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CENTRAL MAGNETIC COOLING AND REFRIGERATION MACHINES (CHILLER) AND THEIR ASSESSMENT

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Table of content

Zusammenfassung		4
Summary		5
Objectives of the project		5
1.	Rotative magnetic chillers	6
1.1.	Design and simulations of permanent magnet assemblies	7
1.2.	Simulations on the design, the thermodynamics and fluid dynamics characteristics	9
2.	Conclusions	10
Performed work and obtained results		11
National collaborations		11
International collaborations		12
Evaluation 2009 and outlook 2010		13
References		13

Zusammenfassung

Der Jahres-End-Bericht 2008 [1] dieses Projektes zeigte einen Bedarf den Entwurf und die Betriebscharakteristiken von magnetischen Chillern zu beschreiben. Diese wurden da als ein Thema für weitere Untersuchungen dargestellt. Im Jahre 2009 wurde dies ausgeführt und die entsprechenden Arbeiten und deren Resultate sind in diesem neuen Jahres-End-Bericht zusammengefasst. Im Kontext dieser Machbarkeitsstudie wurden ein mathematisch-physikalisches Modell und ein spezielles numerisches Werkzeug (Computer-Programm) entwickelt. Diese dienen als Basis für den Entwurf, Energie-Analysen und die Optimierung von verschiedenen Chillern. Die Studie enthält gleichzeitig Arbeiten, die mit eigenen numerischen Werkzeugen durchgeführt worden sind, wie auch solche mit kommerziell erhältlicher Software für die numerische Berechnung von magnetischen Magnet-Feld-Verteilungen. Eine erste Analyse zeigt eine Grenze der Grösse von Magnet-Konfigurationen auf. Basierend auf Daten von heute erhältlichen magnetokalorischen und Permanent-Magnet-Materialien wird geschlossen, dass magnetische Chiller – die mit Permanent-Magneten ausgestattet sind – bis ungefähr 100 kW Kälteleistung eingesetzt werden können. Dies ist die Konsequenz von Grenzen, die durch sinnvolle äussere Durchmesser von Magnetkonfigurationen gegeben werden. Daher werden sogar Chiller mit 100 kW Kälteleistung mit kleineren Modulen zusammengebaut werden müssen, um eine Kälteeinheit zu bilden. Eine weitere Einschränkung für verschiedene magnetische Chiller-Anwendungen ist in Bezug auf die Temperaturdifferenz zwischen den Temperaturen der Wärmequelle und der Wärmesenke gegeben.

Heute sind einzig magnetische Chiller, die mit Flüssigkeiten arbeiten, eine gute Alternative, währenddem luftgekühlte Chiller in ihren thermodynamischen Zyklen zu hohe Temperaturdifferenzen verlangen. Als Konsequenz davon resultieren zu hohe Massen der Magnet-Konfigurationen. Luftgekühlte magnetische Chiller können zum Einsatz kommen, wenn nur kleine Temperaturdifferenzen verlangt werden. Solche sind zum Beispiel Industrie-Chiller oder –Trockner. Zu grosse Magnetmassen führen direkt zu unrealistischen Kosten von Chiller-Apparaten. Die Kosten steigen substanziell an, wenn eine gute Effizienz und eine grosse Temperaturspanne erreicht werden sollen. Die Herausforderung dieser Studie ist hauptsächlich eine gute Optimierung des Designs der Maschine (geometrische Parameter) und der Betriebs-Parameter. Für diesen Zweck wurde entschieden, dass die Leistungsziffer (der Coefficent Of Performance, *COP*) sogar für einen kleinen magnetischen Chiller Werte der besten grossen Kompressor-Flüssigkeits-Chiller erreichen soll (z.B. von einem gross-skaligen Turbo-Kompressor). Deshalb wurde in allen Optimierungsprozessen ein *COP* von 5.5 angestrebt.

