Resurseffektiva kyl- och värmepumpssystem

Magnetic heat pumping and refrigeration

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Energimyndigheten

Foreword

This report is on the research done at the Department of Energy, Royal Institute of Technology (KTH) under the project EP13- magnetocaloric heat pumping technology.

The project is financed by Swedish Energy Agency and Electrolux. Electrolux has contributed in the project by sharing expertise and resources as well.

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Sammanfattning

Efter manga års forskning och utveckling har den traditionella ångkompressionsprocessen blivit en mogen teknik, och kraftiga förbättringar i prestanda för värmepumpar och kylsystem baserade på denna teknik är inte att vänta.

Bland de alternativa tekniker som föreslagits är magnetkyla en av de mest lovande. Som påpekas i olika litteraturreferenser, så kan magnetkyla, förutom att ha potential för hög energieffektivitet, förväntas arbeta med mindre oväsen och vibrationer, utan användning av potentiellt miljöfarliga köldmedier, och samtidigt ha mer kompakta mått än ångkompressionsprocessen.

Detta projekt syftar till att undersöka möjligheterna att ersätta konventionella kyl- och värmepumsystem med magnetiska processer. Inom projektet har litteratur inom ämnet från flera decenniers studier av magnetkyla i rumstemperatur studerats. Miljöinverkan av magnetkyla har undersökts och en datormodell för detaljerad simulering av magnetkylsystem har utvecklats, med hjälp av vilken det är möjligt att optimera utformningen av sådana system. Alla dessa aktiviteter har bidragit till att bygga upp kunnandet i Sverige inom området.

För att kunna minska elanvändningen, och därmed driftskostnaderna och miljöbelastningen av magnetkylsystem krävs optimering och förbättringar av designen, vilket är målsättningen med konstruktionen av den numeriska modellen. En effektiv metod för att öka prestanda och ge flexibilitet i användningen är att använda en matris med lager (skikt) av olika magnetokaloriska material. Optimering av utformningen av dessa lager har genomförts i detalj inom projektet.

Ett ytterligare mål med utformningen och optimeringen har varit att minska mängden magnetokaloriskt material och mängden magnetiskt material för en given effekt.

Eftersom dessa material innehåller sällsynta metaller så har mängden material stor inverkan på miljöeffekterna av den magnetiska kylprocessen, allt enligt den livscykelanalys som genomförts inom projektet.

Ett annat sätt att minska miljöinverkan av dessa system är att utveckla nya magnetiska material och nya processer för utvinning och förädling. Detta kan potentiellt leda till mindre system med mindre miljöeffekt.

Mindre mängder magnetokaloriska material, och därmed även mindre magneter, skulle innebära lägre kostnader, eftersom magnetmaterialet är det dyraste i denna typ av system. Högre prestanda kan också åstadkommas genom användning av nya magnetokaloriska material med högre magnetokalorisk effekt och bättre värmeöverföringsegenskaper.

Ett återstående arbete som var planerat men ej kunnat genomföras inom projektets tidsram är experimentell validering av de numeriska modellerna. Detta förväntas kunna göras inom ramen för ett fortsatt projekt, om ett sådant blir finansierat.

Summary

After many years of research and development, vapor-compression technology has become a mature technology, by which significant improvement in performance of heat pump or refrigeration systems is not expected. Among the alternative technologies proposed to improve the performance of such systems even further, magnetic refrigeration is one of the most promising technologies. As mentioned in the literature, apart from the possibility of achieving higher energy efficiency, the magnetic refrigeration systems can be expected to operate with less noise and vibration, free of greenhouse gases, and to have a more compact size than vapor compression systems.

This project is in the direction of investigating the possibilities of replacing conventional heat pump or refrigeration systems with magnetic systems. In the project several decades of activity in room temperature magnetic refrigeration has been reviewed during the conducted extensive literature study; the environmental impacts of magnetic refrigeration have been investigated; a software model simulating magnetic refrigeration systems is developed; improvements of the design of multi-layer regenerators leading to enhanced performance have been studied. All these activities are in line with building expertise in this field of technology.

Reducing electricity consumption, and thereby the operation costs and environmental impacts, of magnetic refrigeration systems requires optimization and improved design of the units which is aimed by developing the simulation model in this project. An effective method to enhance the performance and add flexibility to working conditions is using layers of different magnetocaloric materials. Optimizing the layers, as a part of the magnetic refrigeration system, has been investigated in depth in the project.

