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Preliminary Investigation on a Rotary Magnetocaloric Refrigerator Prototype

F. Albertini[a], C. Bennati[a], M. Bianchi[b], L. Branchini [b], F. Cugini[c], A. De Pascale[b], S. Fabbrici[d], F. Melino[b], S. Ottaviano[e], A. Peretto[b], J. Rosati[f],*, M. Solzi[c]

[a] IMEM-CNR, Parco Area delle Scienze 37/A, 43124 Parma, Italy
[b] DIN - Alma Mater Studiorum University of Bologna – Viale del Risorgimento 2 - 40136 Bologna, Italy
[c] DiFeST - Università di Parma – Parco Area delle Scienze 7/A 43124 Parma, Italy
[d] MIST E-R Laboratory, via Gobetti 101, 40129 Bologna, Italy
[e] Università di Ferrara – ENDIF, via Saragat 1 - 44122 Ferrara, Italy
[f] CIRI-EA - Alma Mater Studiorum University of Bologna – Via Angherà 22 - 47900 Rimini, Italy

Abstract

Environmental legislations are currently imposing important restrictions to regulate the use of refrigerant fluids in order to reduce the greenhouse gases emissions and global warming potential. To overcome these issues, a valid alternative to replace conventional refrigeration systems can be represented by magnetic refrigeration. Since magnetic refrigeration is based on the magnetocaloric effect it represents an environmental friendly technology that avoids the use of Chlorinated refrigerants. In this paper a preliminary analysis of a novel magnetocaloric refrigerator is presented. The magnetocaloric refrigeration prototype uses Gadolinium as refrigerant and water as heat exchange medium, and relies on permanent magnets as magnetic field source. The device operates according to the active regenerative principle with a rotary movement.
A detailed description of the main components included in the design of the prototype device is presented along with a schematic representation of the hydraulic circuit. Focusing on the regenerators beds, some simulations have been carried out to quantify the heat energy fluxes between water and gadolinium. The results of the simulations show a decrease on gadolinium temperature distribution cycle by cycle highlighting the actual effect of the regeneration.

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Keywords: refrigeration, gadolinium, magnetic refrigeration, simulation, prototype

* Corresponding author. Tel.: +39-051-2093320; fax: +39-051-2093320.
E-mail address: jessica.rosati3@unibo.it

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1. Introduction

The refrigeration industry plays a major and increasing role in today's global economy. Refrigeration represents up to 15% of the global energy consumption [1]. Indeed, about one sixth of the energy demand is satisfied by compression refrigeration systems, working with refrigerant fluids – in most cases Hydrofluorocarbons (HFC) – characterized by a significant Global Warming Potential (GWP) index. Specific environmental legislations, such as the Kyoto Protocol (first stipulate in 1997), impose restrictive objectives, for members country, to regulate the use of refrigerant fluids in order to reduce the greenhouse gases emissions and global warming potential. To overcome these issues, a valid alternative can be represented by magnetic refrigeration [2] that allows to replace conventional refrigeration systems with an environmental friendly technology avoiding the use of refrigerant fluids.

Magnetic refrigeration is based on magnetocaloric effect [3], discovered by Warburg in 1881 [4], who observed that introducing an iron sample under a magnetic field, a temperature increase occurred. Conversely, removing the sample from the magnetic field, its temperature decreases [5, 6]. The first study of magneto-thermal effect near room temperature using a ferromagnetic material date back to 1976 by Brown et al. [7]. In 1982, the first Active Magnetic Regenerator (AMR) [8] has been shown in order to provide efficient refrigeration over relatively large temperature ranges [9, 10, 11].

Based on this fundamentals, a lot of prototypes have been developed until now [12, 13, 14, 15] and noteworthy results have been reached in terms of temperature span, energetic performances and cooling power. [16, 17]

The research has been progressively expanded towards an in-depth analysis of the more suitable magnetic materials [18, 19].

