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Simulations and design of a refrigerating device based on a rotating magnetocaloric disc

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ABSTRACT

The possibility of utilizing a Gd disc as an active magnetic regenerator (AMR) is investigated. We have designed a demonstration device based on a rotating disc with a fixed magnetic circuit covering one quarter of its area. The device implies zero thermal load with the operation fluid flowing through. Simulations are based on discretization of the heat transfer equations for the disc and the fluid domains using the finite difference method. The magnetocaloric effect (MCE) is included in the model as an instantaneous adiabatic temperature change of each element entering the magnetic field. Regenerative effect is obtained as at each radius of the disc the magnetocaloric material (MCM) operates switching its temperature around a different average, which decreases from periphery to centre. This allows the total temperature drop of the operational fluid to be several times larger than the adiabatic temperature change.

Keywords: MCE, Magnetic Refrigeration, Gadolinium.

1. INTRODUCTION

Although discovered in early 20th century (Weiss and Piccard, 1917) the MCE still remains one of the demanded, yet pre-industrial technologies. The reason for this boils down to the two main challenges. The first one is related to MCE phenomenon itself: adiabatic temperature change for MCMs is relatively low under a reasonable magnetic field that wouldn't require enormous magnets. The second one is of the heat exchange nature: the surface to volume ratio of the regenerators should be maximized to boost heat exchange. Researchers have been approaching these issues from different fronts: material scientists are in search for new alloys to deliver higher MCE at room temperature, physicists are working on optimizing the magnets, engineers are creating complex fluid circuits and AMRs. In this vast field of studies, we decided to come up with something simple and lean, designing a device that uses a disc of Gd as an AMR. The disc is cycled through the magnetic field covering one quarter of its area and the operational fluid flows radially along the disc exchanging heat with the disc's surface: initially being cooled by the cold part of the disc, outside the magnetic field and then cooling the hot part of the disc under magnetic field. The disc configuration has received little attention as a possible AMR; instead we consider it handy for demonstrative and measurement purposes, and for testing MCMs. The device implies zero thermal load, the operation fluid (water) flows through the device and then is disposed, thus no fluid cycling inside the device is foreseen. No pumps and valves are required, and the flow happens by gravity. Regenerators generally used in models and prototypes are mostly parallel-plate or packed spheres heat-exchangers (Tušek et al., 2013), fed by complex circuits with valves and pumps. We believe that using a magnetocaloric body as simple as a disc will allow for explicit evaluation and comparison of MCMs and subsequently for getting a new insight for the future technology development.

2. SIMULATIONS AND DESIGN

The AMR of our device is composed of a rotating magnetocaloric disc made of Gd and the magnetic field is constantly present on one quarter of the disc with operational fluid flowing over the disc radially (outside-in, then inside-out). The MCE is included in the model as an instantaneous adiabatic temperature change of each single element entering the magnetic field. The disc is subdivided in four sectors: two adiabatic zones free from magnetic field and heat exchange, the heating zone under magnetic field and the (opposite) cooling zone free from magnetic field. The fluid enters at the periphery of the cooling zone, moving radially, and its temperature decreases to a minimum at the centre of the disc. Then the fluid comes out radially through the heating zone, reaching a final temperature higher than the initial one. Regenerative effect is obtained as at each radius of the disc the MCE manifests at a different average temperature, which decreases from periphery to centre. This allows to achieve the cooling of the operational fluid by several times the adiabatic temperature change of the MCM. Further sections contain aspects of mathematical modelling, simulations and mechanical design of the device.

2.1. Mathematical model

A model of an MCE disc cycled through the magnetic field and subjected to the radial fluid flow is shown in Fig. 1. The disc is subdivided in four sectors: "A" denotes the two adiabatic zones free from magnetic field and heat exchange; "H" denotes the heating zone under magnetic field; "C" denotes the cooling zone free from magnetic field. The arrows show the direction of the fluid flow. In the heating zone the disc temperature is higher than the fluid's and the flow is directed to the outside. In the cooling zone, vice versa, the fluid arrives from the outside and flows to the centre.

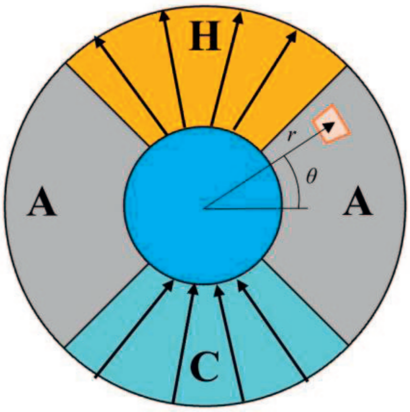

Figure 1: Scheme of the disc and the fluid flow with heat-exchange and adiabatic zones.

