Time- and space-resolved temperature measurements on a periodically magnetized Gadolinium plate

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Abstract: The present work provides space- and time-resolved measurements of the temperature field inside a simplified flat-plate heat exchanger made of Gadolinium which serves as the magneto-caloric material (MCM). To measure the temperature field during periodic magnetization and demagnetization cycles of the MCM, both thermocouples and a Mach-Zehnder interferometer were used. Particular attention is paid to the analysis of the thermal boundary layer close the MCM, from which the heat flux into the fluid can be calculated.

1. Introduction

Magnetic cooling, based on the adiabatic temperature change of magneto-caloric materials (MCM) in a changing magnetic field, is an emerging new cooling technology [1]. Due to important advantages compared to conventional cooling based on gas compression, this technology has drawn an increasing concern. It has the potential of operating more silently and uses both non-toxic solid cooling material and environment-friendly heat transfer fluids. Besides, zero ozone depletion potential and less energy consumption makes it a promising alternative of next generation cooling technology. Furthermore and most importantly, the magneto-caloric cooling machines potentially possess a high efficiency, which is theoretically close to the Carnot cycle [1].

Despite increasing research on the thermodynamic principles and measurements [2,3] of magneto-caloric effect (MCE), corrosion and anticorrosion substitute solution studies [4] numerous issues have to be resolved before a widespread commercial use of the technique is achieved. The significant heat resistances in the active magneto-caloric regenerator, i.e. the suboptimal heat transfer from the MCM into the heat transfer fluid belong to these issues.

In this work, we provide for the first time space- and time- resolved temperature measurement in a simplified prototype of an active magnetic regenerator. For this purpose, both a Mach-Zehnder (M-Z) interferometer and direct measurement with thermocouples were applied to map the temperature field of the heat transfer fluid. Additionally, numerical simulation of the one-dimensional heat conduction was performed to facilitate the selection of heat transfer fluids suitable for interferometry.

2. Experimental setup and numerical simulation

Gadolinium (99.5% pure) was used as MCM. The Gd plates have an area of 9.6 mm x 9.6 mm and a thickness of 0.8 mm and were polished to a roughness of less than 0.01 mm. Two Gd plates were glued at the side walls of an optical cuvette (Hellma) with an inner geometry of 10 x 10 x 10 mm^3. The resulting space between the Gadolinium plates is 8.4 mm. This cuvette was filled either with deionized water or synthesis grade n-decane. Two NdFeB magnets (50 x

30 x 12 mm^3) were used to generate a magnetic field of 350 mT inside a gap of 15 mm. The inhomogeneity at height of the Gd plates is less than 3 mT. The pair of magnets is mounted on a 1-D motorized translation stage to generate a periodic magnetic field by means of which the Gd plates are exposed to periodic magnetization and demagnetization cycles. The experimental setup is schematically illustrated in Fig. 1.

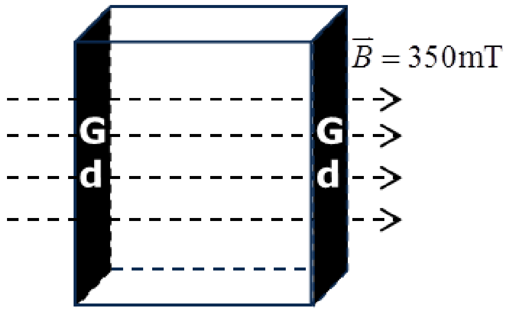


Figure 1: MCE measurement under a homogeneous magnetic field

Initially, the direct temperature measurements of the temperature change of Gd were performed with 0.25 mm thick ungrounded Type E thermocouples. For these measurements, four thermocouples were inserted into the gap of two parallel Gd plates, i.e. they are directly sandwiched by the plates. The thermocouples were adhered to the Gd plate and connected to a digital multimeter (Keithley 2700 including switching model 7708). The temperature data, gained by the thermocouples, served as calibration data for interferometric measurement to increase the accuracy and extend the measurement area of temperature field specifically near the surface of the Gd plates.

In the next step a Mach-Zehnder (M-Z) interferometer, employing a He-Ne laser (632.8 nm), was used to monitor the time and space- resolved temperature field *T(x,y,t)* during periodic magnetization and demagnetization of Gd. The interferograms were recorded with a frame rate of 30 Hz. Each experiment set was repeated for at least 3 times.

To support the selection of a heat transfer fluid which is suitable for temperature measurements in the interferometer, the one-dimensional unsteady heat conduction equation in the form

$$\frac{\partial T}{\partial x} = \frac{k}{\rho c_p} \frac{\partial^2 T}{\partial x^2} \qquad (1)$$

is solved by means of the finite volume method. In eq. (1), T is temperature; x is space distance normal to the Gd plate; k is the heat conductivity; ρ the density and c_p is the specific heat capacity. The harmonic mean heat conductivity k at the boundary of Gd and fluid is defined as

$$k = \frac{1}{\frac{1}{k_{Gd}} + \frac{1}{k_{fluid}}}. \qquad (2)$$

In accordance with our application, natural convection during heat transfer from Gd to fluid or vice versa can be neglected due to the small temperature differences.

