New concept for magnetocaloric heat pumps based on thermal diodes and latent heat transfer

K. Bartholomé*, T. Hess, A. Mahlke, J. König
Fraunhofer-Institute for Physical Measurement Techniques IPM
(Heidenhofstraße 8, 79110 Freiburg, Germany)
*Corresponding author. E-mail: kilian.bartholome@ipm.fraunhofer.de

ABSTRACT

Since the beginning of the last decade, several dozens of magnetocaloric heat pump systems have been built by different groups. Basically all of these systems are based on the Active Magnetic Regenerator (AMR) concept, where a heat transfer fluid is actively pumped through a bed of magnetocaloric material in order to transfer thermal energy to hot and cold side heat exchangers. Hereby several powerful systems were built, generating large temperature spans of more than 50 K while others provided large cooling capacities of several kW. However, up to now no system has been built which provides large temperature span and cooling capacity while having a coefficient-of-performance (COP) better than standard compressor-based cooling systems [1].

In this work a new concept and first experimental data of a magnetocaloric heat pump will be presented. In this concept, the heat transfer is realized by the combination of magnetocaloric material with thermal diodes which are based on latent heat transfer. Similar to thermosyphons, thermal energy is efficiently transported by condensation and evaporation processes leading to heat transfer rates which are several orders of magnitude larger than in conventional systems. At the same time, no additional pumps are required for transporting the heat exchange fluids, enabling systems which large temperature spans and competitive COPs.

1. INTRODUCTION

The efficient transfer of heat between the magnetocaloric material and the heat exchanger is a decisive factor in the overall efficiency of a cooling system based on magnetocalorics. Since the discovery of the giant magnetocaloric effect by Pecharsky and Gschneidner in 1997 [2], many different magnetocaloric prototype systems for room temperature cooling have been built, demonstrating the capability of this technology to generate large temperature differences [3] as well as large cooling capacities [4]. Typically all of these prototypes are based on the concept of “active magnetic regeneration” (AMR), in which a liquid is pumped through the magnetocaloric material to transfer heat. The main challenges in the AMR-approach are restricted heat transfer coefficients, large pressure drops within the regenerator associated with internal friction of the liquid, resulting in low cycle frequency as well as large amounts of pumping energy required. Current research activities on the AMR-concept are therefore focused on the optimization of the magnetocaloric heat exchanger structures in order to minimize friction as well as pressure losses in the regenerator and thereby maximize the system efficiency. Nevertheless, up until today no magnetocaloric system has demonstrated the large potential of magnetocaloric cooling in terms of maximum system efficiency.

In this work an alternative system design based on thermal diodes in combination with latent heat transport using evaporation and condensation is presented. Hereby, the transport of thermal energy is in analogy to the heat transfer in heat pipes [5]. By evaporating a fluid such as water or ethanol at the magnetocaloric material and subsequently condensing it at the heat sink, it is possible to achieve heat transfer coefficients that are several orders of magnitude higher than those achieved in traditional heat transfer by means of thermal conduction or convection.

2. CONCEPT

2.1. Heat Pipes for Efficient Thermal Transport

The concept of efficient heat transfer using latent heat of evaporation and condensation is realized in heat pipes and thermosyphon since almost 180 years. Thereby, a fluid is contained in a hermetically sealed tube usually made of copper, in which all non-condensable gases have been removed. The fluid is present in the liquid as well as the gaseous phase; the equilibrium between the two phases adjusts itself according to the vapor pressure and the temperature. Inside this tube, a small temperature increase, e.g. induced by the magnetocaloric material, leads to an evaporation of the liquid and an increase in vapor pressure. This in turn results in a condensation of fluid on the condenser parts inside the heat pipe. Heat is passively transported from the magnetocaloric material into the condenser section. The heat transfer coefficient of such an evaporation process reaches values of up to 100 kW / (m^2 K), which are orders of magnitude larger than for conventional heat transfer processes, in which the heat is transferred by actively pumping a fluid.

Depending on the design of the heat pipe, efficient thermal diodes can be realized: The simplest are gravitational-based thermosyphons, where the fluid is fed back from the condenser to the evaporator by gravitational force. Reflux of the fluid does not occur against gravity, and therefore in this direction the heat transfer is blocked. Alternative approaches or the realization of thermal diodes are the use of valves or superhydrophobic surface treatments [6] for producing highly efficient thermal diodes.

2.2. System Design

The central component of the magnetocaloric cooling unit system is shown in Figure 1. It consists of individual segments (1) with magnetocaloric material, which are connected in series and are cyclically heated and cooled by rotation of a magnetic system (2). By designing these magnetocaloric segments as thermal diodes, the heat generated in these segments is “pushed” in one direction, resulting in cooling one side while heating up the other side.

