

Application of Magnetocaloric Heat Pumps in Mobile Air-Conditioning

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ABSTRACT

Air-conditioning (AC) is an important sub-system in electric vehicles (EVs). AC is responsible for the highest energy consumption among all the auxiliary systems. As the energy is delivered by the batteries, the power consumption for air-conditioning can imply a significant reduction of the vehicle autonomy.

Given the actual state of the art and the temperature and power requirements, electrically driven compressors are the most feasible solution. However, vapour-compression systems are reaching their maximum efficiency. Using innovative technologies can improve the performance of standard systems and hereby increase the vehicle autonomy.

This paper presents the first steps in the design of a magnetocaloric air-conditioner for an electric minibus. The system will include two reversible magnetocaloric heat pumps, one in the front part of a minibus and one on the rear. The heat rejection system of the power electronics will be coupled to the air-conditioning system.

In order to assist the design of the system, a dynamic model has been developed for the cabin, the hydraulic loops and heat exchangers, and the magnetocaloric units. An integrated design of the complete system is necessary, as it will work under dynamic conditions which depend on the thermal load in the cabin. In this paper, the operation conditions of the magnetocaloric units are presented and the design of the magnetocaloric air-conditioner is discussed.

This work has been developed under the frame of the European Project ICE which aims to develop an innovative mobile air-conditioning system for EVs based on a magnetocaloric heat pump.

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INTRODUCTION

Current AC systems are based on the compression of refrigerants. The chillers are used to remove heat from a cold source (useful cooling power) and transfer it to a warmer sink. The associated energy transfer is performed by a refrigerant fluid which undergoes a continuous thermodynamic cycle which consists of a succession of phase changes (vapour and liquid states). However, these refrigerant gases and the associated gas leakages have a

noxious effect on the atmosphere, namely climatic warming, ozonosphere degradation and pollution.

Currently, the AC system in vehicles presents the highest power consumption of the auxiliary components, especially in electric cars, in which there is no waste heat available in the engine. If a state-of-art efficient vapour-compression heat pump is used, the autonomy of the vehicle can be shortened by 8% in winter and by 4% in summer [1-2]. These numbers are not expected to be significantly improved by using conventional technologies. Hereby, the application of

breakthrough technologies in this field could have a major impact on the vehicle range.

A new efficient and clean cooling and heating technology that has great potential to replace conventional vapour compression systems is **magnetic refrigeration**.

The magnetocaloric heat pump (MCHP) technology has been widely investigated in the past years [3]. Currently, this technology is in pre-industrialisation phase, and in several years it can be expected to find such technologies in the market, for instance in domestic refrigeration applications, where leader companies are investing money and resources to finalise the technology development [4]. It is also worthwhile to highlight that the IIR (International Institute for Refrigeration) organises a Working Party on Magnetic Refrigeration [5], a scientific society gathering scientists worldwide, that promotes the magnetic refrigeration as a viable energy efficient and environmentally friendly cooling technology.

The main features of MCHPs are:

- No refrigerant, therefore neither GHG emissions, nor leakages.
- High efficiency, theoretically the performance of vapour-compression systems can double the one of vapor-compression chillers.
- Operation in reverse mode as a heat pump with high efficiency also at low ambient temperature.
- Compact packaging.
- Electrically driven.
- Low working pressures (< 2 bars).
- Does not demand any specific training for the assemblers.
- Less noise than current compressors.

Taking into account these considerations, the European commission decided to support magnetic refrigeration within the European Project ICE [6] (2010-2014), which proposes to develop an efficient air conditioning and heating system based on MCHP technology and a new system architecture to fulfill the thermal comfort and energy requirements of fully electric vehicles (FEVs). Using a MCHP with a higher EER and COP than a conventional heat pump can reduce the energy consumption of the air-conditioning system auxiliaries and hereby increase the FEV autonomy. This fact will promote the diffusion of the electric and hybrid vehicles and also a reduction on greenhouse gasses emissions.