Dieser Bericht zeigt Resultate von verschiedenen Untersuchungen für variierende Design- und Betriebs-Parameter von Rotations-Flüssigkeits-Chillern. Der Bericht präsentiert Entwürfe und Chararakteristiken verschiedener Magnet-Konfigurationen. Eine optimale Konfiguration, für den der Studie zugrunde gelegten Chiller, wurde ausgewählt. Der Design und die Betriebsparameter werden gegeben. Weitere zu machende Arbeiten werden beschrieben, welche durchgeführt und im Schlussbericht dieses Projektes dargestellt werden sollen.

Schlüsselbegriffe: Kältetechnik, Chiller, magnetische Kältetechnik, magnetokalorisch, Energie-Effizienz.

Summary

The end-of-year report 2008 [1] of this project indicated needs to describe the design and operation characteristics of magnetic chillers. These then would be a subject for further analyses. In 2009 this was performed and the work and results are summarized in this new end-of-year report. In the context of this feasibility study a mathematical-physical model and a special numerical tool were developed. They serve as the basis for the design, analyses on energy characteristics and the optimization of different magnetic chillers. The study comprises simultaneous work with own developed numerical tools and commercially available software for the numerical calculation of magnetic field distributions. A first analysis shows a limit related to the size of magnet assemblies. Based on data of at present available magnetocaloric and permanent magnet materials, it is concluded that magnetic chillers, operating with permanent magnets, can be applied for cooling powers up to approximately 100 kW. This is the consequence of limits given by reasonable outer dimensions of magnet assemblies. Therefore, even chillers of 100 kW cooling power are comprised of smaller modules connected together to yield a single device. A further restriction for different magnetic chiller applications is given by the temperature difference between the temperatures of the heat source and the heat sink.

At present only liquid magnetic chillers show a good alternative, while the air cooled chillers require too large temperature differences in their thermodynamic cycles. As a consequence, too large masses of magnet assemblies result. Air cooled magnetic chillers may be applied, if only small temperature differences are required. Such are e.g. industrial chillers or dryers. Too high magnet's masses directly lead to unrealistic costs of chiller devices. Costs substantially increase when a good efficiency and a large temperature span needs to be achieved. The ambition of this study was mainly a good optimization of the design (geometrical parameters) and the operating parameters. For this purpose, it was decided that the <u>C</u>oefficient <u>O</u>f the <u>P</u>erformance, *COP*, even for a small magnetic chiller should reach the value of the best large compressor liquid chiller (e.g. a large scale turbo-compressor). This is why a *COP*=5.5 was targeted in all optimization processes.

This report shows the results of different analyses for varying design and operation parameters of liquid rotary magnetic chillers. The report presents designs and characteristics of different magnet assemblies. An optimal configuration for the magnetic chiller has been selected. Its design and operating parameters are presented. Further work is indicated which will be achieved and presented in the final report of this project.

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

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. This then also implied that in different journals breakthroughs of this technology in some markets of refrigeration were predicted. Only the time scales of such breakthroughs were differently estimated. Such predictions vary between two and ten years. Researchers of HEIG-VD in Yverdon-les-Bains have deposited some interesting patents of magnetic refrigerators, heat pumps and magnetic energy conversion machines and have established a group of some reputation in the field of magneto-thermodynamics.

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. The 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.

1. Rotary magnetic liquid chillers

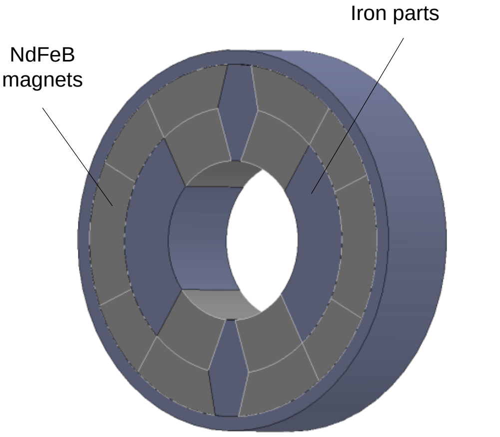
Calculations have been made iteratively with an own developed numerical tool to determine the thermodynamic and fluid dynamic related characteristics and two commercial software's to calculate the 2-d (first approximations) and 3-d (final calculations) magnetic field line distributions. The air-cooled magnetic chillers are not a subject of a comprehensive analysis. The reason for not considering the air cooled chillers is that they require a too large temperature span of the thermodynamic cycle. This is caused by the occurring increased irreversible heat transfer losses. In order to obtain a good efficiency, in such devices large magnet assemblies would be required, which is very cost intensive. Based on such insight this study is focused only on liquid magnetic chillers.

