RESEARCH ON ROTARY POROUS WHEEL MAGNETIC HEAT PUMPS IN SWITZERLAND

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Abstract: Since the discovery of the "giant" magneto caloric effect in 1997 magnetic heating and refrigeration reveals a realistic potential to enter some markets with machines based on the rectilinear or rotational operation principle. The Swiss Federal Office of Energy demanded a feasibility study to evaluate the efficiency and cost of a magnetic heat pump operating in a minimal energy house (Minergy house). This system operates between a ground heat source and a floor heating system and, therefore, shows the following characteristic data: heating power 8 kW, source temperature 0°C, sink temperature 35 °C. This technical and economic study reveals that a magnetic heat pump has a higher efficiency than that of a conventional compression/expansion heat pump. The price obtained for such a magnetic heat pump – with the assumption of a basic cost of magneto caloric material of 125 Euro/kg – is estimated to be approximately 30 % higher than that of a conventional one.

Key Words: magnetic *heat pump, ground heat source, floor heating, coefficient of performance*

1 INTRODUCTION

In magnetic heating and refrigeration the highest number of articles are devoted to the magneto caloric materials developments. Because of the large number of papers also some comprehensive review articles have been published (see e.g. Ref.'s: Gschneidner *et al.,* 2005; Tishin and Spichkin, 2003; Brück, 2005; Yu *et al*., 2003; Pecharsky and Gschneidner, 2006). A mile stone - almost comparable to the discovery of the magneto caloric effect by Warburg in 1881 - was the discovery of the «giant » magneto caloric effect by Pecharsky and Gschneidner, 1997a. This publication and some following one's by these authors (e.g. Pecharsky and Gschneidner, 1997b) and the one of Tegus *et al*. in 2002 are responsible that since the end of the 1990's magnetic heating and refrigeration started to reveal a realistic potential for commercial room temperature applications at least for certain market segments.

A smaller number of papers deals with thermodynamic machine design and calculation. In the field of room temperature applications a mark stone development was the room temperature refrigerator designed by Brown in 1976. A further magnetic refrigerator of Stirling type was presented by Barclay and Steyert, another one by Zimm *et al*. in a collaboration of Astronautics Corporation with the AMES laboratory at the IOWA State University. Noteworthy early developments were also performed by Chubu/Toshiba in Japan and the University of Victoria in Canada. Today twenty-eight published prototypes can be found in the scientific literature. For some information on the above mentioned prototypes and a table with technical data on these machines consult the reference Gschneidner *et al.,* 2005. More recent demonstrators and prototypes are at present in design and building, some under temporary confidential circumstances, which therefore have not yet been presented. A further review article presenting all prototypes, which have been published up to present, is in preparation by B. Yu, M. Liu together with two authors of this article.

Already in 1982 Purnell made a performance prediction for a room temperature Ericsson cycle magnetic heat pump with $\mu_0 H$= 2 and 7 Tesla magnetic field strength, representing the at that time upper limits for a machine with conventional electro magnets and super conducting magnets. Van-Haften and Mills, 1984, investigated the feasibility of magnetic heat pumps in industrial applications. They figure out the importance to match the operation temperatures to the materials Curie temperature. In 1988 Hull and Uherka reported on basic aspects of the magnetic heat pump technology also for near room temperature operation. Kirol and Dacus 1987/1988 designed a machine with a rotary cylinder with NdFeB permanent magnets having in the air gap a field strength of 0.9 T. In 1989 the same authors presented a first feasibility study on magnetic heat pumps. In 1990 Barclay performed a review on this kind of magnetic machines. In 1992 Chen *et al*. have published work on magnetic heat pumps. In one of them the characteristics of different magnetic heat pump cycles are investigated, namely for the Carnot, Ericsson, Stirling and a regenerative cycle. Drost and White, in their study on magnetic heat pumps published in 1994, figured out the importance of pressure drop reduction to efficiently operate such a machine. In 1995 at NASA a magnetic rotary-type heat pump with flow diverters, to avoid mixing of the cold and warm flows, was studied.

The magnetic heat pump and magnetic refrigeration technology has been explained in great detail in numerous articles, and as a result of this it is not outlined in this article anymore. A well understandable presentation for non-specialists has been published by the International Institute of Refrigeration (see Egolf and Rosensweig, 2007). Noteworthy is that a physical analogy exists between a magnetic heat pump and a conventional heat pump that helps a thermal engineer to better understand the operation principle of the alternative technology.