In addition, through advanced design and optimization the required amount of the magnet material and magnetocaloric materials can be reduced. Such materials, mainly because of rare-earth elements in their compounds, have a major share in the environmental impacts of magnetic refrigeration, according to the life cycle assessment done in the project. In addition to the design improvements, development of new magnetic materials and improvements in processing them allow designing smaller units with less environmental impacts associated with the magnetic materials. Smaller amount of high density magnetocaloric materials, and therefore smaller magnet size, lowers the costs, since the magnet material is the most expensive one in such systems. Higher performance of magnetic refrigeration systems is also expected with

magnetocaloric materials with higher magnetocaloric effect and desirable heat transfer properties.

A part of future work is to test magnetic refrigeration systems experimentally in the laboratory.

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Background

Conventional refrigeration technologies such as vapor-compression technology have been developed and used for many decades. As they are mature technologies, drastic improvement in their performance is not expected; therefore, to reach even higher performance levels, looking for alternative technologies is necessary. In addition, gaseous refrigerants used in vapor-compression systems have safety and environmental issues which make alternative refrigeration technologies free from gaseous refrigerants attractive.

Among alternative technologies, magnetic refrigeration is perhaps the most promising candidate. Magnetic refrigeration is based on the temperature change of some materials when exposed to an external magnetic field. The adiabatic temperature change or isothermal entropy change of the materials caused by an external magnetic field is called magnetocaloric effect, and the materials showing such behavior are called magnetocaloric materials. Magnetocaloric effect is maximal close to the transition temperature (Curie temperature) of the materials.

The most well-known magnetocaloric material suitable for room temperature applications with Curie temperature of about 290 K is Gadolinium. A breakthrough in room temperature magnetic refrigeration was discovery of so-called giant magnetocaloric effect in $Gd_5Si_2Ge_2$ by Pecharsky and Gschneidner Jr (2008), which undergoes a much higher entropy change when magnetized. Since then many other materials have been studied and research on magnetocaloric materials for room temperature applications is still ongoing (Brück et al., 2008) (Gschneidner Jr et al., 2005). Along with the research on the magnetocaloric materials, designing the machines utilizing magnetocaloric effect effectively for heat pumping or refrigeration purposes is an important field of research. Many research prototypes are reported in the scientific literature (Yu et al., 2010). In addition, for predicting the performance of magnetic refrigeration systems and optimization purposes, a great deal of effort has been expended on modeling magnetic refrigeration machines (Nielsen et al., 2011).

The working principle of magnetic refrigeration and its analogy with Joule-Brayton cycle is shown in Figure 1: when a magnetocaloric material at room temperature is exposed to an external field it becomes warm due to magnetocaloric effect. Then, the temperature of the warm, magnetized material is reduced as it rejects heat to the ambient. At this point when the magnetic field is removed the material becomes cold (colder than the ambient) and the cold material can accept heat from cold reservoir. By repeating the cycle, heat is pumped from the cold reservoir to the warm reservoir which is the aim of heat pump or refrigeration applications. Apart from the Brayton cycle described by Figure 1, magnetic refrigeration can work based on many other thermodynamic cycles such as Ericson cycle (Kitanovski et al., 2014).

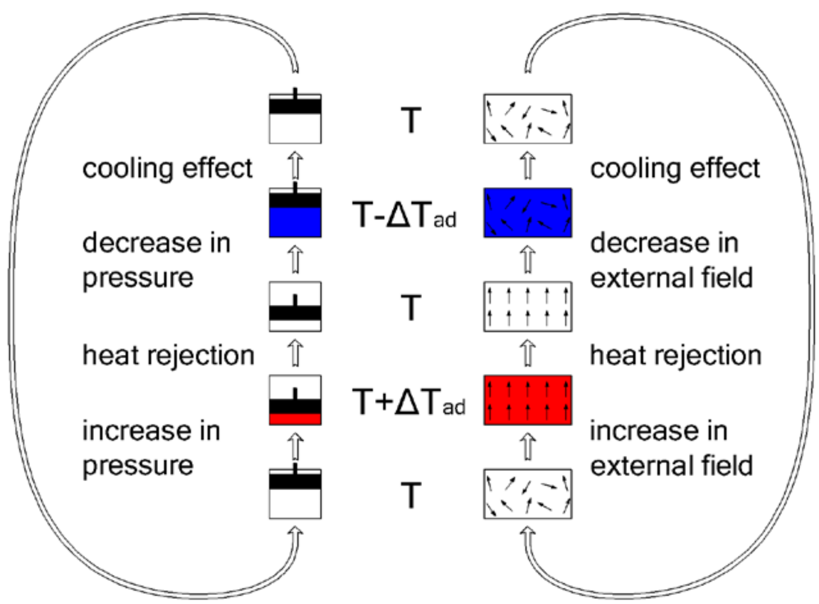

Figure 1 working principle of magnetic refrigeration (right) and its analogy with Joule-Brayton cycle (left)

Different technical aspects of a magnetic refrigeration system are summarized in Figure 2.