Within the ICE project, an industrial prototype of a magnetocaloric heat pump will be developed, thus realizing a real new generation of heat pump equipment able to replace the vapour-compression system not only in FEVs but also in all the other vehicle or even stationary applications.

Nevertheless, before integrating MCHP pumps in practical installations, a significant progress is still required to design and optimize such systems. The design of a MCHP

is determined, among other variables, by the working temperatures. Hence, it is essential to size the system properly and predict the effect of variable conditions on the external loops of the regenerator.

In this paper, the operating principle of MCHP is firstly described. Next, the first steps in the design of the magnetocaloric air-conditioner for the demonstrator electric minibus of the ICE project are presented. They include sizing the system taking into account its overall performance under transient conditions. Finally, the design of the MCHP is discussed and the latest results in its development are presented.

MAGNETIC REFRIGERATION

The fundamental principal of magnetic cooling is the magnetocaloric effect (MCE) and was discovered by E. Warburg in the iron in 1881. Along the 20th century, the MCE was applied in very low temperature applications. In 1976, Brown published the first study that showed that it was possible to use the MCE to produce a substantial cooling effect near room temperature [7]. The major breakthrough, however, occurred in 1997 when the Ames Laboratory/Astronautics proof-of-principle refrigerator showed that magnetic refrigeration was competitive with conventional gas compression cooling. Since then, many experimental prototypes of magnetic refrigerators at room temperature have been developed [3] with different configurations and operating conditions.

The MCE is an intrinsic property of magnetic materials which results in a reversible temperature of the material when subjected to a magnetic field. This phenomenon is maximal in the vicinity of the ordering temperature of the magnetic material (the Curie or the Néel temperature). Generally all magnetic materials subjected to sufficiently high magnetic fields show a MCE, although the intensity of the effect depends on the properties of each material. During the last decade much effort has been devoted to find new materials and alloys with a strong MCE at room temperature. For instance, gadolinium (Gd) is a well-known magnetocaloric material.

Figure 1 explains the MCE with the two sequences of a direct magnetocaloric cycle. A magnetic assembly composed of two permanent magnets generates between their poles (N and S) an intense constant magnetic field H . A plate of MCM material is placed alternatively between the magnetic poles, inside of the magnetic field ($H > 1$ Tesla) or outside of the magnetic field ($H = 0$ Tesla). Due to the change in magnetic entropy, the material heats up when it is magnetized and cools down when it is demagnetized.

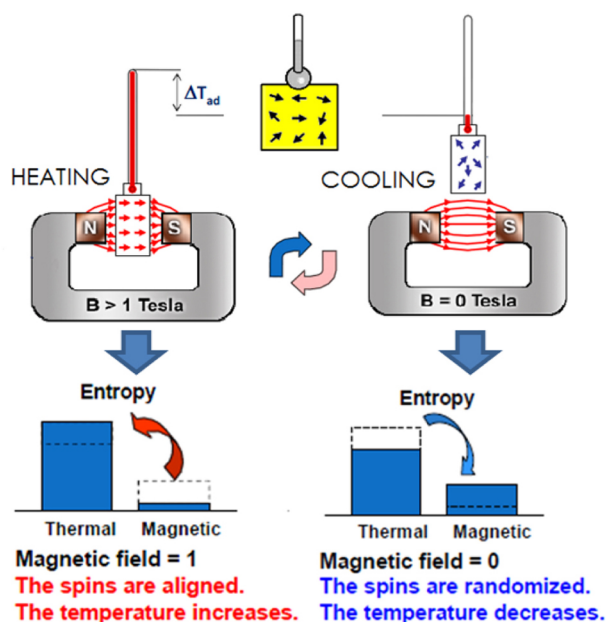


Figure 1. Magnetocaloric effect [8]