3. Result and discussion

Fig. 2 shows the temperature changes at the surface of the Gadolinium plate during one complete cycle of magnetization (120 s) and demagnetization (120 s), measured by four thermocouples at room temperature by T_0=(295.2±0.2) K. Immediately after magnetization, the temperature rises by ΔT = (0.35 ± 0.05) K to exponentially decrease later on to T_0. Here, the temperature histories of the four thermocouples agree well since the temperature differences between the four thermocouples are less than 0.1 K. After removing the magnet, the temperature rapidly drops down by ΔT.

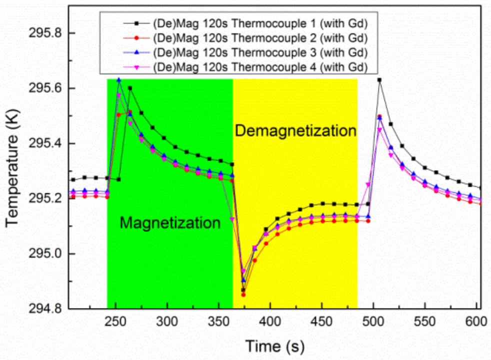
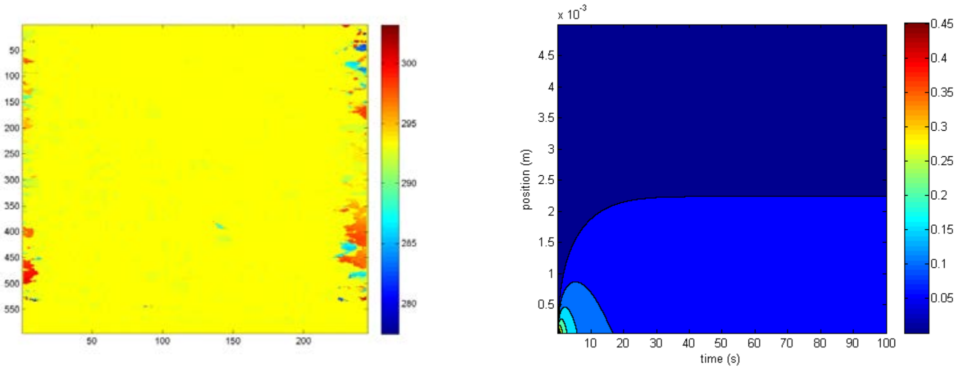


Figure 2: Temperature measurement with thermocouples during a full cycle of magnetization and demagnetization over 120 s.

In the next step we have investigated, by means of Mach-Zehnder interferometry, how the measured temperature change of the Gadolinium plate translates into the temperature field of the fluid surrounding the Gd plate. First, water was taken for that purpose because it is naturally the first choice of an environment friendly heat transfer fluid. However, Fig. 3a shows the disillusioning result that the temperature rise in water is smaller than the noise in the measurement, hence not reliably resolvable by the instrument.



(a) (b)

Figure 3: (a) M-Z Interferometer temperature measurement of heat transfer from 2 magneto-caloric plates into water; (b) 1-D unsteady thermo-diffusion simulation of heat transfer into water between two parallel magneto-caloric Gd plates.

The simulation in Fig. 3b reveals the reason why. It shows the 1-D temperature profile normal to the Gd plate with progressing time. Only in the very beginning, a measurable ΔT of about 0.3 K appears. However, by virtue of the comparatively high thermal diffusivity $\kappa = k / (\rho\ c_p)$, of water this temperature rise is diminished to less than 0.1 K within about 5 sec.

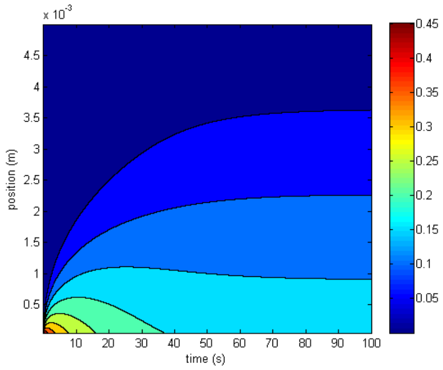
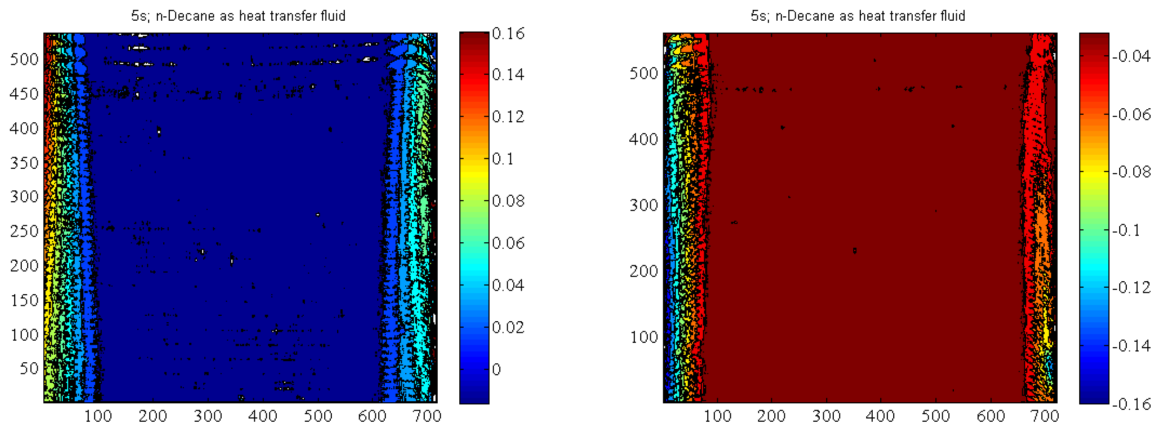