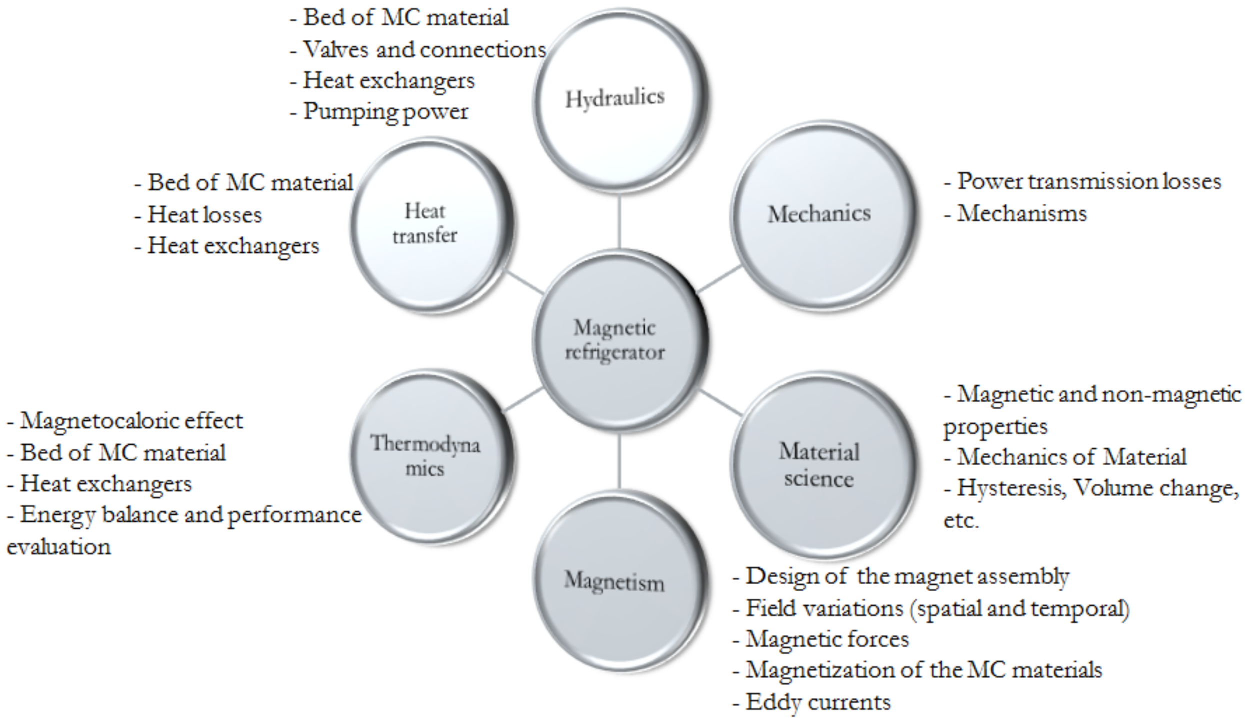

Figure 2 Technical aspects of a magnetic refrigeration system

The advantages of magnetic refrigeration mentioned in the open literature over conventional refrigeration technologies are being potentially more energy efficient, being more compact, making less noise and vibrations, being free from gaseous refrigerants' release to the environment, and being more environmentally friendly (Yu et al., 2010).

However, magnetic refrigeration technology at room temperature has not been commercialized yet; thus, the potential advantages of magnetic refrigeration over vapor-compression technology have not been shown in practice. Some companies, meanwhile, claim that they can already build magnetic refrigeration systems competing with vapor-compression ones, but the details of their machines have not been published. Accordingly, independent research work is needed to evaluate the potential of magnetic refrigeration to reach higher performance and cause less environmental damage. This project aims to acquire knowledge of magnetic refrigeration technology and investigate the opportunities for further development of refrigeration systems.