Under magnetic fields that can be generated with permanent magnets (1 to 2 T), the MCE produces a temperature span between the cold source and heat sink of only a few Kelvin. A larger temperature span is required for applying this phenomenon to air conditioning systems. In order to achieve such spans, the MCE is integrated within a thermodynamic cycle. The best known is the active magnetic regenerative (AMR), which has been represented schematically in Figure 2. In this cycle, during the magnetization step the heat generated by the MCE material is rejected to the hot source. During the demagnetization step heat is provided to the MCE material from the cold source. A coolant liquid (water + antifreeze) manages the heat transfer between the MCHP and the thermal sources. The magnetocaloric material (MCM) acts hereby as a regenerator, recovering and storing thermal energy of the fluid when it flows from the hot source to the cold source, and then restoring it at the next stage.

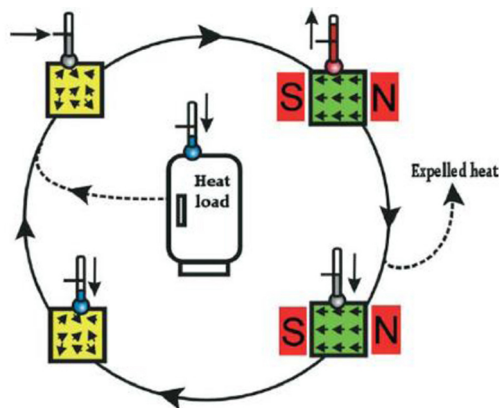


Figure 2. AMR cycle [4]

In order to produce the thermal power continuously, this cycle has to be implemented in a rotary device, for instance like the one presented by Vasile and Muller [9] and shown in Figure 3. In this prototype, each piece of the magnetic material (insert) is a micro-channel heat exchanger. An electric motor moves the permanent magnets and a system of valves controls the fluid flows to the hot and cold circuits, ensuring that each insert performs a different stage of the cycle at a given time.

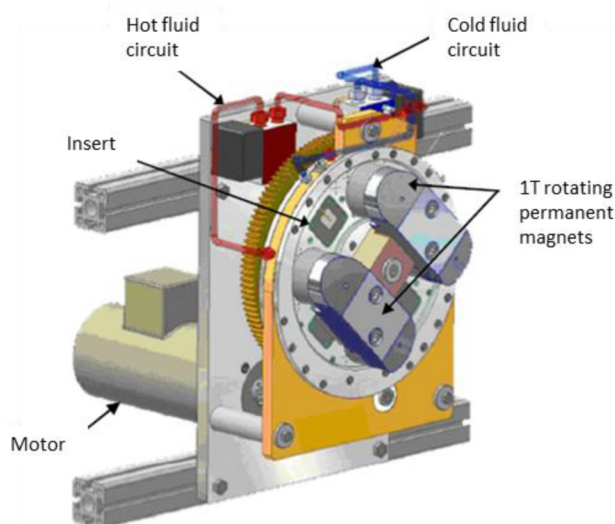


Figure 3. Magnetocaloric heat pump prototype [9]

The design of a magnetocaloric refrigeration system is an interdisciplinary subject that requires the knowledge of the MCM properties, of the mechanical configuration and of the design of the permanent magnet flux source. A comprehensive discussion on these different subjects and the connection among them can be found in literature [10].

From an external system point of view, considering the MCHP as a black box, it can be integrated in vehicles like a conventional water-to-water heat pump, electrically or mechanically driven. Figure 4 is a scheme of the integration of a MCHP in a mobile air conditioning (MAC) system.

THE ICE PROJECT: A MAGNETOCALORIC AIR CONDITIONING SYSTEM

The main objective of the ICE project [6] is the development of an innovative efficient air conditioning system for electric vehicles based on magnetocaloric refrigeration and on a new thermal power distribution and microclimate control strategies. The system will be able to assure on-board thermal comfort while improving the thermal management and the overall vehicle energy efficiency, and all this at a sustainable cost.