AN INTRODUCTION TO MAGNETIC REFRIGERATION

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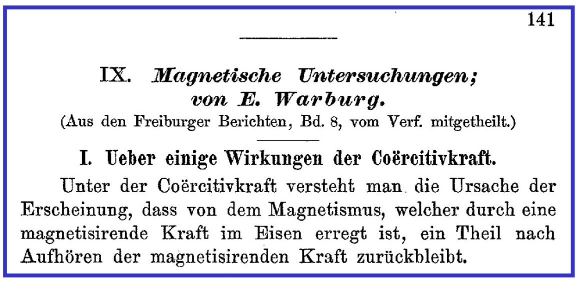
ABSTRACT

At present a great amount of research work is performed to develop new magneto caloric materials, which are the refrigerants of magnetic refrigerators. This leads to a continuous development of more performant magnetic refrigerants with higher entropy differences ΔS, higher adiabatic temperature differences ΔT_{ad} and lower hysteresis effects. Also an increased activity to design better thermo-magnetic refrigerators is occuring and numerous promising patents on machines with magneto caloric porous beds have been deposited. In a new IIR working party on magnetic refrigeration the different activity groups get into close relation, leading to welcome interactions between material scientists, physicists working on magnetism and specialists on fluid dynamics and thermodynamic machine design. All these increasing activities lead to a very high potential of magnetic refrigerators for a market penetration, which most probably at first will occur in some niche markets. After that for some main sales domains of refrigeration - e.g. as for usual commercial refrigerators - an entrance to the market also seems feasible. Other markets are in air conditioning, heat pump applications, process technics, automobile industry, medical domains, etc.

1. INTRODUCTION

Emil Gabriel Warburg (1846-1931) was a German physicist who during his career was professor of physics at the Universities of Strassburg, Freiburg and Berlin. He carried out research in the areas of kinetic theory of gases, electrical conductivity, gas discharges, ferromagnetism and photochemistry (Wikipedia, 2007). In 1881 he discovered the magneto caloric effect in an iron sample, which heated a few Millikelvins when moved into a magnetic field and cooled down again, when removed out of it (Warburg, 1881 and FIG.1).



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IX. *Magnetische Untersuchungen; von E. Warburg.*
(Aus den Freiburger Berichten, Bd. 8, vom Verf. mitgetheilt.)

I. Ueber einige Wirkungen der Coërcitivkraft.

Unter der Coërcitivkraft versteht man die Ursache der Erscheinung, dass von dem Magnetismus, welcher durch eine magnetisirende Kraft im Eisen erregt ist, ein Theil nach Aufhören der magnetisirenden Kraft zurückbleibt.

Figure 1: The title area of Emil Wartburg's scientific article is shown on the left (from Pecharsky, 2006) and a portrait photograph of the German physicist on the right (with permission by Encyclopaedia Wikipedia).

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This technology was successfully applied in low temperature physics since the 1930's to cool down samples from a few Kelvin to a few hundreds of a Kelvin above the absolute zero point (-273.15 K). But today, because of two important aspects, also applications for the refrigeration market seem feasible. The first one is the availability of magneto caloric materials with Curie temperatures at room temperature and above. Furthermore, by the "giant" magneto caloric effect (see below) new magneto caloric materials have become a factor two to three more performing.

Because this article shall only give an overview on the technology of magnetic refrigeration written for non-specialists, readers with a deeper interest are referred to some comprehensive review articles.

In magnetic heating, refrigeration and power conversion the highest number of articles are devoted to the magneto caloric material developments. Because of the large number of papers also some comprehensive books and review articles have been published (see e.g. Tishin and Spichkin, 2003, Gschneidner *et al.*, 2005, Brück, 2005, Pecharsky and Gschneidner, 2006). A mile stone - almost comparable to the discovery of the magneto caloric effect by Warburg - was in 1997 the discovery of the «giant » magneto caloric effect (Pecharsky and Gschneidner, 1997a). This publication and some following one's by these authors (Gschneidner and Pecharsky, 1997b) and also of Tegus *et al*., 2002, are responsible that since the beginning of this millenium magnetic refrigeration started to reveal a realistic potential for commercial room temperature applications at least for certain suitable 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 magnetic refrigerator designed by Brown (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 nearly two dozen of published prototypes can be found in the scientific literature. For information on the above mentioned prototypes and a table with technical data on these machines consult Gschneidner *et al*., 2005. Another comprehensive remarkable review was published by Yu *et al*., 2003. More recent demonstrators and prototypes are at present in design and building, some under temporary confidential circumstances, which therefore have not yet been presented.