Objectives

- Doing a literature survey to investigate the current situation and weaknesses and strengths of magnetic refrigeration
- To build up expertise in Sweden and Electrolux
- Developing a simulation model including heat exchangers, heat transfer losses, channeling effect, etc.
- To build and test a magnetic refrigeration prototype

Project participants

The project is mainly done at the Department of Technology, Royal Institute of Technology (KTH). The project is financed by Swedish Energy Agency (Energimyndigheten) through Effsys+ program and Electrolux. Electrolux, in addition to partly financing the project, shares resources and expertise.

The work done

The project started with studying the basic principles of magnetization and the thermodynamics of magnetocaloric effect and magnetic processes with the focus on the concepts applicable to magnetic refrigeration. In addition, since regeneration and packed beds as regenerators are used widely in magnetic refrigeration, heat transfer and hydraulics in packed beds has been studied. A comprehensive literature survey on the built prototypes and experimental studies done at different research institutes around the world has been done to know the current state of development of magnetic refrigeration and the practical limitations. This part of the literature study was complemented by making contact with different companies active in the field not to miss the advancements not reported in open literature. Another part of the literature survey was focused on collecting information about the magnetocaloric materials suitable for room temperature applications. In addition to the magnetocaloric materials, the magnet assemblies and their different suggested designs were studied briefly. Covered in the literature survey were also the works done on modeling the magnetic refrigeration systems since one of the objectives of the project is developing a model useful for predicting the performance and optimization of magnetic refrigerators.

In the literature survey it was noticed that many researchers mentioned less environmental damage as an advantage of magnetic refrigeration over conventional technologies; nevertheless, a thorough study of different life cycle stages of a magnetic refrigeration system, supporting the hypothesis of being more environmentally friendly, was missing. Regarding the importance of less environmental damages, which can be one of the main drives to move from vapor-compression to alternative technologies, we decided to do a life cycle assessment to compare the magnetic refrigeration and vapor-compression refrigeration. The main stages, inputs and outputs, and the system boundary used for the life cycle assessment are shown in Figure 3. Although small household magnetic and vapor-compression refrigerators are compared in the assessment, the conclusions of the study can be used for more general cases with some care and considerations.

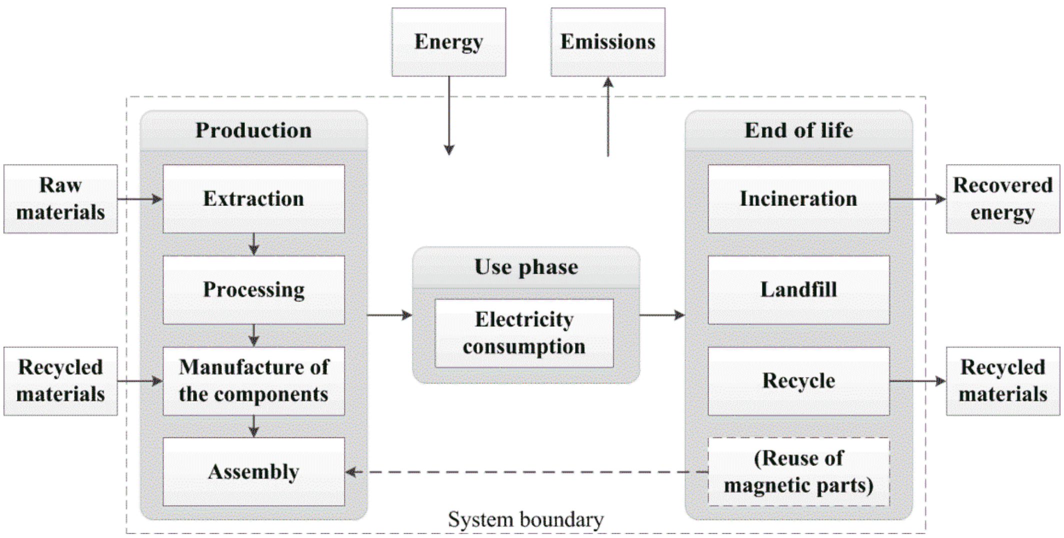

Figure 3 main stages, inputs and outputs, and the system boundary used for the life cycle assessment (Monfared et al., 2014)