The calculation of the behaviour of liquid rotary magnetic chillers is based on the following parameters: the chilled liquid supply temperature to the outer system being 7°C and the cooling fluid exit temperature coming in from the magnetic chiller being assumed to be 32°C. The return temperature of chilled fluid and the supply temperature of the cooling fluid were varied in the simulation process. A 20% ethanol/water solution was chosen as working fluid. 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 with a thickness of 0.1 mm.

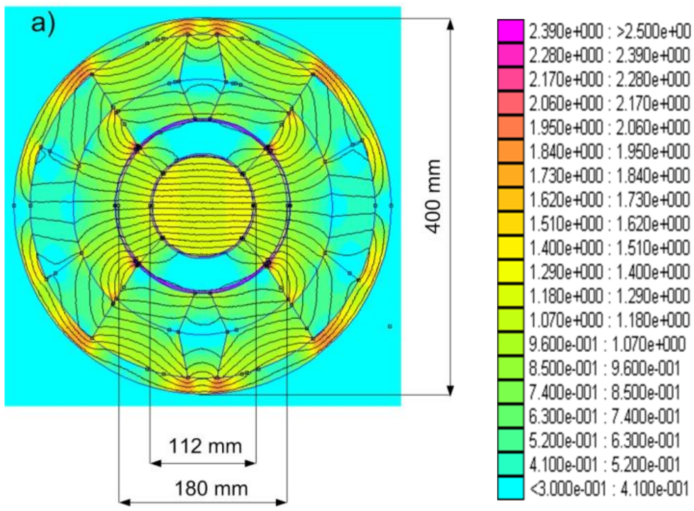
In this study – contrary to other previous feasibility studies, where pure gadolinium was the magnetocaloric marterial – for modelling purposes the thermodynamic properties of La (Fe, Si, H) (see in Ref.'s [3] - [5]) was chosen. It was assumed that layering leads to 80% of the maximum magnetocaloric effect of these materials. The target was a *COP* value of 5.5 and this was the value kept fixed in all calculations. 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.

1.1. Design and simulations of permanent magnet assemblies

A basic design concept for the magnet assembly was made (see Fig. 1). Based on this, three different kinds of 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 2-d magnetic simulation results resulting from an application of a finite element analysis. 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.

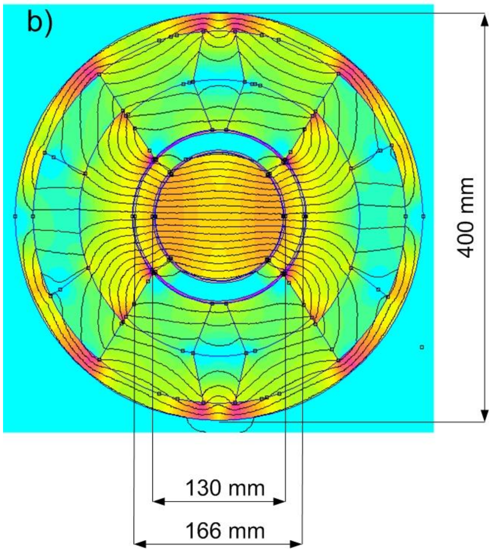


Figur 1: *The design of the magnet assembly for a magnetic chiller is presented. To obtain a clear presentation, the inner core part (made of soft iron) and the magnetocaloric structure of the ring are not shown.*