2 GENERAL FEATURES OF MAGNETIC HEAT PUMPS

2.1 Environmentally benign refrigerants

Magneto caloric materials in magnetic refrigerators are metals, which may be pure metals, sintered metals or alloys, which very often contain rare earth materials. Their ozone depletion potential (*ODP)* and global warming potential (*GWP)* are zero. This is not the case for most of the refrigerants, which at present are applied in conventional heat pumps.

2.2 Low pressures

In a magnetic heat pump the pressure differences are much smaller than 1 bar. This is a significant advantage when comparing magnetic heat pump materials to conventional refrigerants.

2.3 High exergy efficiency and coefficient of performance (COP)

In the conventional hermetic compressor based heat pumps, which operate with a Rankine like cycle, large irreversible losses occur due to moderate compressor efficiencies (e.g. polytropic compression, isenthalpic expansion). Furthermore, in numerous cases the motor heats up the refrigerant what may be beneficial in order to prevent liquid refrigerant to enter the compressor. But this heat is an additional burden, which needs to be rejected in hermetic compressor systems and leads to an additional irreversibility. The irreversibility also occurs in the case of regenerative heating by a use of condensed vapour. In conventional hermetic compressors the irreversible loss due to this effect may be 30%. In an analogy between the magnetic heat pump cycle and a conventional compression heat pump cycle the magnetization of the magneto caloric material is the analog physical process to the compression and the demagnetization to the expansion. In a magnetic heat pump some loss is related to the magnetization and demagnetization of the solid material - which here acts as a refrigerant - due to a hysteresis effect. For example, for gadolinium this loss is approximately one percent. Another loss is given by eddy currents in magnetic parts of a magnetic heat pump. Previous investigations have shown that also this kind of loss does not lead to a large reduction of the coefficient of performance of the machine. It is approximately 3-5%, but it may be also smaller depending on the specific application.

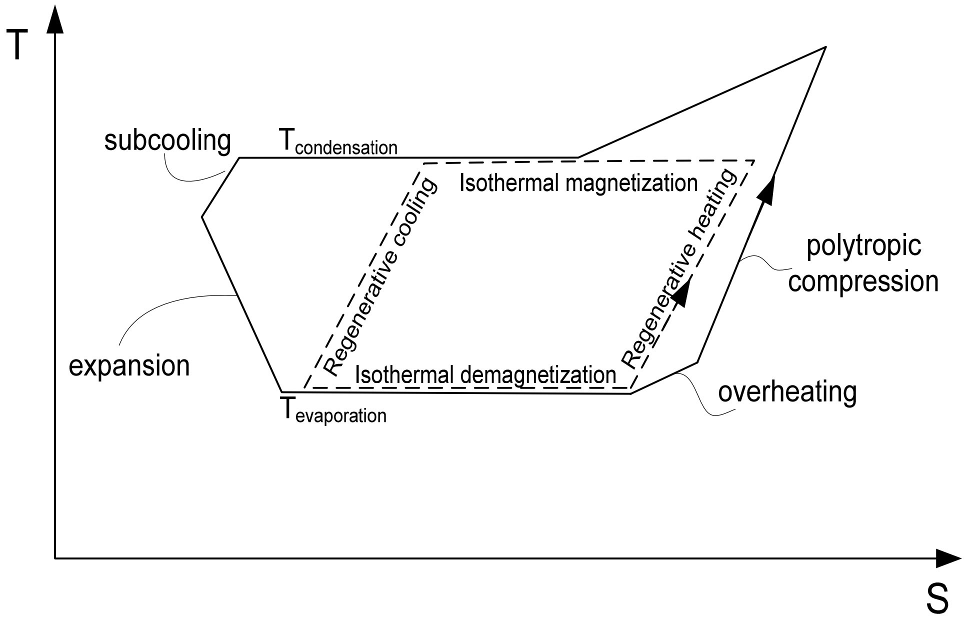

Figure 1: A Rankine conventional heat pump cycle (continuous line) and an Ericsson magnetic heat pump cycle (dotted line) are shown.

It is thus obvious that the magnetic heat pump technology enables a 20 % to 30 % higher exergy efficiency and also coefficient of performance, *COP,* compared to the conventional hermetic compressor system operating under identical conditions.

FIG. 1 presents an illustrative theoretical comparison between the two different technologies operating at same heat source and heat sink temperature and with an equal heating energy. The cycle shown with dotted lines is a magnetic Ericsson cycle, which operates between two isotherms and two isofields (constant magnetic field lines), and the continuous line presents a conventional Rankine cycle with overheating and subcooling of the refrigerant. The surfaces inside the cycles represent the works which are required for the operations of the corresponding machines. From this figure it is obvious that the work required to operate a conventional cycle shows a larger area (work) than the one of a magnetic heat pump.