The system in Fig. 1 is characterized by the heat transfer in the disc and the fluid domain. The finite difference method was used for the simulation of the heat exchange in the transient regime inside the disc and of the energy balance for the moving fluid in direct contact with the disc. The magnetocaloric effect is included in the model as an instantaneous adiabatic temperature change of each single element entering the magnetic field, as addressed further.

2.2. Numerical solution

The 2D model in Fig. 1 is described through polar coordinates r and θ. The disc is discretized into finite elements using N_r circumferences and N_θ sectors, with steps dr and $d\theta$ correspondingly. Since the disc is rotating, the elements are only moving in the circumferential direction and the time step $d\tau$ for any grid and rotation speed ω is adjusted in a way that an element after a single time step finds itself in the position of the next element in the grid. In other words, the disc does not have to be re-meshed on each time step. Thus, the time step is calculated using Eq. (1).

$$d\tau = \frac{d\theta}{\omega} \qquad \text{Eq. (1)}$$

An arbitrary element dA in a previous timeframe had a radial position i_r and an angular position i_θ, and a temperature $T(i_r, i_\theta)$, at the current point of time when the computation is performed, this element has a position $(i_r, i_\theta+1)$ and the temperature $T(i_r, i_{\theta+1})$. During the interval $d\tau$ it has exchanged heat for conduction with the neighbour elements, being (i_{r-1}, i_θ), (i_{r+1}, i_θ), $(i_r, i_{\theta-1})$, $(i_r, i_{\theta+1})$, and for convection with the fluid of temperature $T_f(i_r, i_{\theta+1})$. When the element enters the magnetic field, which starts at $\theta=\pi/4$, it experiences an adiabatic temperature change $\Delta T_{ad}(T)$ due to the MCE, subsequently when the element reaches $\theta=3\pi/4$ and exits the magnetic field its temperature drops by another $\Delta T_{ad}(T)$. While moving between these two positions, the element exchanges heat with the fluid that has a lower temperature. After the heating zone, see Fig. 1, there is an adiabatic zone between $3\pi/4$ and $5\pi/4$, followed by the cooling zone from $5\pi/4$ to $7\pi/4$ where the disc has a lower temperature than the fluid. Finally, the second adiabatic zone ends at $\pi/4$ where the cycle begins again.

2.2.1. Balance equation of a finite element

The net balance between the heat received and the heat transferred by the finite element dA determines its temperature variation, as shown in Eq. (2). Here and further T is the temperature, being the function of time and coordinates, c_p is the specific heat, λ is the thermal conductivity, and h is the convection coefficient, dM is the element mass, and s is the disc thickness; index f where used indicates the fluid domain and no index refers to the disc.

$$T\left(i_r, i_\theta + 1, \tau + 1\right) - T\left(i_r, i_\theta, \tau\right) = \frac{\dot{Q} \cdot d\tau}{dM \cdot c_p} \quad \text{Eq. (2)}$$

The received and absorbed thermal power is calculated as an algebraic sum of five terms: fluid convection exchange and conductive exchanges with the four adjacent elements, see Eq. (3).

$$\dot{Q} = \dot{Q}_{conv} + \sum_{k=1}^{4} \dot{Q}_k^{cond} \quad \text{Eq. (3)}$$

The terms in Eq. (3) are given by the formulas in Eq. (4)

$$\begin{aligned}
\dot{Q}_{conv} &= 2 \cdot h \cdot dA \cdot \left(T_f(i_r, i_\theta, \tau) - T(i_r, i_\theta, \tau)\right) \\
\dot{Q}_1^{cond} &= \frac{\lambda s dr}{r d\theta}\left(T(i_r, i_\theta + 1, \tau) - T(i_r, i_\theta, \tau)\right) \\
\dot{Q}_2^{cond} &= \frac{\lambda s dr}{r d\theta}\left(T(i_r, i_\theta - 1, \tau) - T(i_r, i_\theta, \tau)\right) \\
\dot{Q}_3^{cond} &= \frac{\lambda s (r - dr/2) d\theta}{dr} \cdot \left(T(i_r - 1, i_\theta, \tau) - T(i_r, i_\theta, \tau)\right) \\
\dot{Q}_4^{cond} &= \frac{\lambda s (r + dr/2) d\theta}{dr} \cdot \left(T(i_r + 1, i_\theta, \tau) - T(i_r, i_\theta, \tau)\right)
\end{aligned} \quad \text{Eq. (4)}$$

Thus, Eqs. (2) and (4) constitute an explicit recursive formula for calculating the element temperature at each time step in the adiabatic zone where there is no heat exchange with the fluid.