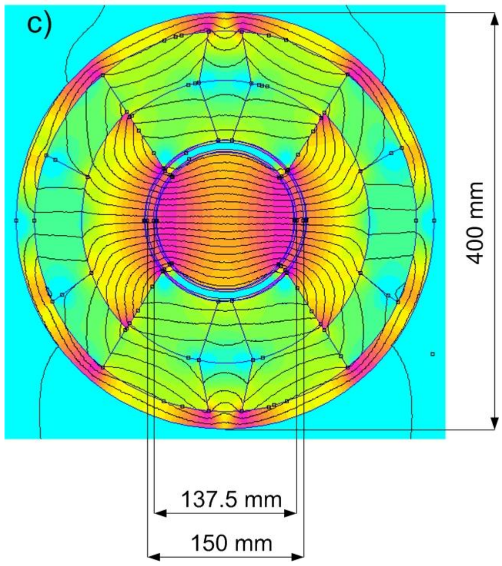


Figur 2a: *The results of magnetic simulations, with a finite element analysis (1 T magnet assembly), are shown. A large gap enables a large amount of magnetocaloric material to be located in it.*

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. This is valid for the structure and magnetocaloric properties that were taken into account. 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.

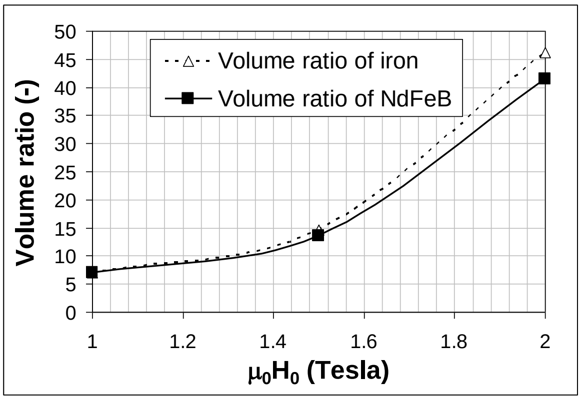


Figur 2b: *The results of magnetic simulations with finite element analysis (1.5 T magnet assembly) are shown. The legend of Fig. 2a is also valid for this figure.*



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

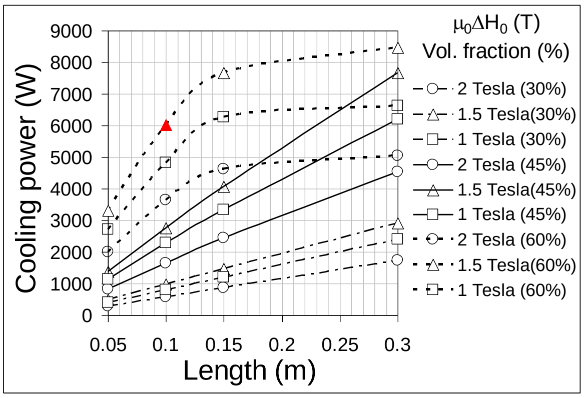
Instructive information is contained in Fig. 3. It shows the volume ratio between the volume of the magnet material (NdFeB) and the volume of the magnetized region for different magnetic flux densities. It also presents the volume ratio between the volume of soft iron and the volume of the magnetized 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.



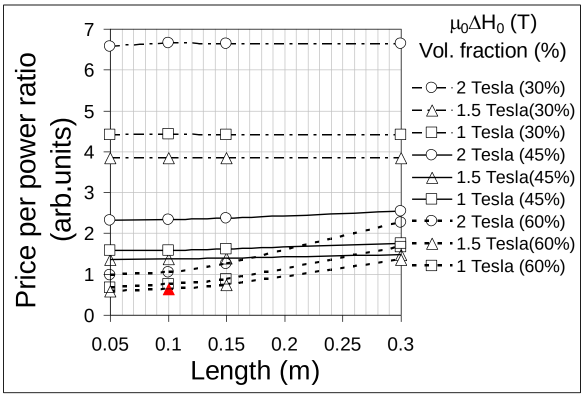
Figur 3: *The volume ratio between the volume of magnets or soft iron and the volume of the magnetized region for different magnetic flux densities. The figure clearly demonstrates the sudden large growth of the volume of a magnet assembly when the magnetic flux density is higher than 1.4 T. This is 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 (see also in Chapt. 1.2).*

1.2. Simulations on design, thermodynamic and fluid dynamic characteristics

The analysis was performed for three different magnet assemblies that are presented in Fig.'s 2a-c. Based on this, information on the coaxial ring is given. It is filled with the 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 4-6 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 4-6 magnetic flux densities of 1, 1.5 and 2 T correspond to the magnet assemblies in Fig.'s. 2a-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.