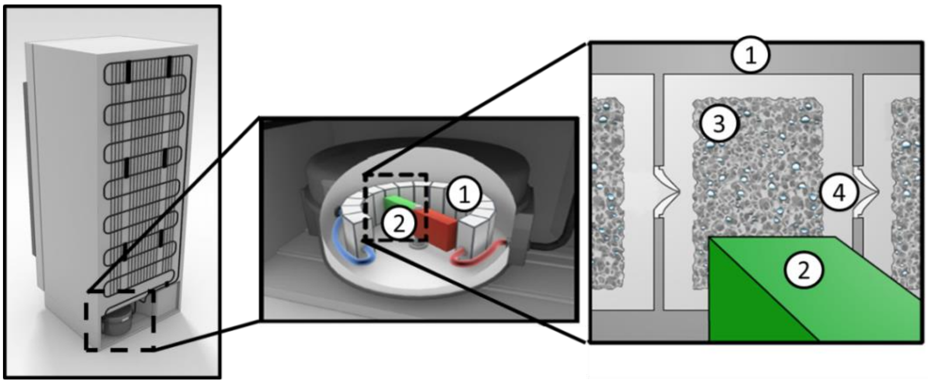

Figure 1: Left: Magnetocaloric cooling unit replaces compressor system in refrigerator.
Center: Magnetocaloric cooling unit consisting of magnetocaloric segments (1) and magnetic system (2).
Right: Magnetocaloric segment consisting of magnetocaloric heat exchanger (3) and pressure relief valve (4).

In each of the segments is magnetocaloric material, designed as a heat exchanger unit (3). The segments are separated by pressure relief valves (4). The valves are passively opened and closed by the pressure changes which are induced by temperature changes inside the individual segments due to the magnetization and demagnetization process. Thus, a directed flow of the gaseous fluid is ensured, and the magnetocaloric segments act as thermal diodes (Figure 2).

Each segment creates a temperature difference of a few Kelvin. In order to achieve a large temperature lift of some 10 K, several of these units must be connected in series. A parallel connection of the same units results in a higher heat pumping capacity.

The main advantages of this concept are the following:

- **Increase in systems efficiency:** For the transfer of the thermal energy from the magnetocaloric material to the heat exchanger, no additional pumps and therefore no additional energy is required, which increases the systems efficiency.
- **Larger cooling power**: Heat transfer based on latent heat is several orders of magnitude larger than heat transfer using sensible heat by pumping of fluids. This opens the possibility to realize magnetocaloric systems being capable of system frequencies > 10 Hz, which results in an increase of cooling power.
- **Reduced system costs**: Due to an increase in the system frequency, the amount of magnetic as well as magnetocaloric material required to produce a specific cooling power can be significantly reduced, which in turn reduces the perspective costs of a magnetocaloric cooling system.

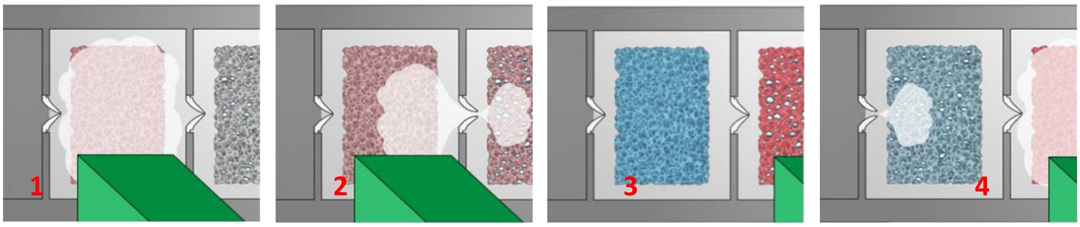

Figure 2: Concept of thermal diode
Phase 1: Magnetic field applied to magnetocaloric heat exchanger: 1. The magnetic field is applied. Thereby, the magnetocaloric material is heated and liquid is evaporated. 2. The pressure increases due to the evaporation of the liquid. The valve to the right opens, fluid in the gas phase transmits latent heat to the next segment.
Phase 2: Magnetic field is turned off by rotation of the magnet: 3.The magnetocaloric material cools down due to the decrease in the magnetic field strength. 4. Fluid from the gas phase condensates on the magnetocaloric material, the vapor pressure decreases below the value in the foregoing segment. Now the valve to the left opens, gaseous fluid from the left enters and heat is absorbed from the foregoing segment.

3. EXPERIMENTAL RESULTS

In order to demonstrate the latent heat transfer from magnetocaloric material to a condenser, a glass heat pipe containing granular magnetocaloric material (Calorivac-H from Vacuumschmelze GmbH, Curie-Temperature at 21.2 °C) as evaporator and degassed ethanol as fluid was built. A thermocouple of type K was used as a condenser, capable of measuring the temperature T_{Cond}. The temperature of the magnetocaloric material T_{MC} was measured using a second type-K-thermocouple. The thermocouples were inserted into the glass tube via a butyl-rubber-plug, which hermetically sealed the glass tube. The glass tube was then attached to a vacuum pump by using a vacuum cannula in order to remove all non-condensable gases from the tube.