2.4 Noise and vibrations

An important advantage of the magnetic heat pump technology is its silent operation conditions. Noise is created only by the rotation of magneto caloric material, by valves, by an operation of pumps and by a laminar fluid flow through a porous structure. If the machine is well designed, these contributions are usually negligible. Furthermore, a magnetic heat pump operates at a substantially lower rotation frequency than a compressor. Therefore, it will not lead to any vibrations, which could be disturbing.

2.5 Small number of moving parts

In magnetic heat pumps generally less moving parts are required compared to sophisticated compressor systems. For magnetic heat pumps there exist very simple assemblies and this enables a low maintenance as well as an expectation of a long durability of the machine.

2.6 Improvement of materials

The development of new materials for permanent magnets is still ongoing and new improved magnetic materials still discovered from time to time (see FIG. 2).

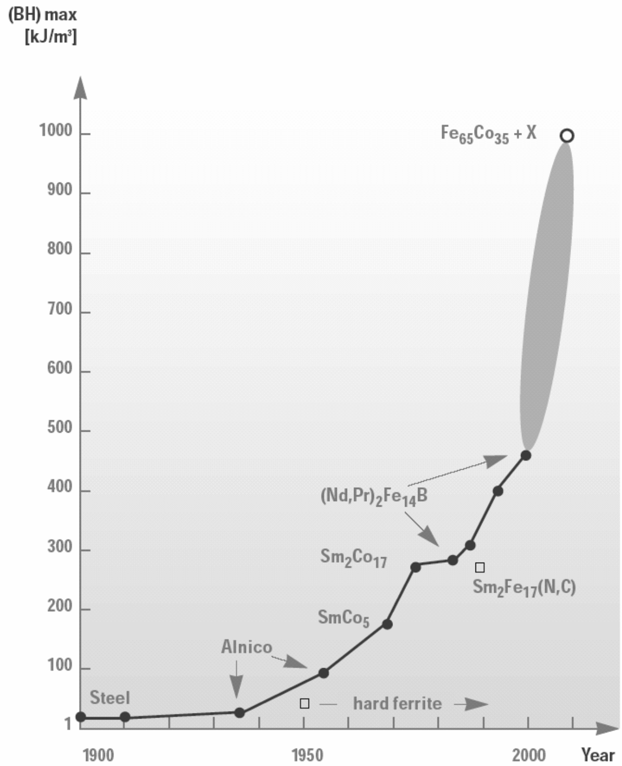

Figure 2: Development of permanent magnets (H. Kronmüller, J.M.D. Coey, 2001).

Even more than the materials of magnets the magneto caloric materials are under a strong development showing much improvement per time unit. In the near future one may expect new more performing materials. By shimming the magnetic flux density may be increased to higher values (Rowe *et al*., 2007). It has also to be noted that a large German chemical company, namely BASF (Future Technologies), has entered the investigation and production of magneto caloric materials. This could accelerate the development of more performing machines and shorten the time to the first occurrence of a break trough of the magnetic heat pump technology to industrialization and a related entering into markets.

2.7 Mass and compactness

There exists a high possibility that in the near future the frequency of operation of magnetic heat pumps will be increased up to five or maybe even ten Hertz. This will directly affect the required mass of magneto caloric material and thus its volume. The smaller the portion of magneto caloric material is, the simpler and smaller the magnets assemblies may be designed. Finally a magnetic heat pump operating at a higher frequency shows a higher heating power and a substantially reduced mass and volume.

2.8 Costs and commercialization

As further research will lead to more performing magnets and magneto caloric materials with higher adiabatic temperature differences, the coefficient of performance of magnetic heat pumps will further rise. Higher operation frequencies will also allow smaller machines and by this smaller production costs. Since the International Institute of Refrigeration has created a Working Party on Magnetic Refrigeration at Room Temperature (Egolf and Kitanovski, 2005) world wide scientists and industrial experts work together highly correlated. Therefore, one expects a first commercialization in market niches to occur already in five to six years. This prediction was made by Gschneidner in 2007 on the basis that a first commercialization of such a product occurs when 1000 prototypes are produced per year (see FIG. 3).