Figur 4: *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.*



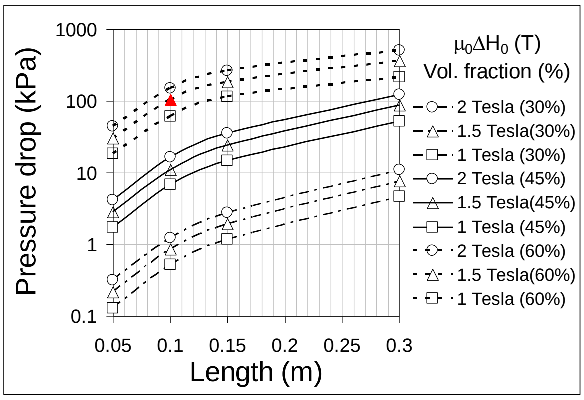
Figur 5: *The price per power ratio of a magnet assembly for different lengths, different magnetic flux densities and different volume fractions are presented in this figure. The ratio gives an important basis for further economic evaluations*

According to Fig. 4 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. 5 shows the price per power ratio at different design and operating conditions. 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. 5 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. 5), 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. 5, the dependence of the price per power ratio is more sensitive to the length of the magnet assembly at higher volume fraction than at a lower one. Fig. 6 shows pressure losses for different design and operation conditions.



Figur 6: *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. 2a-c and 4.*

2. Conclusions

The results of the analyses presented 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 16 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 4-6. 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 a smaller cooling power. This also causes 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 100 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.

Performed work and obtained results

This report shows important information regarding the design of the magnet assembly and operating characteristics of liquid rotary magnetic chillers. It further explains the optimization process that leads to a selection of a close-to-optimal magnetic chiller and its operation characteristics. The study will go on and more results will be reported in the final report of this project. Based on the results presented in this report, the preferable and selected type of a magnet's assembly has a length of 10 cm and provides a magnetic flux density of 1.5 T. Because the magnetic simulations were made for only two space dimensions, additional numerical simulations in 3-d performance are required. This means magnetic numerical simulations with the Ansys Multiphysics software. They are required to check the design characteristics, magnetic flux densities, their distribution and eventually their flux leakage into the surrounding space. A comprehensive analysis will be performed for the selected optimal case. This will lead to a full description of the characteristics of a rotary magnetic chiller depending on its different important operation parameters. For these the selected cooling power 6 kW and *COP*=5.5 will present only a point of nominal operation. An investigation of the effect of an increase in thickness of the magnetocaloric structure will also be evaluated. Additionally, certain analyses will be performed for air-cooled chillers in order to prove the occurrence of higher costs of "air machines" compared to such operating with water-based liquids. Some results will probably demonstrate a potential for magnetic air cooled chillers in applications as industrial chillers and air dryers.

Moreover, simulation results of magnetic chiller machines, applying other more advanced heat transfer fluids, will also be presented. Because the maximum cooling power of the rotary magnetic chillers (based on permanent magnets) is restricted to approximately 100 kW, there most probably exists a certain gap in market applications at medium to high cooling powers. However, in Ref. [2] it was reported that for very large-scale application superconducting magnets may be the best solution. The final report will comprise a number of different results considering this topic. An economic comparison of the selected magnetic chiller (with its modular design) and a conventional compressor liquid chiller will be made. A small description of future developments of magnetic chillers will be also outlined in the final report.