In this context, this study presents the preliminary investigations carried out on a novel refrigeration prototype based on magnetocaloric effect. More in details, Section 2 describes the prototype device under investigation: main components are illustrated along with a schematic representation of the hydraulic circuit. Section 3 presents the main hypothesis assumed for simulation purpose along with results discussion. Preliminary conclusions are summarized in Section 4.

Nomenclature

AMR	Active Magnetic Regenerator
GWP	Global Warming Potential
HE	Heat exchanger
HFC	Hydrofluorocarbons
P1	Pump
R	Regenerative bed

2. Prototype development

The magnetocaloric refrigeration prototype uses Gadolinium as refrigerant and water as heat exchange medium, and relies on permanent magnets as magnetic field source: the device – shown in Fig. 1. – operates according to the active regenerative principle with a rotary movement. It is composed by a stator, consisting of four Active Magnetic Regenerators (AMR) beds (R1, R2, R3 and R4 in Fig. 1) and a rotor consisting of two permanent magnets assemblies.

The magnetic system is characterized by two coupled composite magnets, based on the Halbach array configuration, fixed on a FeCo structure arranged on two rotating parallel disk. The rotor is coupled with a drive system, consisting on an AC asynchronous gear-motor, rotating at constant speed (less than or equals to 1 rpm). As can be noted from Fig. 1a., the two couples of regenerative beds, lying at 180°, are magnetized and demagnetized at the same time by the couple of magnets, changing their magnetization state every quarter of revolution.

Each regenerator, as shown in Fig. 2., has been designed in order to obtain a regenerative effect run by run, i.e. the increase of the temperature span due to the inversion of the water path from the magnetization phase to the demagnetization phase.

The regenerator has been characterized by two sections divided by a polymeric wall; also two diffuser duct have been placed to facilitate the inlet and the outlet of the water.

Each AMR has been designed considering a maximum amount of gadolinium equals to 0.1 kg, equally distributed in parallel polymeric plates spaced by polymeric inserts as shown in Fig. 2b. and in Fig. 3.

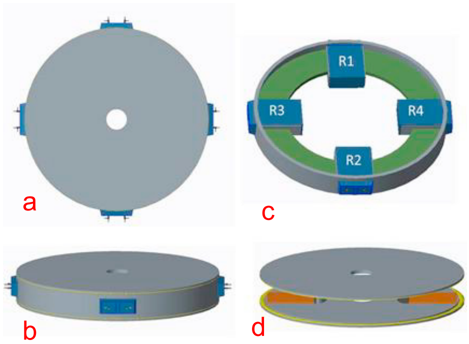

Fig. 1. (a) and (b)Prototype assembly, (c) regenerators layer, (d) permanent magnets layer