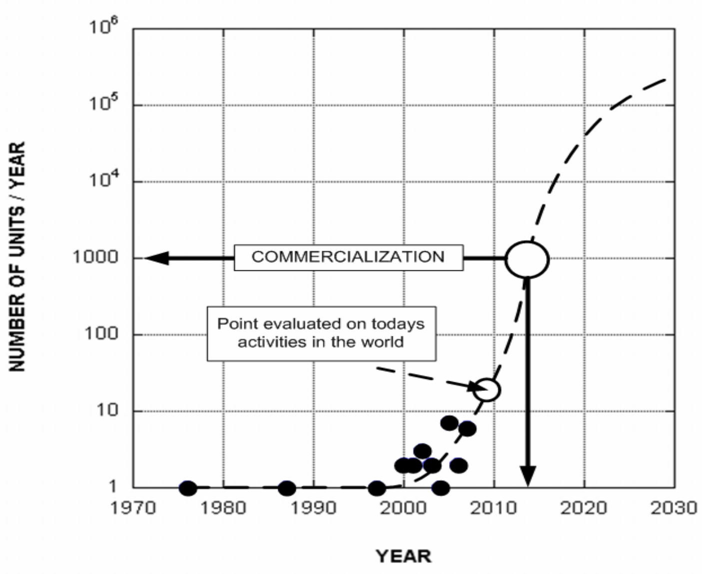

Figure 3: Magnetic refrigerators and heat pumps follow the S-growth curve of new technologies (from K.A. Gschneidner, 2007).

A study containing a technology foresight performed in the USA (S. Fischer *et al.*, 2000) shows that - besides of the conventional gas compression technology - there are no serious new alternative technologies existing, which can compete with the magnetic refrigeration and heat pump technology. The study includes thermo acoustics, sorption technologies, thermo-electric refrigeration, etc. Based on this and other insights the US Department of Energy supports research in the field of magneto-thermodynamic material science and machine design (see also the ARTI Research Roadmap or Powdermatrix Technology Roadmaps).

3 MODEL CALCULATIONS

In a study initiated by the Swiss Federal Office of Energy a magnetic heat pump with a heating power of 8 kW and a ground heat source and a floor heating system (see Egolf *et al*., 2006) has been performed. In this study simple models were developed taking the main features of magnetic heating and its irreversible energy losses into consideration. These models have been slightly improved and will be presented elsewhere. Here we list losses, which are taken into consideration in the newest version of the model:

- electric motor and fluid pump losses
- fluid friction losses
- heat transfer losses
- heat losses

- eddy current losses
- losses by the hysteresis of the magnetocaloric material.

Based on these physical-mathematical models, for the two mass fractions 10 % and 30 % of magneto caloric material, the coefficient of performance (*COP*) was determined for different other parameters, e.g. the heat source temperature and rotation frequency (see FIG. 4 and 5). For the purpose of comparison the operation characteristic's of a high-quality conventional heat pump, which is obtainable on the market, was taken into consideration. According to results shown in figures 4 and 5 the magnetic heat pumps show a much more efficient heat production than the conventional machines. In these figures it may also be seen that a substantial improvement of the magnetic heat pump operation occurs when the volume fraction of magneto caloric porous material increases. The performed analysis shows that it is possible to increase the volume fraction without obtaining a substantial increase of the pressure drop due to fluid friction. This leads to a higher power of a magnetic heat pump for the same volume of the permanent magnet assembly and then results in reduced specific losses. Higher volume fractions than 30% usually cause too high pressure drops. To obtain higher packing degrees the structures must be thicker and then the time for heat diffusion may become too large. These two figures also show that a magnetic flux density corresponding to 2 Tesla magnetic field induction is sufficient for a magnetic heat pump to be competitive with the conventional compression/expansion heat pump. Our technical-scientific evaluation reveals a better performance of the magnetic heat pump technology in the case that smaller temperature spans occur between the heat source and heat sink. This leads to the insight that ground heat based heat pumps are more effective than air heat pumps.

Figures 6 and 7 show the *COP* depending on the magnetic flux density for different frequencies of operation (magnetization/demagnetization cycles). Notify that 10 % volume fraction of magneto caloric material even enables competitive devices when they are operating with low frequencies and magnetic flux densities only slightly above 1 Tesla. If the volume fraction of magneto caloric material is increased, the magnetic heat pump technology becomes even more promising. Considering this, one may conclude that the frequency of operation could be increased even beyond 10 Hz. This will positively influence the compactness and weight reduction of magnetic heat pumps. It has to be noted that the analysis does not include machines with superconducting magnets. Such magnets lead to very high magnetic flux densities and can also result in promising heat pumps. But this is not subject of this article. However, the application of superconductivity for heat pumps is economic only in large scale applications, e.g. in heat pumps with a heating power of several Megawatts. This is due to the fact that the price of a superconducting magnet system and its losses in relation to the total prize and losses becomes smaller in large systems. Large heat pump applications with the conventional technology are well known for example in combination with district energy systems.

