THE REVERSIBILITY OF THE MAGNETOCALORIC EFFECT AND ITS CONSEQUENCES FOR THE ACTIVE MAGNETIC REGENERATOR REFRIGERATION CYCLE

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Abstract. *Magnetic refrigeration is a promising alternative cooling technology for application at near-room temperature conditions. Therefore, in order to advance the technology and make it more competitive, it is essential to understand the sources of energy losses and to quantify them in the context of the active magnetic regenerator (AMR) refrigeration cycle. One of such losses is related to the reversibility of the magnetocaloric effect (MCE) with respect to the magnetization and demagnetization of the solid refrigerant under adiabatic conditions. In the present work, the reversibility of the MCE of gadolinium (Gd) will be evaluated experimentally and, by means of a numerical code for the thermal performance of a parallel-plate AMR, this effect will be incorporated into the analysis so as to quantify the impact of the reversibility on the thermal cycle of the AMR.*

Keywords: *magnetocaloric effect, magnetic regenerator, reversibility, direct measurements*

1. INTRODUCTION

Magnetic refrigeration is a cooling technology based on the magnetocaloric effect (MCE). The MCE is characterized by a reversible temperature variation of the material when subjected to a changing magnetic field. Some classes of magnetic materials exhibit a significant MCE at near room temperature, which makes them potential candidates for utilization as refrigerants in active magnetic regeneration refrigeration cycles (Tishin and Spichkin, 2003).

The MCE is the result of the influence of changing magnetic field (ΔH) on the total entropy of the system ($S(H,T)$). The total entropy of a magnetic solid is the sum of the magnetic ($S_M(H,T)$), electronic ($S_{el}(T)$) and lattice entropies ($S_{lat}(T)$) as follows (Pecharsky and Gschneidner, 1999(a); Pecharsky *et al.*, 2001; Tishin and Spichkin, 2003),

$$S(H,T) = S_M(H,T) + S_{lat}(T) + S_{el}(T) \tag{1}$$

If the external magnetic field changes and the temperature (T) of the system remains constant, the electronic and lattice entropies do not change ($\Delta S_{lat}(T) = \Delta S_{el}(T) = 0$), and the variations of the total entropy and magnetic entropy are equal ($\Delta S(H,T) = \Delta S_M(H,T)$). On the other hand, if the system is adiabatic, the total entropy does not change ($\Delta S(H,T) = 0$), but the magnetic entropy changes due to the magnetic field variation, which results in a thermal lattice and electronic entropy variation ($-\Delta S_M(H,T) = \Delta S_{lat}(T) + \Delta S_{el}(T)$). This, in turn, causes an increase in the temperature of the magnetic material known as the adiabatic temperature change (ΔT_{ad}) (Pecharsky *et al.*, 2001).

The MCE can be characterized by ΔS_M or by ΔT_{ad}. Both are thermodynamic properties that can be quantified *indirectly* by means of the Maxwell relations in conjunction with experimental data on the magnetization and specific heat capacity of the magnetic material. The experimental characterization of those properties is relatively complex and expensive and requires thermodynamic equilibrium (i.e., quasi-static) conditions. ΔT_{ad}, nevertheless, can be also measured *directly* by means of temperature detectors, such as thermocouples or infrared thermography (Christensen *et al.*, 2010). In essence, ΔT_{ad} is defined as the difference between the temperatures of the magnetic material measured after and before its magnetization, as defined by the following relationship (Pecharsky and Gschneidner, 1999(b); Pecharsky *et al.*, 2001; Tishin and Spichkin, 2003).

$$\Delta T_{ad} = T(H > 0) - T(H = 0) \tag{2}$$

Thus, it is clear that the *direct* approach is simpler in terms of experimentation and data analysis. Moreover, adiabatic and quasi-static conditions (compulsory for specific heat measurements), depending on the nature of the direct measurement tests, need not to be respected. This ensures more realistic results from the point of view of the application in a refrigeration system, since it is likely that in the real application there will be heat transfer to or from the solid refrigerant over a finite amount of time (Trevizoli *et al.*, 2009; Trevizoli, 2010).