The environmental impacts of each refrigerator are categorized into 18 categories according to the impact assessment method of ReCiPe with Hierarchist perspective (Goedkoop et al., 2013). Since magnetic refrigeration at room temperature has not been commercialized yet and it is a rather new technology, the currently built magnetic refrigeration prototypes cannot represent what can be achieved by magnetic refrigeration in terms of performance and effective use of materials. Accordingly, different scenarios have been considered in the assessment to cover the possible future advancements. The main conclusions of the assessment are: if both vapor-compression and magnetic refrigerators have the same energy efficiency, the magnetic refrigerator has higher environmental impacts mainly due to the use of rare-earth elements; use-phase electricity determines how important is the extra impacts of magnetic refrigeration relative to the total impacts; the impacts of the magnetic refrigerator can be lowered by reusing magnetic materials and/or reducing the amount of needed magnetic materials through optimized designs; the magnetic refrigerator has less environmental impacts in some categories if magnetic refrigerator achieves energy efficiencies higher than that of vapor-compression refrigerator. This study, assessment of life cycle environmental impacts of magnetic refrigerators, and the analysis of its results are unique. The detailed results and discussion are published in the *International Journal of Refrigeration* (Monfared et al., 2014).

Since building prototypes are costly it is beneficial to be able to predict the performance of a designed machine through modeling. In addition, models are useful for optimization purposes. Therefore, a numerical model of a magnetic refrigeration or heat pump system consisting of the packed bed of the magnetocaloric materials interacting with the heat transfer fluid and the two heat exchangers have been developed. The equations describing the packed bed of magnetocaloric material and the heat transfer fluid, which are coupled by convective heat transfer term, are based on the “continuous solid phase model” (Wakao and Kaguei, 1982). The model accept different heat transfer flow patterns, different magnetic field variation patterns, number and dimensions of packed bed(s), magnetocaloric material properties, heat transfer fluid properties, frequency of operation, cooling load, heat source temperature, and heat sink temperature as inputs. The results obtainable from the model are cooling capacity, heating capacity, magnetic power, pumping power, electricity consumption, coefficient of performance, Carnot efficiency, temperatures along the packed bed at each moment of a cycle for both fluid and solid phases, and temperatures in heat exchangers. Major losses such as pressure drop in the packed bed, viscous dissipation, longitudinal conduction in magnetocaloric material, axial diffusion in the heat transfer fluid, and temperature difference in the heat exchangers are considered in the model. Since experimental equations describing heat transfer and pressure drop in the packed beds are used, it is considered that channeling effect is indirectly addressed in the model. The current simulation model is the second one developed in this project since the first model had limitations in stability. Detailed information about the model and the results is included in the accompanying report.

As the magnetic refrigeration system works a temperature gradient is built along the regenerator, made of magnetocaloric materials. Due to the fact that the magnetocaloric effect is insignificant at temperatures even not very far from the transition temperatures (Curie temperatures) of the magnetocaloric materials, it is desirable to use layers of different materials with different transition temperatures along the regenerator. Through layering, the size of the magnetocaloric materials, magnet assembly, and therefore, the whole unit can be reduced effectively, which results in lower cost and environmental impacts. In addition, the power consumption can be lower since the desired cooling power can be reached by fewer numbers of cycles per second or fewer parallel regenerators. The choice of materials and geometry of the regenerator should, however, match the working temperatures and loads very well to get the benefits of layering. In this project, optimizing the layers of the regenerator has been investigated. An article, which is going to be submitted as a journal paper, has been written on the study and its outcomes.

Fulfilled objectives

An extensive literature survey has been done as mentioned in the body of the report. The simulation model has been developed. Literature study, developing simulation model, working on layered regenerators, and life cycle assessment are all in line with developing expertise in Sweden and Electrolux. Testing on prototype was postponed: it was planned that a cooperating partner to Electrolux would provide the prototype, but to find the partner who could supply the prototype took longer time than anticipated. Building the prototype has already started and it is planned to be ready by the end of this year.

Learnings

During the literature survey knowledge about magnetism and the concepts applicable to magnetic refrigeration, different magnetocaloric materials, thermodynamics of magnetization, packed beds and regeneration, magnetic refrigeration cycles, different designs of magnet assembly, different magnetic refrigeration systems, loss mechanisms and practical limitations, and opportunities with magnetic refrigeration has been acquired.

The developed life cycle model provides a unique tool to evaluate magnetic refrigeration at room temperature from environmental point of view. The type of results and their analysis had not been reported before. To create the life cycle model and to analyze the results obtained from modeling are in line with developing expertise in this field in Sweden and Electrolux.