Also the exergy efficiencies of magnetic heat pumps beat those of the conventional technology. This may be seen in the examples shown in FIG.'s 8 and 9.

Very important is also the total mass of a magnetic heat pump and its comparison with the mass of a conventional heat pump (see FIG.'s 10 and 11). For this purpose data from a conventional heat pump, which is well established on the market, is used. The figures showing the total mass of the machines clearly show higher weights of the magnetic heat pumps. And this is even the case, if the volume fraction of the magneto caloric material is increased. However, the possibility exists to increase the frequency beyond 10 Hz, and then the total mass of magnetic heat pumps approach those of conventional machines.

The presented analysis is based on a present state of the art of the magnetic heat pump technology and not on any future perspectives. But these predictions are only of theoretical nature and to become really confirmed must be also proven by extended experimentation.

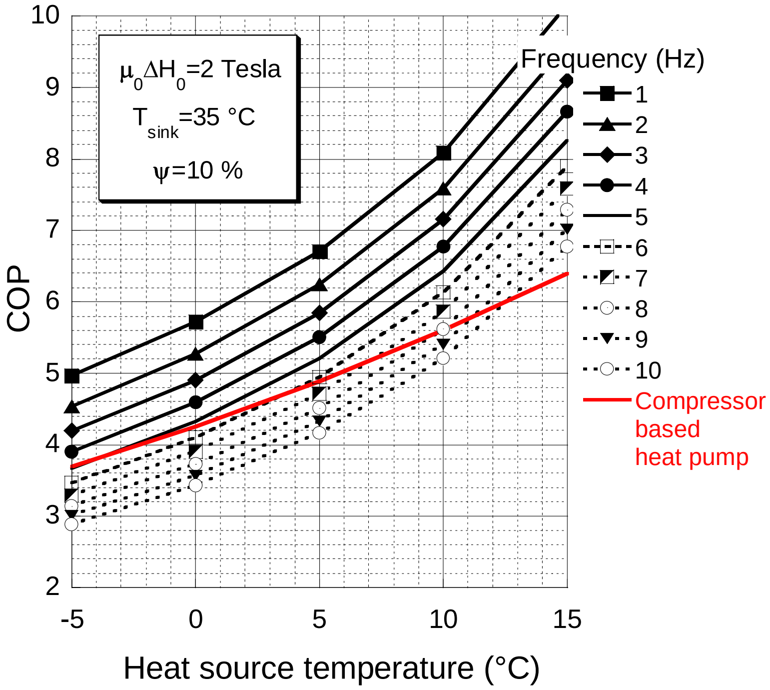

Figure 4: Coefficient of performance of a magnetic heat pump as a function of the heat source temperature and the rotation frequency for a magnetic field induction of 2 Tesla, a temperature of the sink of 35 °C and a volume packing degree of 10 %.

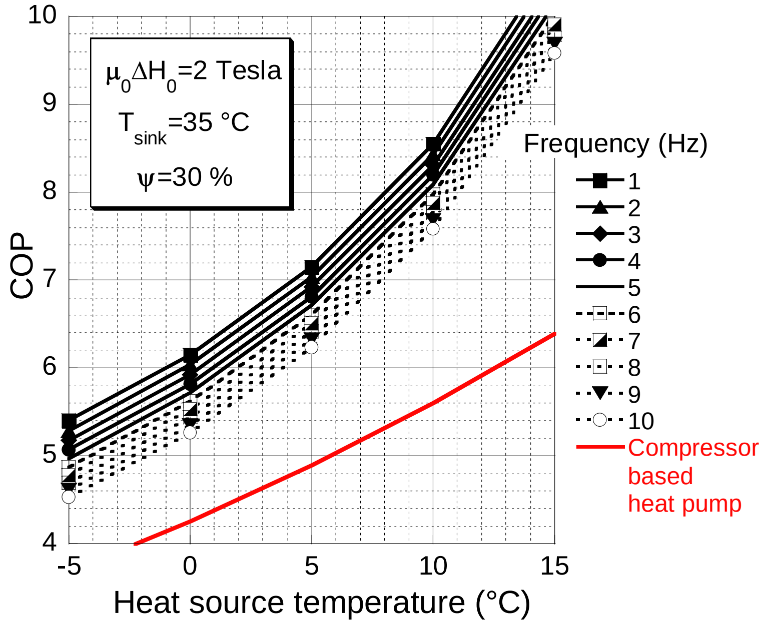

Figure 5: Coefficient of performance of a magnetic heat pump as a function of the heat source temperature and the rotation frequency for a magnetic field induction of 2 Tesla, a temperature of the sink of 35 °C and a volume packing degree of 30 %.