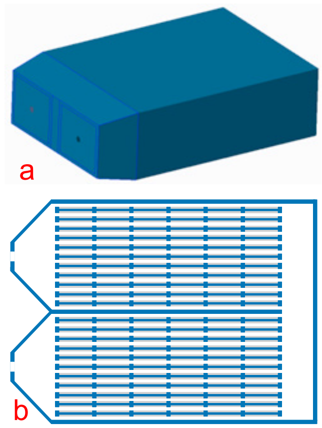

Fig. 2. (a) Regenerative bed; (b) regenerator section

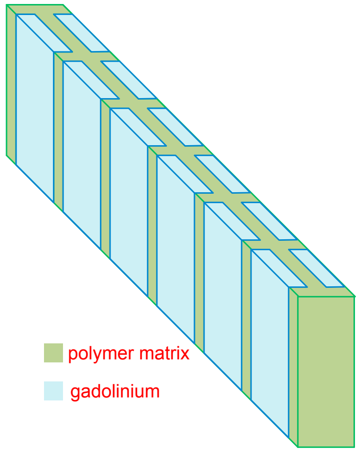

Fig. 3. Single parallel plates composed by gadolinium pieces

The hydraulic system has been represented in Fig.4. Demineralised water has been assumed as refrigerant fluid. A pump (P1 in Fig. 4) push the cold fluid to the magnetized regenerators (red block in Fig. 4) to remove the heat generated during the magnetization and discharge it into the environment through a heat exchanger (HE_{hot} in Fig. 4). Then the refrigerant fluid is sent to the demagnetized regenerators (blue block in Fig. 4) in which a new heat exchange occurs and then the water is sent to the cold room, represented as a heat exchanger (HE_{cold} in Fig. 4) to obtain the refrigeration effect. Thanks to a series of valves, at each quarter revolution the refrigerant fluid is pushed first into the magnetized regenerators and then into the demagnetized ones, according to the regenerative effect aforementioned. The realized scheme allows to use only one pump for the fluid flow inversion across the AMR.

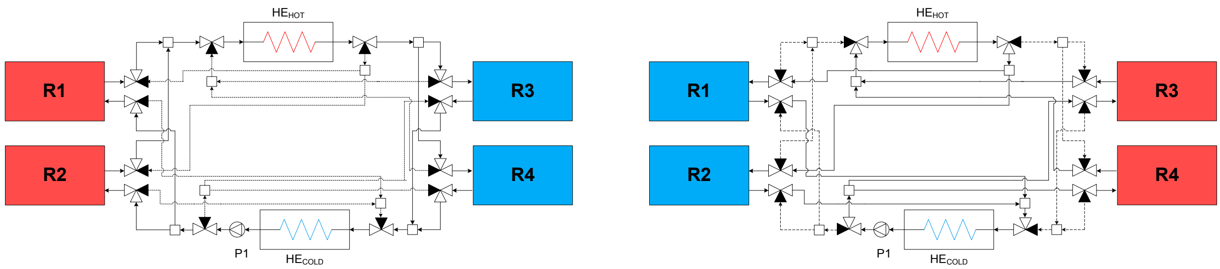

Fig. 4. (a) R1, R2 magnetized and R3, R4 demagnetized (b) R1, R2 demagnetized and R3, R4 magnetized

3. Simulations and results discussion

In order to understand the thermodynamic performance the magnetocaloric device a preliminary simulation has been carried out by means of commercial software. More in details, two consecutive plates (one per each section of the regenerator, see Fig. 2 b) have been simulated in order to take into account the complete heat exchange between gadolinium and water. The considered simulation model is sketched in Fig. 5.

The simulations, have been set on the basis of the four following step (with reference to Fig. 6): (1) regenerator magnetization (with consequent gadolinium temperature increase), (2) heat exchange gadolinium/water (the heat removed from the gadolinium is discharged into the ambient which is supposed at a constant temperature, see Fig. 4), (3) regenerator demagnetization (with consequent gadolinium temperature decrease), (4) a second heat exchange gadolinium/water (in this case the obtained cold water represents the useful effect of the system). These four steps, together, have been considered as a single cycle.