2.2.2. Enthalpy balance of the fluid flow

The radial fluid flow is divided into $N_\theta/4$ flow pipes, each with an angular opening $d\theta$. Hence, we carry out the energetic analysis of the open system consisting of the fluid finite volume above and below an arbitrary element (i_r, i_θ). The exchanged thermal power contains the logarithmic mean temperature difference defined by Eq. (5)

$$\Delta T_{ml} \cong T\left(i_r, i_\theta, \tau\right) - \frac{T_f\left(i_r, i_\theta, \tau\right) + T_f\left(i_r + 1, i_\theta, \tau\right)}{2} \quad \text{Eq. (5)}$$

We choose to use a linear average between inlet and outlet temperature of the fluid, naturally, the smaller the fluid temperature rise across the considered finite volume, the more accurate this approximation is. Therefore, the energy balance of the system is given by Eq. (6), where $\dot{M}_f$ denotes the flow rate across one flow pipe.

$$\dot{M}_f c_{pf}\left[T_f\left(i_r + 1, i_\theta, \tau\right) - T_f\left(i_r, i_\theta, \tau\right)\right] = h dA \Delta T_{ml} \quad \text{Eq. (6)}$$

Given the inlet temperature and using the simplified expression for ΔT_{ml}, the fluid outlet temperature is compute from Eq. (7).

$$T_f\left(i_r+1,i_\theta,\tau\right)=\frac{T_f\left(i_r,i_\theta,\tau\right)\left[\dot{M}_f c_{pf}-\frac{hdA}{2}\right]+hdAT\left(i_r,i_\theta,\tau\right)}{\dot{M}_f c_{pf}+\frac{hdA}{2}} \qquad \text{Eq. (7)}$$

Eq. (7) is written for the magnetic field area where the flow direction is from the centre to the external edge, in the cooling zone where the fluid flows to the centre, signs must be adjusted.

The finite difference solution contained in recursive formulas of Eqs. (2) and (7) is implemented in Matlab. The code requires input values of the physical properties of the fluid and the disc material: density, thermal conductivity, specific heat capacity; magnetocaloric disc material property as a function of temperature and magnetic field $\Delta T_{ad}(T, \mu_0 H)$; room temperature T_0; disc dimensions and thickness; rotation frequency; meshing parameters. Thus, we can evaluate the influence of these parameters on the performance which we assess in terms of the temperature drop ΔT_{final} between the fluid temperature in the centre of the disc at the regime T_{final} and the room temperature T_0, and the power transferred to the external environment $\dot{Q}_{cool}$ given by Eq. (8).

$$\dot{Q}_{cool}=\dot{M}_f^{total} c_{pf}\Delta T_{final} \qquad \text{Eq. (8)}$$

2.3. Simulation results and discussion

First, we run the simulations for a pure Gd disc. Magnetocaloric and thermal properties of Gd were measured in the laboratory of IMEM in Parma and verified with Bjørk et al. (2010). Other input parameters required by the Matlab code are given in Table 1. The rotational frequency and the flow rate are optimized to achieve lower temperature at the regime (T_{final}).

Table 1. Model parameters

Disc thickness	s=1 mm	Magnetic field	$\mu_0 H$=1 T
Disc inner diameter	d_{in}=40 mm	Flow rate	$\dot{M}_f^{total}$=0.3416 g/s
Disc outer diameter	d_{out}=118 mm	Frequency	f=0.5 Hz
Air gap between the disc and the magnet	g=1.5 mm	Room temperature (entering fluid)	T_0=20 °C

The temperature of each finite element evolves with rotation until the system reaches a regime. Following an element represents the Lagrangian approach captured in Fig. 2, where temperature vs. time for two elements (one on the internal and another on the external edges of the disc) is plotted. To observe the temperature evolution in the fluid domain using Eulerian approach, we evaluate T_f at positions θ=45° and θ=135° (heating zone "H" under magnetic field) on three circumferences of the grid, the mean outlet temperature of the fluid leaving the system and the lowest fluid temperature in the centre, see Fig. 3. The regime is reached after 260 s or 130 full rotations, with T_{final}=6.89 °C, ΔT_{final}=13.11 °C, $\dot{Q}_{cool}$=18.75 W. Finally, Fig. 4 shows an instant mean temperature profile of the radial fluid flow at 52 s.