2. THE BASIC PRINCIPLE

In Figure 2 the four basic processes of conventional gas compression/expansion refrigeration are shown. These are a compression of a gas, extraction of heat, expansion of the gas, and injection of heat. The two process steps extraction of heat and expansion are responsible for a cooling process in two steps. The main cooling usually occurs by the expansion of the gas.

The magnetic refrigeration process works analogous. By comparing FIG. 2 with FIG. 3 one can see that instead of compression of a gas a magneto caloric material is moved into a magnetic field and that instead of expansion it is moved out of the field. As explained in the previous chapter these processes change the temperature of the material and heat may be extracted, respectively injected just as in the conventional process.

There is a difference between the two processes. The heat rejection and injection in a gaseous refrigerant is a rather fast process, because turbulent motion transports heat very fast and efficient. Unfortunately this is not the case in the solid magneto caloric materials. Here the transport mechanism for heat is the slow molecular diffusion. Therefore, at present filigree porous structures are considered to be the best solution to overcome this problem. The small distances from center regions of the bulk material to an adjacent fluid domain, where a heat transport fluid captors the heat and transports it away from the material's surface, are ideal to make the magnetic cooling process faster.

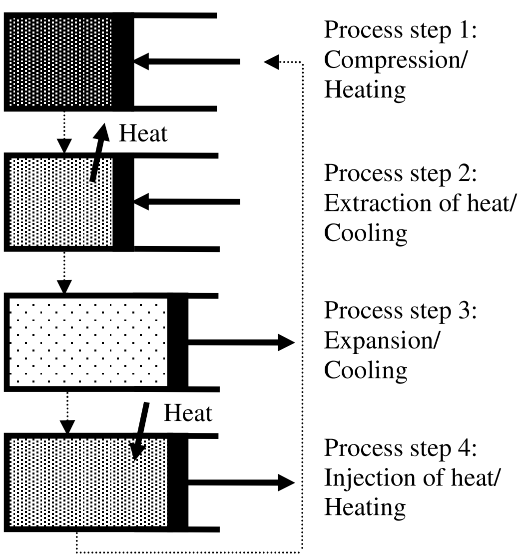


Figure 2: The conventional gas compression process is driven by continuously repeating the four different basic processes shown in this figure.

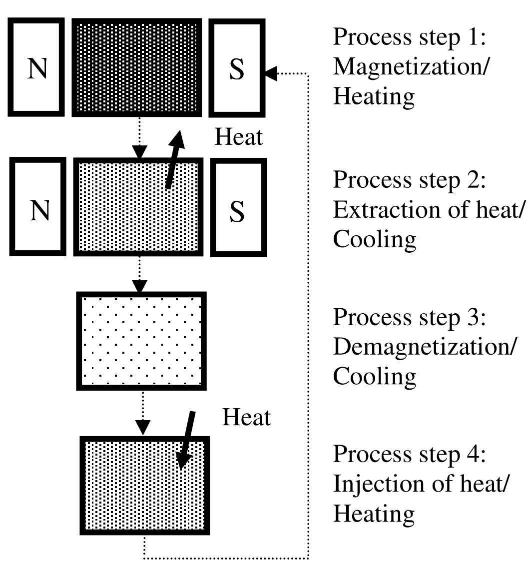


Figure 3: The magnetic refrigeration cycle works analogous. Compression is replaced by adiabatic magnetization and expansion by adiabatic demagnetization.

3. LINEAR AND ROTARY MAGNETIC REFRIGERATORS

The four basic processes of magnetic refrigeration are most simply realized by machines as described e.g. in a patent of the University of Applied Sciences of Western Switzerland (Kitanovski *et al*., 2004). It describes an axial machine (Figure 4, left), whereas a second recently deposited patent idea describes a machine of a radial type of refrigerator (Figure 4, right). There also exist prototypes with rectilinear motion.