Furthermore, by carrying out direct measurements it is possible to quantify important [J1]parameters such as the influence of the demagnetization factor on the adiabatic temperature change and the reversibility of the MCE. Therefore, the main objectives of this study are as follows:

1. To investigate experimentally the reversibility of the MCE. In a previous work (Trevizoli *et al.*, 2009) presented direct measurement results of the magnetocaloric (adiabatic) temperature change (ΔT_{ad}) of gadolinium (Gd) samples subjected only to magnetization have been presented. Using the same method, was investigated the behavior of the MCE under magnetization and demagnetization.

2. To study the influence of the reversibility of the MCE on the AMR performance. This analysis was performed using a mathematical model for the fluid flow and heat transfer in a parallel plate AMR proposed by Oliveira *et al.* (2009a, 2009b).

2. EXPERIMENTAL WORK

The direct measurement apparatus is composed of a $Nd_2Fe_{14}B$ permanent magnet arranged in a Hallbach array and a pneumatic circuit to move the sample into and out of the magnetic field, as shown in Fig. 1. The description of the experiment, sample preparation, experimental conditions and data processing were presented by Trevizoli *et al.* (2009) and Trevizoli (2010), where it was described in detail the behavior of the magnetocaloric temperature change (ΔT_{mag}) of Gd samples as a function of temperature.

The present study will focus on the reversibility of the MCE, which is characterized experimentally via a direct measurement procedure identical to that of Trevizoli *et al.* (2009) and Trevizoli (2010) to quantify ΔT_{mag} under successive events of magnetization and demagnetization with a magnetic field variation of 1.65 T.

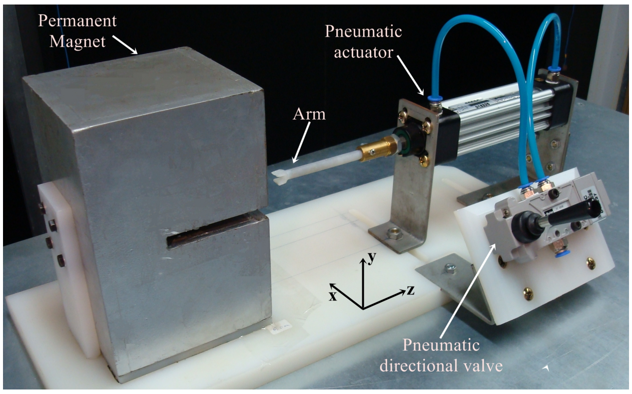

Figure 1. Direct measurement apparatus

As will be seen, the reversibility of the MCE, which can be characterized by subtracting ΔT_{mag} measured under two successive steps of magnetization ($\Delta T_{mag,M}$) and demagnetization ($\Delta T_{mag,D}$), will have impact on the AMR performance. This effect was studied using a mathematical model developed by Oliveira *et al.* (2009a, 2009b). The model enabled the simulation of the four thermodynamic processes in a Brayton-based parallel plate reciprocating AMR using the magnetocaloric temperature change curves obtained experimentally. Table 1 shows the parameters needed to simulate the AMR.

Table 1. Operating parameters of the AMR model (Oliveira *et al.*, 2009a, 2009b).

AMR cycle variable	**Value**
frequency - f	1 Hz
Mass flow rate - $\dot{m}$	between 4.8 and 13.4 kg/h
Gd mass	0.228 kg
Magnetic field variation - ΔH	1.65 T
Temperature span - ΔT	12 K
Hot resevoir temperature - T_{Hot}	301 K
Cold resevoir temperature - T_{Cold}	289 K
Fluid	water

3. RESULTS AND DISCUSSION

3.1 MCE reversibility analysis

Figure 2 presents the MCE curves measured by the direct approach as a function of temperature in the magnetization and demagnetization processes. $\Delta T_{mag,D}$, obviously, has a negative sign (because, when the magnetic field is removed, ΔT is negative). However, to compare the magnetization and demagnetization curves, the absolute values of $\Delta T_{mag,D}$ are plotted. As can be observed, there is a clear temperature shift in the curves, with the peak of the curves taking place at around 293 K (the Curie temperature of Gd) for magnetization and 297 K for demagnetization.