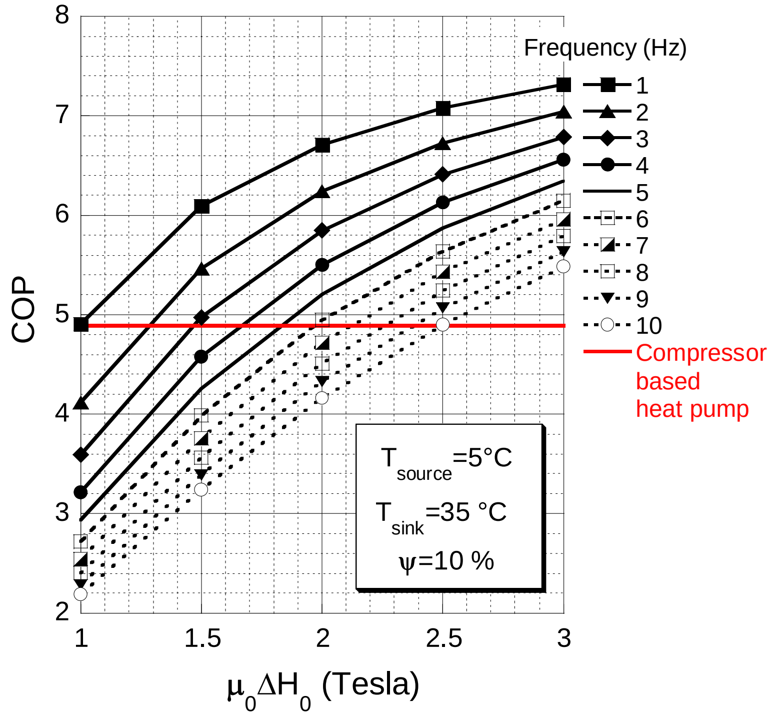

Figure 6: Coefficent of performance of a magnetic heat pump as a function of the magnetic field strength (presented by a magnetic induction) and the rotation frequency for a temperature of the source of 5 °C, a temperature of the sink of 35 °C and a volume packing degree of 10 %.

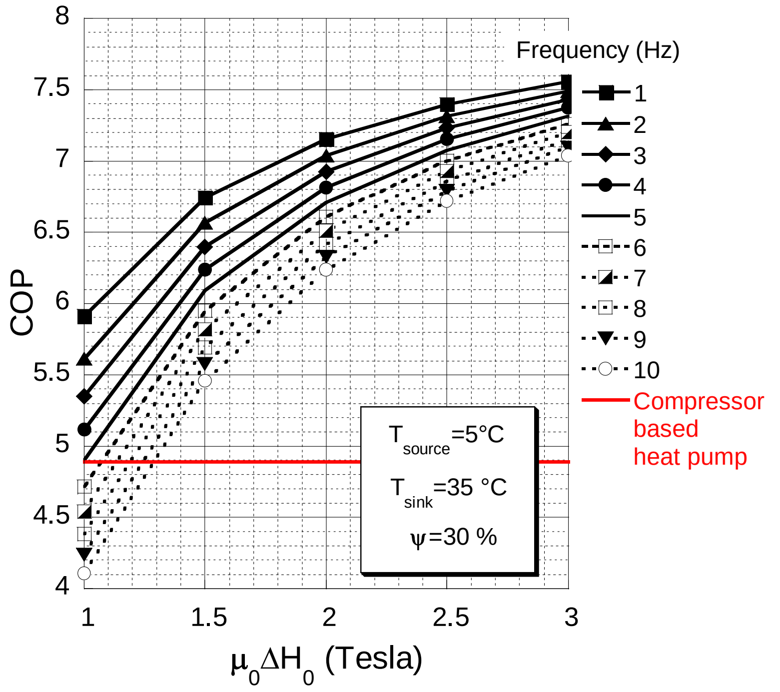

Figure 7: Coefficent of performance of a magnetic heat pump as a function of the magnetic field strength (presented by a magnetic induction) and the rotation frequency for a temperature of the source of 5°C, the temperature of the sink of 35 °C and a volume packing degree of 30 %.