These prototypes work like rotary heat recovery machines applied with success for decades in air conditioning. A first step is the magnetization of a porous solid magneto caloric structure in a magnetic field, followed by a simultaneous heating up of the material (see (A)). By a fluid flow this structure is cooled (also in region (A)), and after that it turns out of the magnetic field and shows a demagnetization process (B). Here the magneto caloric alloy becomes cold and is heated by a fluid flow, which preferable has the opposite direction to the first flow (also in region (B)). If the hot fluid on side (A) is used it's a heat pump application, if the cold fluid is applied then the machine is a cooler or a refrigerator.

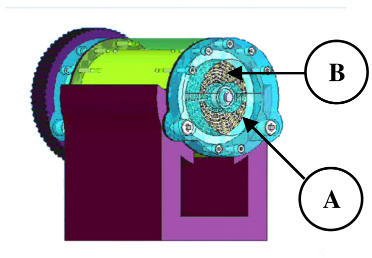
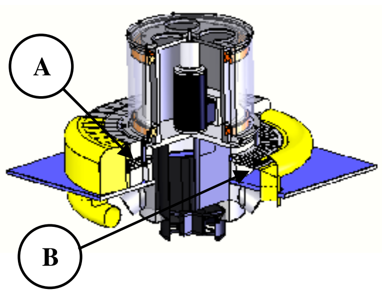


Figure 4: An axial magnetic refrigerator is shown on the left and a radial machine on the right. The first has the advantage of a constant axial fluid velocity and the second a preferable positioning of the magnets assembly (from Egolf *et al*., 2006a).



4. THE THERMODYNAMIC CYCLES

The basic thermodynamic cycle of a machine is the Brayton cycle. A machine following the Brayton cycle operates between two adiabatic and iso-magnetic field lines (see FIG. 5 on the left). The processes 1-2 and 3-4 are the magnetisation from a magnetic field $H_0^{(1)}$ to $H_0^{(2)}$, respectively the inverse demagnetisation.

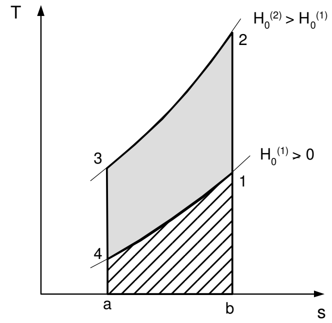
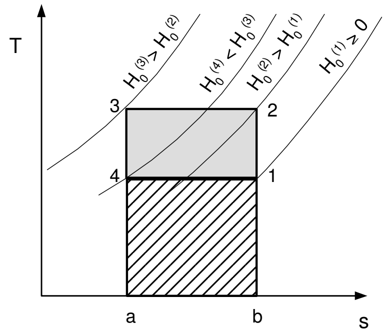


Figure 5: If a rotor in a magnetic refrigerator rotates fast, the temperature in the processes 2-3 and 4-1 of the Brayton cycle (see on the left-hand side) cannot change much. Then the Brayton cycle distorts toward the Carnot cycle. This most ideal cycle is shown on the right-hand side.



Not all the details of the thermodynamics of magnetic refrigeration can be discussed in this overview. A comprehensive review on magneto-thermal cycles was published by Kitanovski and Egolf (2006).

5. MULTI-STAGE MACHINES

To show good performance magnetic refrigerators should operate with permanent magnets. At present a "field strength" $\mu_0 H$= 2 T (Tesla) seems a realistic value for their induction. By optimized structures a field line convergence may locally even allow higher values. If we assume an induction of 2 T, best materials have an adiabatic temperature difference of 7 to 8 K, but only if their hysteresis effects are negligible. A hysteresis leads to irreversibility's, which lower the coefficient of performance of a machine. From this one concludes that applications with smaller temperature differences are more adapted to magnetic refrigeration as those with very large temperature spans. Furthermore, the ideal operation around the Curie temperature of the magneto caloric material favors applications with rather stable operation temperature levels. Because of the first mentioned reason cascade machines (see FIG. 6) or machines with regeneration must be envisaged (more on this subject is found in Kitanovski and Egolf, 2006).

To design a multi-stage machine the following design drawing - showing a two stage refrigerator, respectively heat pump - may be very helpful (see FIG. 7). For more stages the drawing may easily be adapted.