National collaborations

Kitanovsky and Egolf – after writing their review article [6] – pronounced the need of systematic investigations on magnetic forces which relate to the thermodynamic potentials of magneto-thermodynamics. This idea was taken up by O. Sari and led to a joint national research project "Réfrigeration Magnétique: Force magnétique", which is also funded by the SFOE. Numerous professors and their research groups at the University of Applied Sciences of Western Switzerland are involved, as e.g. Prof. Bonhote, Forchelet, Besson, etc.

The HEIG-VD/SIT division has established a very good collaboration with the group of Prof. P. Repetti. In his divison, named Li3C, two further professors, namely Prof. A. Orita and J.-L. Beney are active. This divison has a strong competence in concepts and the building of industrial prototypes.

The research and development project „Magnetic Production of Cold at Room Temperature", which was founded by the Gebert Rüf Foundation in Basel, has been terminated in the first half of the year 2009.

A further large project: "Magnetic Heat Pump with a Ground Heat Source: Optimized Prototype" is supported by the SFOE and the County of Vaud. The planning of the prototype is in its final stage. In the year 2010 the building of the prototype and the experimental validation of its operation are tasks which must be performed.

International collaborations

The HEIG-VD/SIT division started collaboration with a leading global manufacturer, namely Vacuumschmelze (Hanau, Germany), on magnets and magnetocaloric materials. Vacuumschmelze posses competence in the field of permanent magnets and their assemblies. The company is also involved in the development and the production of Lanthanum based magnetocaloric materials.

Another important industrial contact has been established with the company Parker–Hiross, located in Padova, Italy. Parker-Hiross manufactures industrial chillers and dryers. Negotiations about a first feasibility study and a related project in the field of magnetic chillers are in discussion.

The HEIG-SIT has some activity concerning a R&D project for the development of a magnetic refrigerator for developing countries. In a first contact with representatives of UNEP in Paris and UNIDO in Vienna this attractive idea is discussed.

Another action is the preparation of an EU project proposal on a hyperthermia cancer treatment method by the application of the magnetocaloric effect. This project preparation is led by the National Physical Laboratory in the United Kingdom. Among a dozen of classical universities the closest partners of HEIG-VD, namely the divisions of Prof. A. M. Tishin at the Lomonosov State University in Moscow and of Prof. R. Grössinger at the Technical University of Vienna in Austria, are partners. The enterprises Oxford Instruments Magnetic Resonance and Bruker in Italy are also within this team.

An important collaboration, which was already mentioned in the last report, has started with Prof. B. Yu from Jiao Tong University from Xi'an in China. A PhD student, Min Liu, had a four months stay in the HEIG-SIT group. Collaboration started with the production of a review article on all existing magnetic refrigerator prototypes and their operation characteristics [7]. Another part of the collaboration is dedicated to the design and optimization of magnetic refrigerators.

P.W. Egolf is in the management committee of the EU COST Action TU 0802 with the topic/title *Next generation cost effective phase change materials for increased energy efficiency in renewable energy systems in buildings (NeCoE-PCM)*. Egolf et al. have proposed a new solar air-conditioning system for buildings named "Breathing Building", which contains magnetic heating and refrigeration. A more comprehensive description of this system is given in Ref. [8].

A further project to investigate a small refrigerator by performing a feasibility study for an enterprise is in its final stage.

The first and second authors of this report are involved in the organization of the Fourth IIR International Conference on Magnetic Refrigeration at Room Temperature, which will be held from 23-27th of August 2010 in Baotou, China. See in Fig. 7 for more details.

