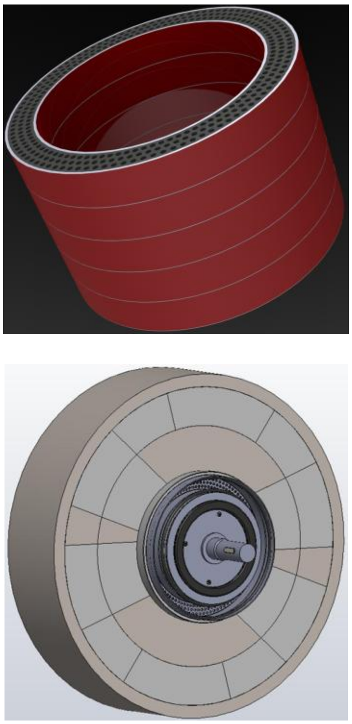


Figure 41: *Above: The coaxial ring consists of micro tubes and magnetocaloric material layers. Below: The magnet assembly and its central parts (the inner static permeable iron part cannot be seen (see e.g. Fig. 3)).*

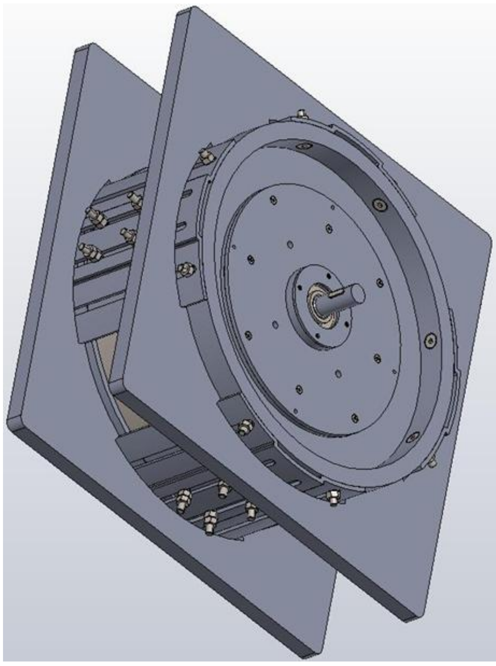


Figure 42: *The unit of the rotary magnetic liquid chiller with its outer housing are presented. The outer fluid connections are not shown in this figure. Their position depends on the modular design of the units. The device may apply and kind of a magnetocaloric structure.*

7. Search for an industrial partner

A main objective of the project was to evaluate on a possible ideal industrial partner producing conventional compression chillers with a high interest in the new magnetocaloric developments of magnetic refrigeration. The precondition, defined by the programme leader of the Swiss Federal Office of Energy (see on page 2), was that such a company should not necessarily have its domicile in Switzerland, but could also be located in any other European country. This made the task for us a little easier to fulfil.

We were in the lucky situation that a main responsible person for Ra &D of a large chiller-producing company at a refrigeration conference contacted Peter W. Egolf and asked him to discuss the development of a magnetic chiller*. Discussions were hold at the University of Applied Sciences of Western Switzerland in Yverdon-les-Bains, Switzerland and in the research and development department of this company. It was arranged to work on a feasibility study to demonstrate the energy efficiency of such chillers for different application domains and to evaluate the costs for different sizes of machines. The specialist for these feasibility studies in the division SIT of Prof. Peter W. Egolf, Dr. Andrej Kitanovski, because of restructuring reasons at the University of Applied Sciences of Western Switzerland, returned back to the University of Ljubljana, Faculty of Mechanical Engineering, Laboratory for Refrigeration. It was decided that the easiest procedure for the feasibility study would be a collaboration between the two universities in Switzerland and Slovenia. Therefore, now the feasibility study is performed in Ljubljana by Kitanovski with a smaller consultancy given by Egolf.

In the case that this feasibility study will show promising results and the company decides to go into prototyping with the academic institutions, a project will be lanced as a collaboration between the industrial company and the two mentioned universities. A support of these activities by the Swiss Federal Office of Energy would be very much appreciated and would, by a more important funding, increase the quality of the project envisaged.

* *Because of confidentiality reasons no information on the company and details of this project are given in this report.*

Conclusions

This reports deals with the assessment of liquid rotary magnetic chillers. A comprehensive analysis was made on the thermodynamic and the economic characteristics of such devices. This was performed for two different kinds of magnetic field sources, permanent magnets and superconducting magnets, respectively. In the analysis a large set of different parameters was varied. This includes operation characteristics, the geometry of the porous structure of the magnetocaloric material and the application of two different fluids, the 20 % ethanol-water solution and the liquid metal Galinstan. The obtained numerical simulation results show that rotary magnetic chillers, based on permanent magnets, have a potential to overcome the efficiency of conventional compressor chillers. However, their price will be always higher, unless new technologies are introduced and developed, which allow higher frequencies of machine operation. Such possible future-oriented technologies and their potentials are briefly described in the last chapter of this report. It is also shown, that the selection of the proper heat transfer fluid drastically influences the efficiency, cooling power as well as the cost of the rotary magnetic chiller. Liquid metals – despite of their high price – show large advantages compared to conventional secondary refrigerants.

Devices based on permanent magnets have a certain restriction (upper limit) for the cooling power. This is related to the geometry of the permanent magnet, which for a large cooling power requires dimensions that may lead to substantially higher manufacturing costs. This is why magnetic chillers, based on the state-of-the-art technologies, can present units of approximately up to 200 kW of cooling power. Even in the highest power limit case, the device would consist of several smaller in parallel connected units.

Superconducting rotary magnetic chillers, when compared to the conventional ones, show an advantage for both, the efficiency and the cost. However, the minimum cooling power for such devices should be not less than 1 MW. All the problems associated with the cost, power density, compactness and the efficiency may be solved in future. However, this requires new approaches. Some of those are briefly described in this report. A conclusion can be made, that magnetic chillers have a good potential to replace the conventional compressor-based technologies one day.

In order to develop this green technology into a desired direction, a strong support of Ra&D from governmental funding organizations will be required. Additionally industry must be more actively involved in such activities. This also requires a critical number of human resources, as well as a strong and “open” international collaboration between different research groups. A good monitoring on developments and the progress should be performed. New good ideas should be highly supported in order to avoid spending of valuable funds for research groups with converging progress and close-to repetitive research activities. If this would be realized, the magnetic heating, cooling, refrigeration, and energy conversion technologies have a large potential to take an important role on several markets.

The report highlights the prospects of an introduction of magnetic chillers. The research group, based on the presented results, proposes that a smaller prototype should be designed, calculated, optimized, built and experimentally tested. This would be the natural further step to one day obtain a first magnetic chiller ready for a market introduction.

Nomenclature

Standard

B	magnetic flux density (T)
C	costs (CHF, Euro)
COMP	compressor
COP	Coefficient of performance (-)
CR	cost ratio (-)
Eth	ethanol
H	magnetic field strength (A m^{-1})
HTS	high temperature superconductor
L	length (m)
LTS	low temperature superconductor
MC	magnetic, magnetocaloric
Q	*heat (J)*
$\dot{Q}$	heat power *(W)*
S	thickness (m)
SMES	superconducting magnetic energy storage
SS	superconducting system
V	volume (m^3)
w	specific work (J kg^{-1})
W	work, energy (J)

Greek

μ	magn. perm. (Wb, $A^{-1}m^{-1}$, NA^{-2}, H m^{-1})
ψ	volume fraction (m^3 m^{-3})

Indices

0	external, vacuum
c	cooling
MC	magnetic, magnetocaloric

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