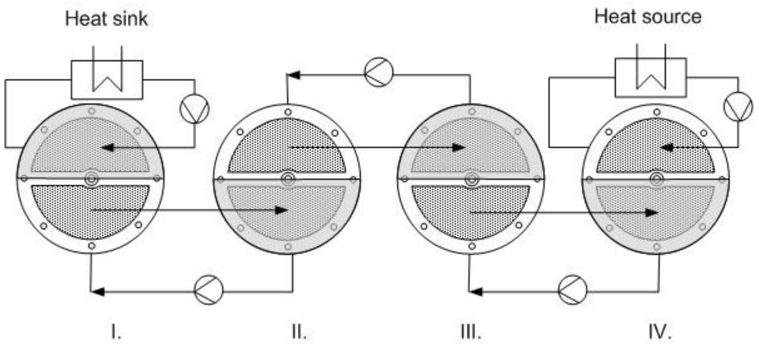


Figure 6: The connections between the stages have to be continuously guaranteed. For this purpose, in the case of four machines, one needs three pumps. Furthermore, a pump each is necessary at the heat sink and heat source. Because of leakages the fluids should be the same in all hydraulic parts.

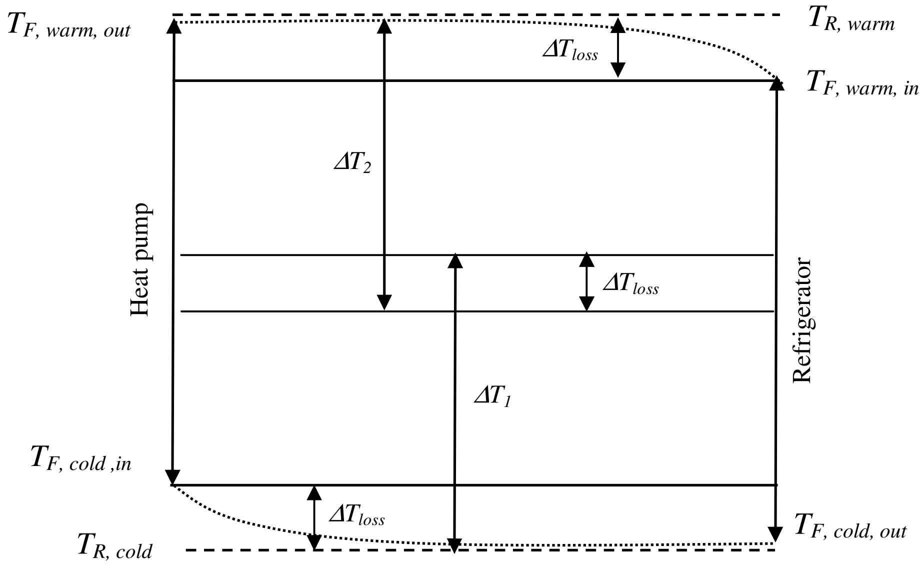


Figure 7: The most important temperatures of a two-stage machine are shown in this figure. The two processes overlap a little. Only then heat may be transferred from the higher to the lower stage. The diagram is presented for a machine with a high thermal inertia of the rotor and a counter flow of the fluids (from Egolf *et al.,* 2006b).

6. ESTIMATE OF THE COEFFICIENT OF PERFORMANCE

In the case that the proposed magnetic refrigerator cannot achieve the required temperature difference between the temperatures of the heat source and the heat sink in a single stage, a cascade or a multi-stage regenerative cycle has to be performed. The number of stages depends on the strenght of the magnetic field change, on the heat transfer efficiency, etc. In order to transfer heat from one stage to the other a temperature difference must exist and this leads to irreversible losses. To determine the final temperature difference, an assumption of overlapping cycles of different stages takes into account the heat transfer rate between them as well as the heat transfer in the heat exchangers at the source and sink. A magnetic refrigerator thermodynamic cycle may reach at least 80 % of Carnot efficiency. But this is only valid for a single stage refrigerator with magneto caloric material with a small hysteresis. One has to be aware that this thermodynamic coefficient of performance COP_{therm} does not yet contain all losses of a magnetic refrigerator. Further irreversibility effects are:

1) The "energy loss" by friction between the cylindrical wheel and its housing, $P_{friction}$
2) Energy losses by a non-ideal motor turning the wheel with efficiency η_{mot}
3) Energy loss of the two counter current flows in the porous structure, P_{matrix}
4) Energy losses by the pumps with a hydraulic and electric efficiency, P_{pumps}
5) Energy loss of fluid flows in connecting tubes, P_{tubes}.