Figur 7: ***The 4th International Conference on Magnetic Refrigeration at Room Temperature is at present organized by Prof. Jiaohong Huang and Madame Yan Wang at the*** **Baotou Research Institute of Rare Earths (BRIRE)** ***together with the HEIG-VD/SIT group. The conference will be held in Baotou in the Inner Mongolia, in China. This presents also the first conference of the IIR Working Party on Magnetic Refrigeration at Room Temperature that will be held in Asia. It is expected that a high number of researchers and industry representati ves from this continent will participate in the conference. See also in Ref. [9] for more details.***

Evaluation 2009 and outlook 2010

The study and the achieved results in 2009 follow the initially given project goals. Certain modifications are expected in the part that concerns the analyses on different types of magnetic chillers. This is a consequence of the results that are shown in this report. Certain domains, with possible applications of the magnetic chiller technology, are not feasible at the present stage of development of the permanent magnets and the magnetocaloric materials. This is why the further study will focus only on realistic applications. For these a comprehensive analysis will be performed, and the results will be presented in the final report. The analyses will comprise 3-d magnetic field simulations, descriptions on the characteristics of the selected best magnetic chillers, as well as a technical and economic comparison with machines of the conventional compression/expansion technology. Additional work on the application of superconducting magnets will be presented. Based on the difficulties that the state-of-the-art technology presents, the first two authors of this report made large efforts in the last few years in order to find appropriate solutions to numerous particular problems. Many new ideas were developed. Some go very much beyond the present state of the art of the magnetic refrigeration technology. The ideas are published in the International Journal of Refrigeration (see Ref. [10]). An idea, which is described in this article, led to a patent application [11]. It is expected that some ideas could lead to future magnetic refrigeration technologies in some different refrigeration domains. However, large research efforts are required to bring some of these new innovative systems to become practical applications.

After this feasibility study, a Swiss research project together with industrial partners from Switzerland or an European country (different contacts have already been established) will be proposed to SFOE. The aim of the project will be the development of a magnetic industrial chiller or air dryer.

References

[1] P. W.Egolf, A. Kitanovski, D. Vuarnoz, C. Gonin, T. Swinnen, **Central magnetic cooling and refrigeration machines (chiller) and their assessment.** End-of-year report for the Swiss Federal Office of Energy, Project No. 102873/153691, 1st of December 2008, pp. 1-9 (in German).

[2] A. Kitanovski, P. W. Egolf, **Application of magnetic refrigeration and its assessment: A feasibility study**, Final reportfor the Swiss Federal Office of Energy, Project No. 101’776/152’191, 29th of. April 2008, pp. 1-42 with three appendices.

[3] A. Fujita, S. Fujieda, K. Fukamichi, **Improvement of magnetocaloric properties toward high efficiency cooling in $La(Fe_xSi_{1-x})_{13}$ by hydrogenation and partial substitution,** ppt presentation, Delft Days 2008, Netherlands.

[4] K. Fukamichi, A. Fujita, S. Fujieda, **Large magnetocaloric effects and thermal transport properties of $La(FeSi)_{13}$ and their hydrides**, Journal of Alloys and Compounds 408–412 (2006), pp. 307–312.

[5] L. G. de Medeiros Jr., N. A. de Oliveira, **Magnetocaloric effect in $La(Fe_xSi_{1-x})_{13}$ doped with hydrogen and under ex ternal pressure**, Journal of Alloys and Compounds 424 (2006), pp. 41–45.

[6] A. Kitanovsi, P.W. Egolf, **The thermodynamics of magnetic refrigeration**, Review article of the International Journal of Refrigeration 29 (2006), pp. 3-21.

[7] B. Yu, M. Liu, P. W. Egolf, A. Kitanovski, **A review of magnetic refrigerator and heat pump prototypes built before the year 2010,** International Journal of Refrigeration, 2009 (submitted).

[8] P. W. Egolf, A. Kitanovski, C. Gonin, P. Repetti, A. Orita, J.-L. Beney, **Magnetic heat pump with earth heat source: Optimized prototype**. Annual report for the Swiss Federal Office of Energy, 2009 (in German).

[9] www.brire.com/thermag4.

[10] A. Kitanovski, P. W. Egolf, **Innovative ideas for future research on magnetocaloric technologies,** International Journal of Refrigeration (accepted).

[11] P. W. Egolf, A. Kitanovski, D. Vuarnoz, **A permeable-magnetocaloric material for a magnetocaloric device**, 2009 WO2009124408 (A1).