Further simulations regarded the use of Ni-Mn-In Heusler alloys, promising MCMs with tuneable T_{Curie}. We tested a single-alloy disc and an AMR composed of three rings of alloys with different T_{Curie}. Keeping the model parameters from Table 1, we obtained ΔT_{final}=4.62 °C, $\dot{Q}_{cool}$=6.61 W and ΔT_{final}=4.73 °C, $\dot{Q}_{cool}$=6.77 W for the single- and multi-material disc correspondingly. Clearly, the MCE of Gd is superior, albeit the large enthalpy change makes it necessary to absorb more thermal power to utilize the MCE, which means lowering the rotation frequency. Indeed, simulations show that the maximum performance for Heusler alloys is reached on higher frequencies, although it remains drastically lower than that of Gd, see Fig. 5. However, the operational range is unlikely to raise above 1 Hz, since the losses due to drag effect and mixing, which was neglected in the numerical model, will become significant (Tagliafico, 2006).

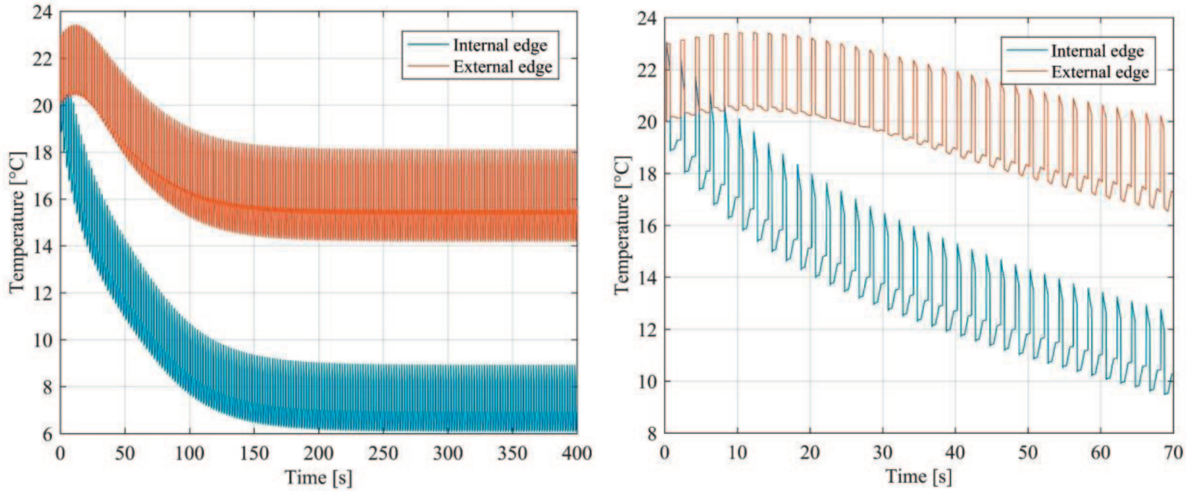

Figure 2: Gd disc temperature evolution (element follower) for 400s and 70s.

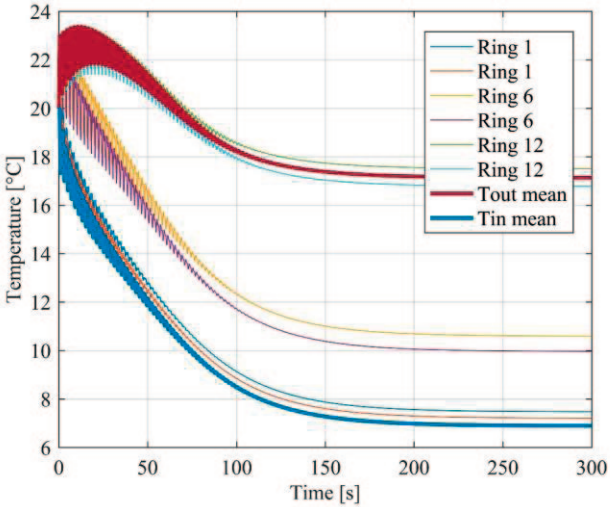

Figure 3: Fluid temperature evolution.