To minimize all these losses the rotation frequency should not be too high. Also the fluid velocities must be rather low, because otherwise the power losses given by a flow through the porous structures decreases the final *COP* value remarkably. The losses by pumps and fluid flows in connecting tubes are almost negligible. For numerous applications higher COP values are expected than those of analogous conventional refrigeration technologies.

7. MAGNETIC FIELD CALCULATIONS

More sophisticated investigations call for theoretical models and numerical simulations of the magnetic and thermodynamic behavior of the operation of such machines. Even more appropriate is a coupled thermo-magnetic treatment of the problems. Then optimization calculations for a defined prototype show, which parameters give best results. Even a simplified approach leads to a 16-dim. space for an optimization calculus (Egolf *et al*., 2006b). In FIG. 8 an example of a magnetic field calculation is shown.

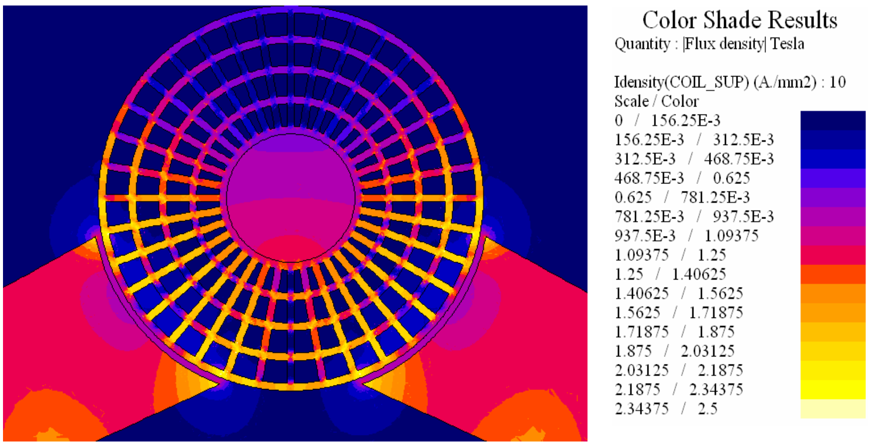


Figure 8: Magnetic scalar field shown by a color shade presentation. The results were calculated by applying the finite element method. The colors show different inductions $\mu_0 H$. The lower half cylinder shows high field intensities and the higher half low field intensities.

8. THERMODYNAMIC CALCULATIONS

Nine different temperature fields in the rotary porous heat exchanger were calculated by a model presented in Kitanovski *et. al.*, 2005 and shown in FIG. 9. The cylindrical wheel is mapped on a rectangle. One can see the cold lower and the warm higher side separated by the adiabatic temperature differences.

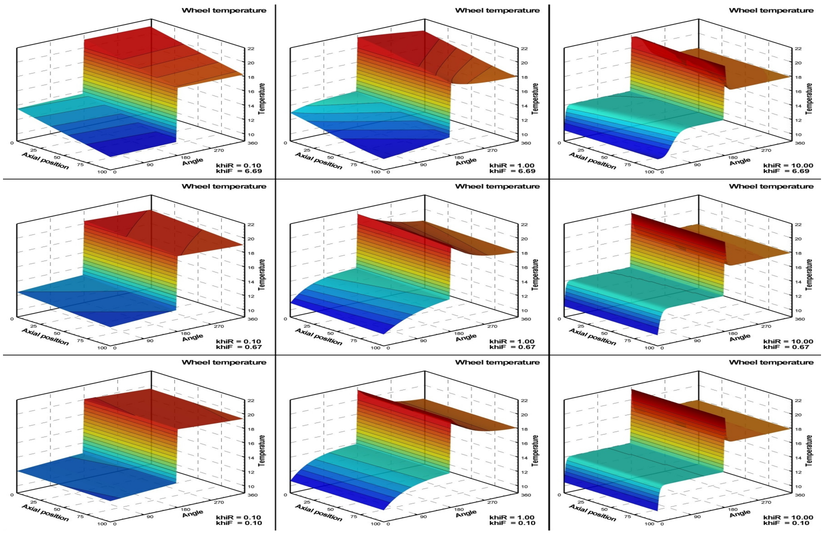


Figure 9: The most simple case is the one in the left lowest corner. Here the temperature fields are constant in azimuth and axial direction. The axial direction is the one going back to the left, where the azimuth direction is leading to the back on the right. The parameters of these calculations are found in Egolf *et al.,* 2006b. The simpler cases are also described by analytical solutions.

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