The glass heat way was placed between the two poles of an electromagnet. During change of the magnetic field strength, the temperature changes of the condenser and the magnetocaloric materials were monitored using a Keithley 2700.

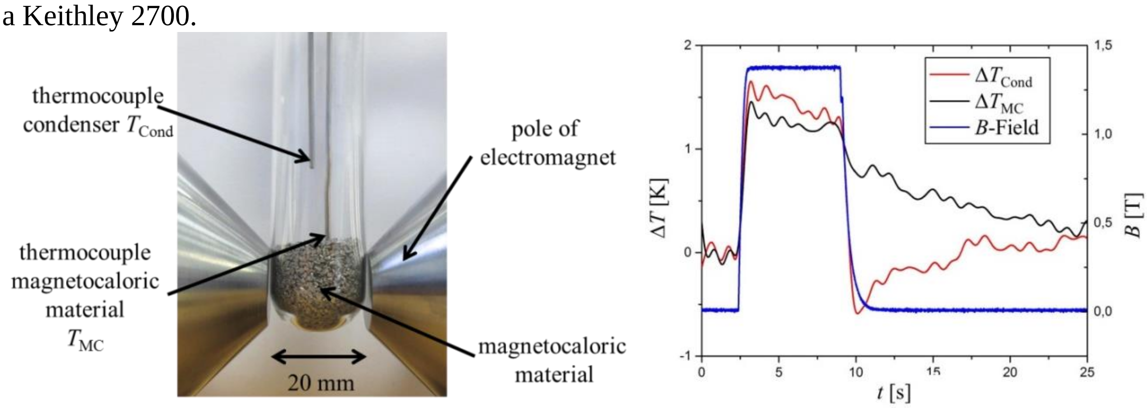

Figure 3: Experimental data on latent heat transfer from magnetocaloric material.
Left: Glass heat pipe prepared with magnetocaloric material, thermocouples for measuring the temperature of the magnetocaloric material (T_{MC}) and condenser (T_{Cond}), placed between the poles of an electromagnet.
Right: Generated temperature difference of magnetocaloric material and condenser as well as strength of B-field plotted versus time.

When the magnetic field is turned on, the temperature rise of the condenser sums up to > 90% of the temperature rise of the magnetocaloric material, and the time shift between both curves is smaller than 0.1 s. This shows that heat transfer by means of latent heat is capable of transferring heat from the magnetocaloric material to the condenser fast and efficiently.

When the magnetic field is turned off however, the cooling of the condenser is much smaller than the cooling of the magnetocaloric material. Apparently, the thermal coupling between magnetocaloric material and condenser is now reduced, which presumably originates from a reduced wetting of the condenser with the fluid.

4. CONCLUSIONS

In this work a new concept for magnetocaloric cooling systems based on latent heat transfer and thermal diodes has been presented. The experimental data indicate that efficient and fast thermal transport using this concept is viable. For the successful implementation of this concept into highly efficient magnetocaloric cooling systems, it is crucial to enhance the diodicity of the thermal diodes. Therefore, two concepts will be investigated in more detail: The first concept is the integration of pressure relief valves between different magnetocaloric segments in order to guarantee a unidirectional thermal transport. The second concept is the manipulation of the surface wetting of the fluid on magnetocaloric material and condenser by superhydrophilic and superhydrophobic surface treatment [7]. Hereby the effect of a reduced thermal transport in reverse direction of the thermal diode can greatly be reduced, resulting in diodicities of more than 100 [6,7]. In combination with a matched magnetic system, a magnetocaloric cooling system with greatly enhanced COP is feasible.

Besides the application to magnetocaloric materials, this concept of latent heat transport is also possible for electrocaloric and mechanocaloric materials.

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REFERENCES

[1] A. Kitanovski, J. Tušek, U. Tomc, U. Plaznik, M. Ozbolt, and A. Poredoš, *Magnetocaloric Energy Conversion* 2015).
[2] V. K. Pecharsky and K. A. Gschneidner, Physical Review Letters **78**, 4494 (1997).
[3] D. Arnold, A. Tura, and A. Rowe, International Journal of Refrigeration **34**, 178 (2011).
[4] S. Jacobs, J. Auringer, A. Boeder, J. Chell, L. Komorowski, J. Leonard, S. Russek, and C. Zimm, International Journal of Refrigeration **37**, 84 (2014).
[5] A. Faghri, Journal of Heat Transfer-Transactions of the Asme **134**, 123001 (2012).
[6] J. B. Boreyko, Y. Zhao, and C.-H. Chen, Applied Physics Letters **99**, 234105 (2011).
[7] T. Hess, A. Mahlke, O. Herm, and K. Bartholomé, in *International Conference on Magnetic Refrigeration at Room Temperature, Thermag VII,* Turin, (2016).