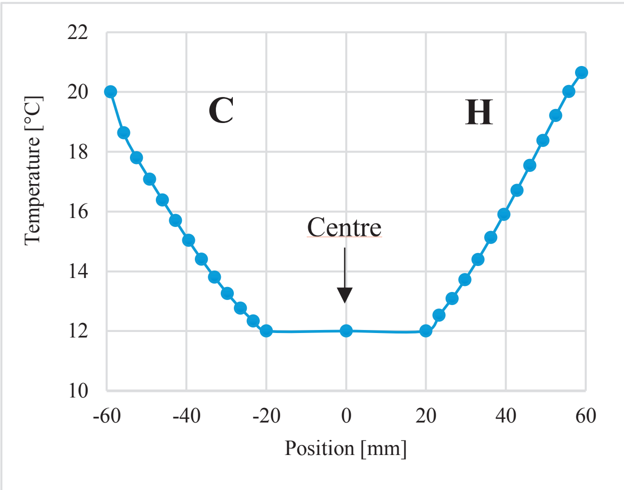

Figure 4: Instant radial fluid flow temperature profile.

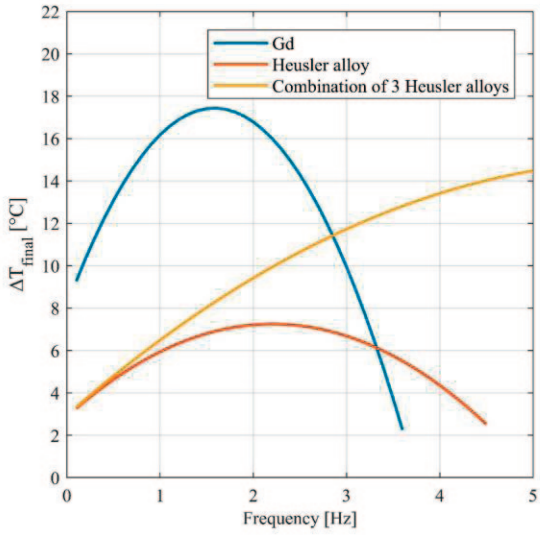

Figure 5: Temperature drop vs. frequency of rotation.

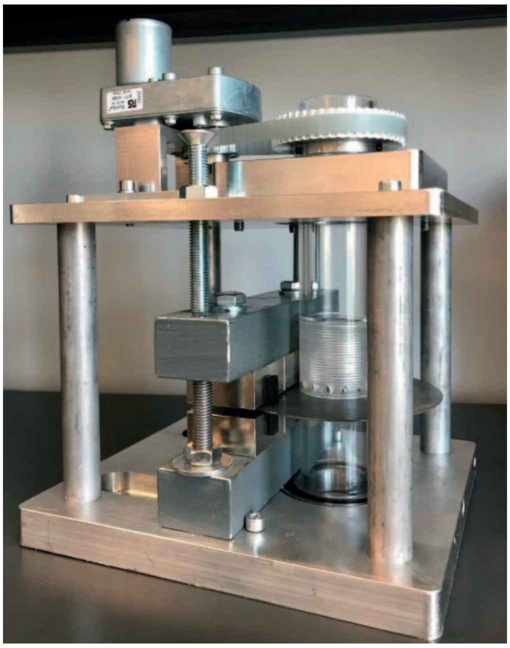

Figure 6: Demo device under construction.

2.4. Design of the device

The testing device in the phase of assembling (without its tank, insulations and operational fluid) is photographed in Fig. 6. The fixed magnetic circuit is composed of six NdFeB magnets that provide the mean field of 1.05 T in the middle of the 4 mm air gap; the gap is adjustable in the range 3-10 mm. The motion is executed by a geared brushless motor with speed control. Our device will allow for MCE demonstration, testing of the disc AMR performance, comparing MCMs and measuring auxiliary parameters, e.g. measuring the braking force acting on the disc while rotating in the magnetic field. Actual results of the experiments will be published in further papers.

3. CONCLUSIONS

In the paper design concept and finite-difference numerical simulations of a refrigerating device based on a Gd disc rotating through a fixed magnetic circuit is presented. The operational fluid enters the system at room temperature T_0, cools down in the colder part of the disc outside of the magnetic field and then absorbs the heat generated by the MCE of the disc under magnetic field, thus, leaving the system with a temperature slightly larger than T_0. The fluid flow is bounded between two adiabatic zones and the reference temperature is measured in the centre, where the fluid is the coldest. We evaluated the influence of various parameters on the performance and at frequency of 0.5 Hz and magnetic field of 1 T, a ΔT_{final}=13.11 °C and $\dot{Q}_{cool}$ =18.75 W were obtained by the numerical simulation. Full utilization of the MCE of Gd requires to increase time for extracting the thermal power, i.e. to lower the rotation frequency. Thus, for materials with a smaller MCE, a higher frequency could be optimal. Currently we are working on the experimental setup to complete the results.

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