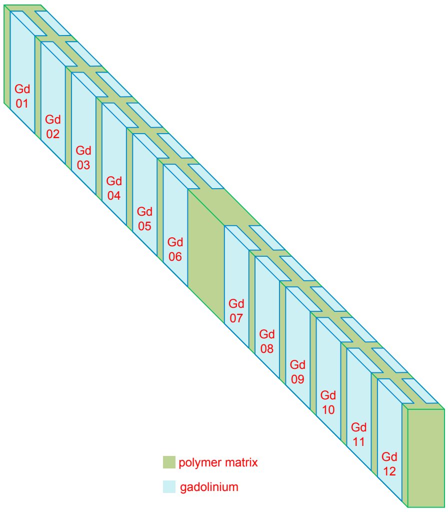

Fig. 5. Simulation model

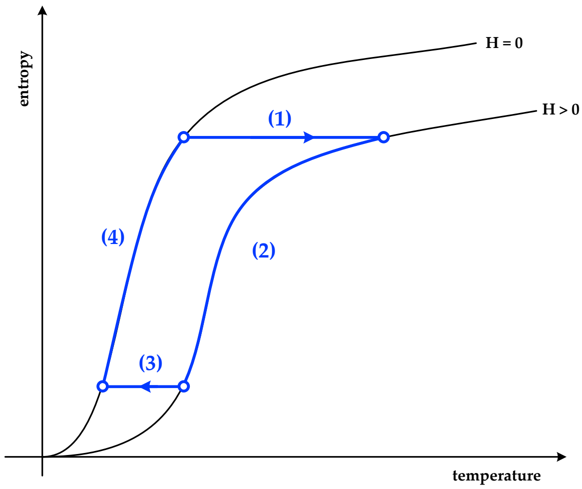

Fig. 6. Magnetocaloric cycle

The hypothesized initial values used to simulate the magnetocaloric device are listed in Tab. 1.

Table 1. Simulations initial values

Properties	value
Water speed	0.036 [m/s]
Water temperature	288.15 [K]
Gadolinium temperature	292.05 [K]
Water density	1000 [kg/m^3]
Gadolinium density	7900 [kg/m^3]
Water specific heat	4186 [J/kg K]
Gadolinium specific heat	340 [J/kg K]

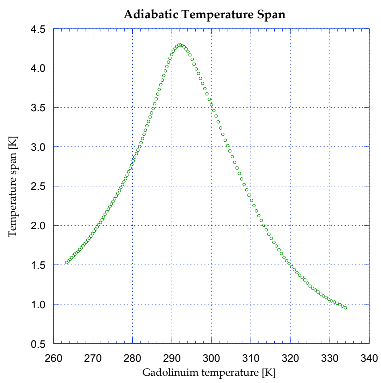

Fig. 7. Gadolinium adiabatic temperature span

The gadolinium adiabatic temperature span changes at different temperatures – shown in Fig. 7. – have has been provide, according to MIST-ER laboratory, directly measured with a purpose built probe consisting of a Cernox temperature sensor in direct and exclusive thermal contact with a sample of Gadolinium while rapidly switching the magnetic field between 0 and considering a magnetic field equals to 1.7 T. A negative temperature change of the same magnitude (not reported in Fig. 7) is measured, as expected, on magnetic field removal.

The fluid dynamic problem, as described above, has been set and computed using the Computational Fluid Dynamic software COMSOL Multiphysics.

Taking into account the enumeration of the gadolinium slice (gd-01 – gd-12) of each plate on Fig. 5 and taking into account the water flow from gd-01 to gd-12 during the magnetization phase and from gd-12 to gd-01 during the demagnetization phases, a total amount of ten cycle has been simulated. In Fig. 8 the results of these simulations have been reported. As can be noted from the figure, the gadolinium initial temperature during the magnetization phases