Trying different approaches to simulate magnetic refrigeration systems, as an objective of the project, a suitable solution and limitations of the other approaches have been found. More in-depth knowledge about use of layers of different materials as regenerator, which is of great importance for optimizing magnetic refrigeration systems, has been acquired. No study on optimizing layered beds similar to the work done during this project is reported in the open literature to the best of our knowledge.

Future work

It is planned to conduct experimental work on a prototype at different working conditions. The simulations model is going to be refined to correspond more to the prototype. Different materials are going to be used in the simulation and the possibilities to optimize magnetic refrigeration systems for different purposes are going to be investigated.

References

BRÜCK, E., TEGUS, O., CAM THANH, D. T., TRUNG, N. T. & BUSCHOW, K. H. J. 2008. A review on Mn based materials for magnetic refrigeration: Structure and properties. *International Journal of Refrigeration,* 31**,** 763-770.

GOEDKOOP, M., HEIJUNGS, R., HUIJBREGTS, M., DE SCHRYVER, A., STRUIJS, J. & VAN ZELM, R. 2013. ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. The Hague.

GSCHNEIDNER JR, A., PECHARSKY, V. K. & TSOKOL, A. O. 2005. Recent developments in magnetocaloric materials. *Reports on Progress in Physics,* 68**,** 1479-1539.

GSCHNEIDNER JR, K. A. & PECHARSKY, V. K. 2008. Thirty years of near room temperature magnetic cooling: Where we are today and future prospects. *International Journal of Refrigeration,* 31**,** 945-961.

KITANOVSKI, A., PLAZNIK, U., TUŠEK, J. & POREDOŠ, A. 2014. New thermodynamic cycles for magnetic refrigeration. *International Journal of Refrigeration,* 37**,** 28-35.

MONFARED, B., FURBERG, R. & PALM, B. 2014. Magnetic vs. vapor-compression household refrigerators: A preliminary comparative life cycle assessment. *International Journal of Refrigeration,* 42**,** 69-76.

NIELSEN, K. K., TUSEK, J., ENGELBRECHT, K., SCHOPFER, S., KITANOVSKI, A., BAHL, C. R. H., SMITH, A., PRYDS, N. & POREDOS, A. 2011. Review on numerical modeling of active magnetic regenerators for room temperature applications. *International Journal of Refrigeration,* 34**,** 603-616.

WAKAO, N. & KAGUEI, S. 1982. *Heat and Mass Transfer in Packed Beds,* New York, Gordon and Breach, Science Publishers, Inc.

YU, B., LIU, M., EGOLF, P. W. & KITANOVSKI, A. 2010. A review of magnetic refrigerator and heat pump prototypes built before the year 2010. *International Journal of Refrigeration,* 33**,** 1029-1060.

Projects scientific publications

MONFARED, B., FURBERG, R. & PALM, B. 2014. Magnetic vs. vapor-compression household refrigerators: A preliminary comparative life cycle assessment. *International Journal of Refrigeration,* 42**,** 69-76

MONFARED, B., PALM, B., (in preparation). Optimized design of layers of magnetocaloric materials in packed bed of magnetic refrigeration devices.

Projects popular science publications and presentations

MONFARED, B., PALM, B., 2011. Magnetic refrigeration at room temperature. EFFSYS+ dagen, Göteborg

MONFARED, B., 2011. Magnetic refrigeration. MONFARED, B., Royal Institute of Technology, Stockholm

LUNDELL, K., 2012. Magnetkyla flyttar från labb till kök. *Energi & Miljö*, 4, 42-43 Stockholm: Energi- och Miljötekniska Föreningen

MONFARED, B., 2012. What can be expected from a MC refrigerator?, *internal report* , Royal Institute of Technology, Stockholm

PALM B., 2012. EFFSYS+ dagen, Göteborg.

MONFARED, B., FURBERG, R., 2012. Magnetocaloric refrigeration: status update, MONFARED, B., FURBERG, R., September 2012, Electrolux, Stockholm

MONFARED, B., 2011. Magnetic vs. conventional refrigeration. MONFARED, B., Royal Institute of Technology, Stockholm

MONFARED, B., FURBERG, R., 2013. Magnetocaloric refrigeration: status update, MONFARED, B., FURBERG, R., September 2013, Electrolux, Stockholm

MONFARED, B., 2014. Simulation model report, *internal report*, Royal Institute of Technology, Stockholm

MONFARED, B., 2014. Magnetic vs. Conventional Refrigeration: A comparative life cycle assessment, MONFARED, B., May 2014, Electrolux, Stockholm