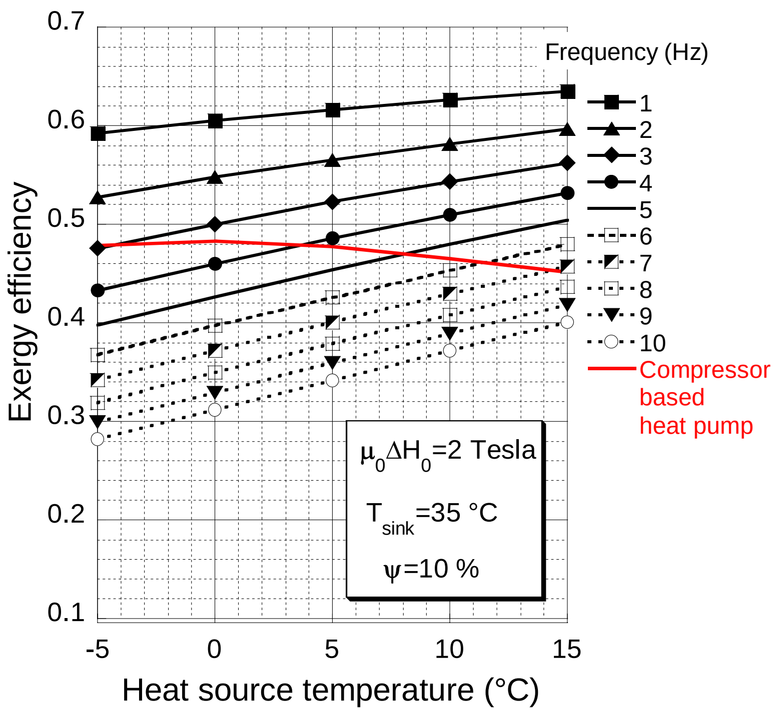

Figure 8: Exergy efficiency of a magnetic heat pump as a function of the heat source temperature and the rotation frequency for a magnetic field induction of 2 Tesla, a temperature of the sink of 35 °C and a volume packing degree of 10 %.

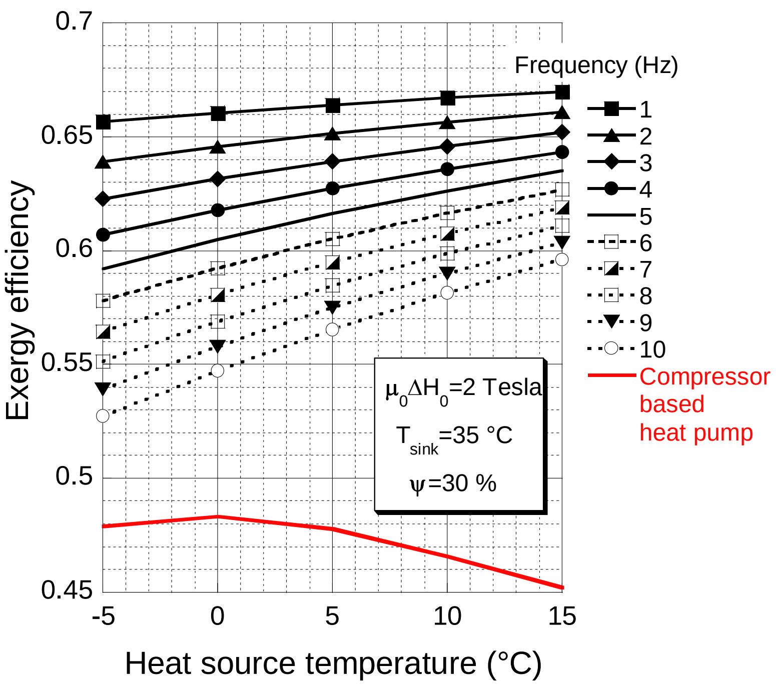

Figure 9: Exergy efficiency of a magnetic heat pump as a function of the heat source temperature and the rotation frequency for a magnetic field induction of 2 Tesla, a temperature of the sink of 35 °C and a volume packing degree of 30 %.