Figure 4: 1-D temperature profile versus time at the center of the Gd plate as obtained from 1-D simulation of the unsteady heat conduction equation (1) of the MCE with n-decane.

After simulation of several other organic liquids of smaller heat capacity, n-decane turned out to be the best compromise. Fig. 4 shows the corresponding 1-D temperature profile $T(x)$ after an adiabatic temperature increase of Gadolinium of 0.5 K. On comparing the simulation of the MCE when using either water (Fig. 3b) or n-decane (Fig. 4) as heat transfer fluid, it is obvious that a clearer and measurable temperature profile with n-decane is theoretically achievable.

The results of the M-Z interferometer experiments using n-decane in the setup of Fig. 1 are shown in Fig. 5. Here, the temperature field is plotted both after 5 s of magnetization (Fig. 5a) and after 5 s of demagnetization (Fig. 5b) with 350 mT. The two Gadolinium plates are located at both vertical boundaries perpendicular to the measurement arm of M-Z interferometer and appear in Fig. 5 as vertical boundary at the left and right side of each picture. The figure shows nicely the formation of the thermal boundary layers at the Gd plates. Heat losses in the upper and lower part of the optical cell as well as a minor variation of the thickness of Gd plates contribute to a slight imperfection of the isotherms. As a result, the isotherms are a bit convex instead of exactly one-dimensional.



(a) (b)

Figure 5: M-Z Interferometer measurement of temperature field in n-decane: (a) 5 s after magnetisation and (b) 5 s after demagnetisation.

The temperature profiles normal to the Gd plates in the cell center, derived from the temperature field in Fig. 5a are plotted with progressing time during the magnetization phase in Fig. 6. The horizontal coordinate is the distance normal to the surface of the Gd plate. The vertical coordinate is the temperature of the n-decane at the specified position. The developments of the T(x) profiles with time is clearly visible. The reason why the measured temperature maximum of 0.15 K after 5 s stays below the maximum temperature rise detected by the thermocouples (0.35 K) is related to the fact that region very close to the Gd plates is currently not visible for the interferometer.

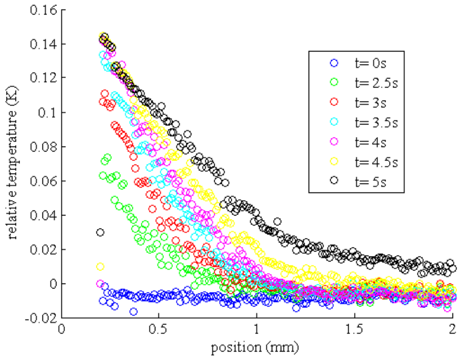


Figure 6: Temperature profile T(x) with progressing time during the magnetization phase, measured by the M-Z interferometer.

This problem is related to the difficulties in the adjustment of the Gd plates parallel to the measurement arm of M-Z interferometer. This leads to a reduction of the accessible field of view in the cell as illustrated in Fig. 7. However, the tilt angles α and β are small and considerably less than 1°. As a result, the temperature data near the Gd plate, i.e. over an interval of $\Delta x \approx 0.2$ mm are missing.

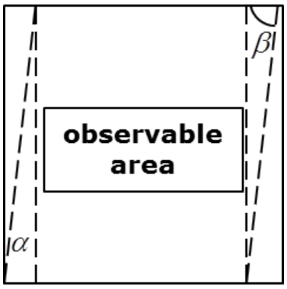


Figure 7: Sketch of the observable area of the M-Z interferometer caused by a small tilt of the Gd plates in the optical cell.

Current work is devoted to two issues: (i) to combine the temperature data acquired by both methods (M-Z interferometer and thermocouples) to obtain the complete time- and space-resolved temperature profiles. (ii) By implementing a magnetohydrodynamic convection we seek to enhance the heat transfer from the Gd plates into the heat transfer fluid.

4. References

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