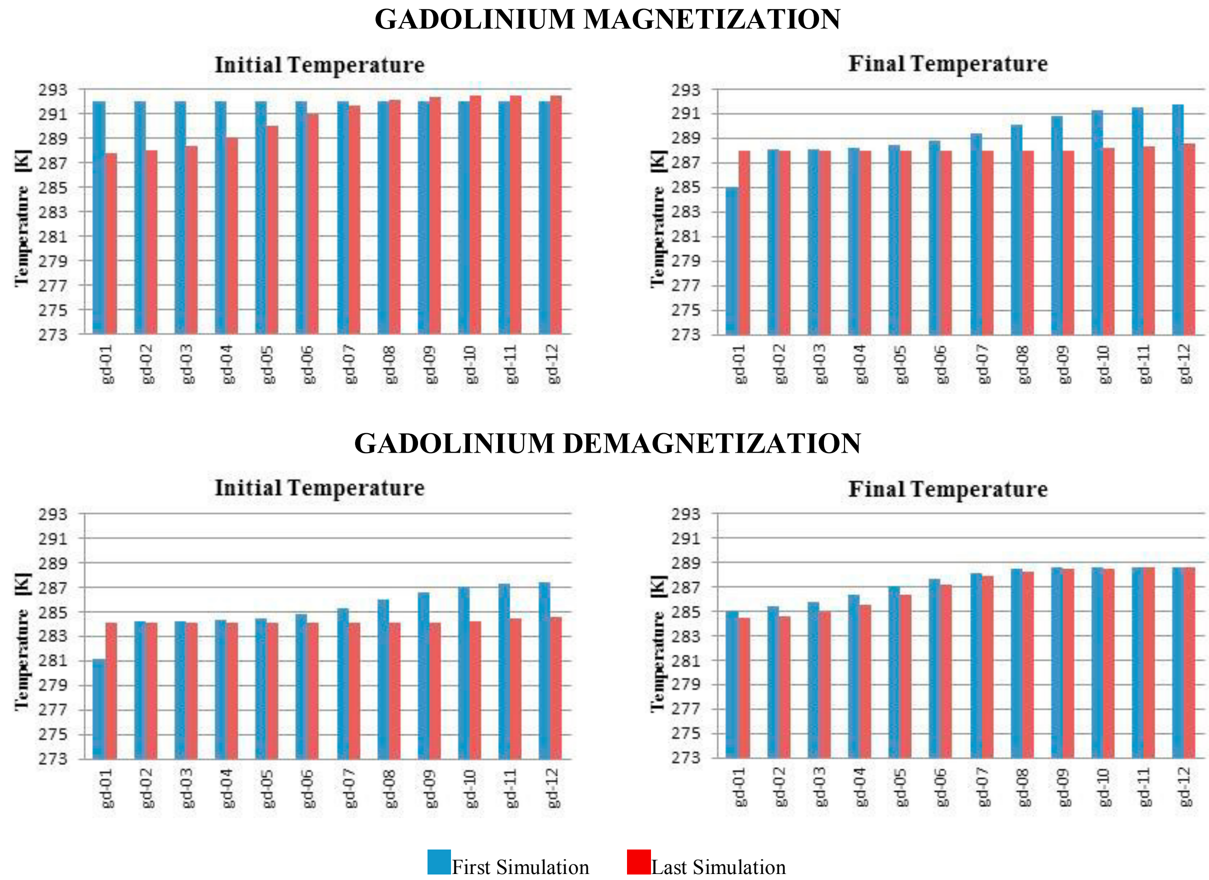

Fig. 8. (a) inlet magnetization temperature, (b) outlet magnetization temperature, (c) inlet demagnetization temperature, (d) outlet demagnetization temperature of the two consequent gadolinium plates

(Fig. 8a.), cycle by cycle, starts to decrease in the first slices of Gadolinium remaining almost constant in the last slices. This evidence can be explained considering that the thermal exchange occurs mainly in the first plate's part

After the magnetization process occurs, and the water has removed the heat from the gadolinium, the temperature distribution is the one shown in Fig. 8b. As can be noted, the final temperature, in the last cycle, presented a quite constant trend in the respect of the first simulation.

For what regards the demagnetization phase, the initial temperature (Fig. 8c.) at first simulation shows an increasing trend passing from gd-01 to gd-12. At last simulated cycle, instead, the final gadolinium slices presented a light increase. Finally, from Fig. 8d it can be note that the temperature trend is similar to the Fig. 8a. Nevertheless it must be noted that in this case the fluid flow moves from gd-12 to gd-01 because of the regeneration hypothesis.

Overall, the obtained results can be seen as a positive index for the regeneration effect. This preliminary study should be extended to more cycle to verify the temperature behaviour.

4. Concluding remarks

A preliminary analysis on magnetocaloric refrigeration has been presented in this paper. A novel regenerator has been design composed by gadolinium parallel plates separate with a polymeric material.

The paper focus on the computational fluid dynamic analysis of the regenerators, and in particular simulation has been carried out using a CFD software.

Each simulation has been made considering the single regenerator's plate to point out the regeneration effect on the gadolinium temperature.

The results show a decrease on gadolinium temperature distribution cycle by cycle highlighting the actual effect of the regeneration.

Future works would be focus on the enlargement of this study with the purpose to realize the designed prototype.

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