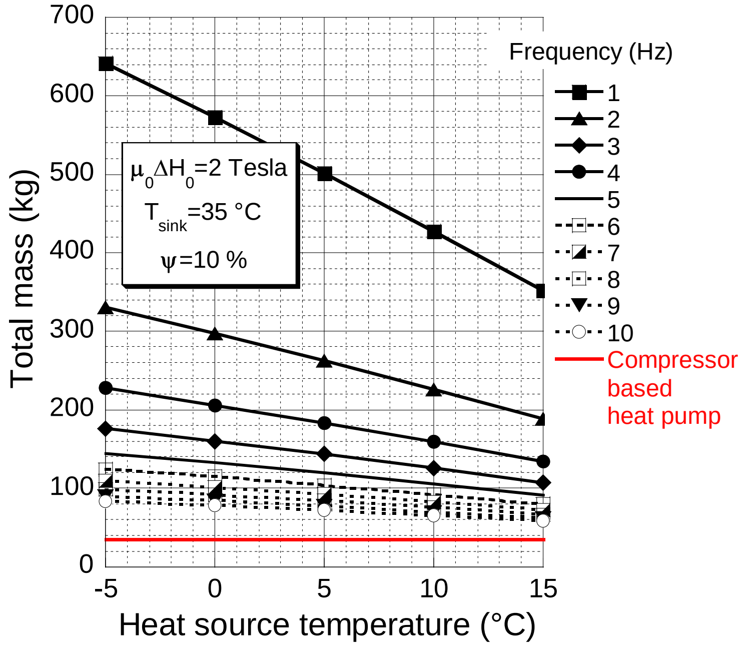

Figure 10: Total mass of a magnetic heat pump as a function of the heat source temperature and the rotation frequency for a magnetic field induction of 2 Tesla, a temperature of the sink of 35 °C and a volume packing degree of 10 %.

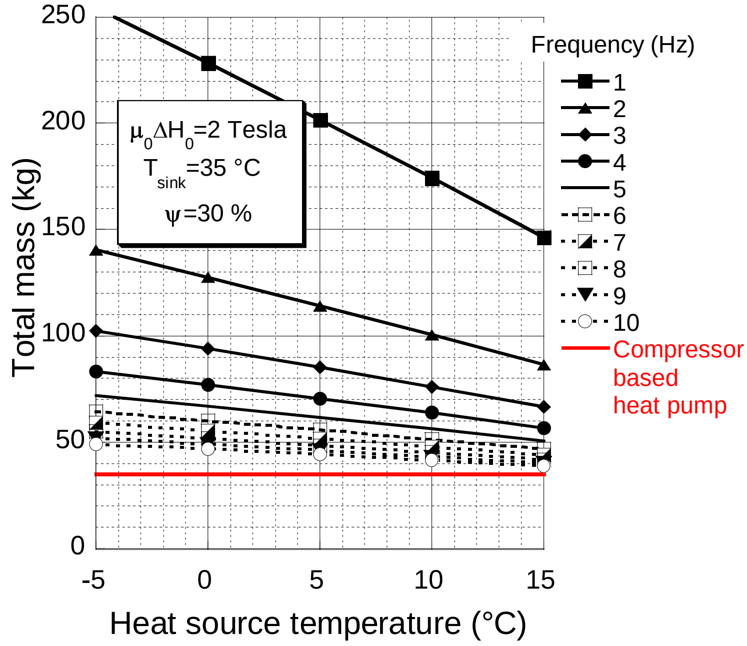

Figure 11: Total mass of a magnetic heat pump as a function of the heat source temperature and the rotation frequency for a magnetic field induction of 2 Tesla, a temperature of the sink of 35 °C and a volume packing degree of 30 %.

4 CONCLUSIONS AND OUTLOOK

In this article some aspects of magnetic heat pumps are discussed. In an introductory part numerous advantages of the magnetic heat pump are listed. Such are the environmentally benign refrigerants. The refrigerant in a magnetic heat pump is a solid body. This leads to a slow heat transport process, because it occurs by molecular diffusion. Therefore, to transfer heat in a reasonable time or to reach higher frequencies in a magnetic heat pump the transport distances must be very short. This can be obtained by porous structure heat exchangers. Such kind of heat exchangers is known for decades in air conditioning. Usually they are rotating wheel systems. Other advantages are the low pressure which occurs in magnetic heat pumps. An increase of pressure only is necessary to drive the heat transfer fluids through the filigree heat exchangers. A few hundred Pascal's are sufficient for this task. A further advantage is the high coefficient of performance, which has its origin in a close to reversible thermodynamic cycle. Furthermore, the level of noise and vibrations created by magnetic heat pumps is very low, especially when compared to conventional heat pumps operating with compressors. A very small number of moving parts makes the magnetic heat pump stable and guarantees a long operation time. Advantageous for the magnetic heat pump technology - again compared to conventional compressor technology - is that in the past decades it was less investigated and, therefore, shows a much higher potential for new improvements. It is foreseen that beside further improvements of permanent magnets especially also the magneto caloric materials will be substantially improved concerning their temperature span and heating/refrigerating capacity.

In a second part of this article, it is shown that the coefficient of performance of a magnetic heat pump may be higher than that of a conventional heat pump. This is specially the case for not too large temperature spans. Large temperature spans demand cascades or regenerative cycles. Because irreversible losses occur in a multi-stage machine also by transferring heat from one stage to the other, improved magneto caloric material will immediately increase the *COP* values of the machines under consideration.

At present the Swiss Federal Office of Energy is funding and supporting the design, building and testing of a heat pump prototype for the ground heat/floor heating application.

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