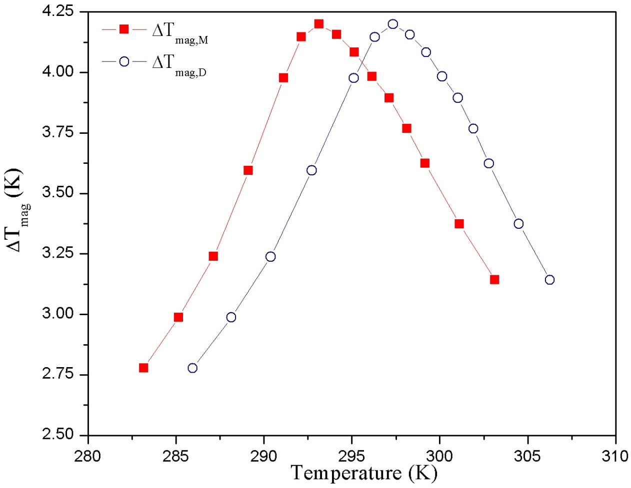

Figure 2. ΔT_{mag} of Gd samples determined via direct measurements under magnetization and demagnetization

This result can be explained on the grounds of the reversibility of MCE under conditions of zero heat transfer. Neglecting any kind of internal irreversibility (homogeneous material, uniform temperature variations), the system is expected to perform a cycle and return to the original state (i.e., zero total entropy variation) with zero entropy generation. The shift of the demagnetization curve with respect to that for magnetization is a consequence of this constraint.

To explain the reversibility of the MCE, it may be helpful to consider the existence of a single curve for magnetization and demagnetization, and to demonstrate that, by doing so, the resulting process is not reversible. By analyzing Fig. 3, considering the magnetization curve for an initial temperature of 293.15 K, the temperature of the sample increases by 4.2 K, and the final temperature is 297.35 K. At this temperature, if the material is demagnetized according to the *magnetization* curve, the temperature decreases by 3.9 K, and the final temperature will be 293.45 K. Thus, the material does not return to the initial state, which does not characterize a reversible process.

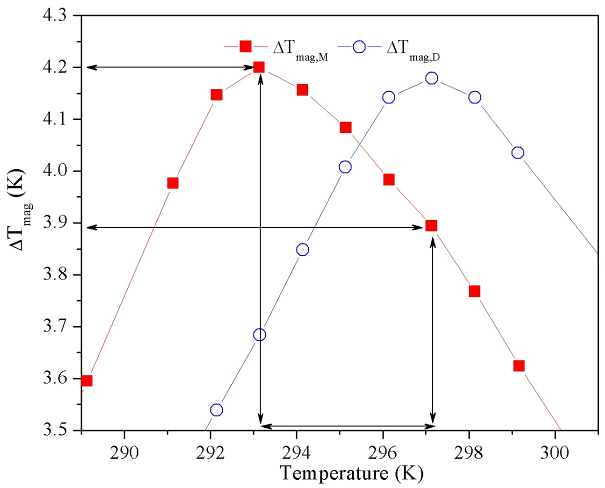

Figure 3. Reversibility analysis considering only the magnetization curve

However, if one now considers the demagnetization curve, as can be seen in Fig. 4, and if the material is demagnetized at 297.35 K, the temperature decreases by approximately 4.2 K, which is the same amount by which the temperature is increased following the magnetization. Thus, in this case, it appears that the reversibility has been demonstrated experimentally.

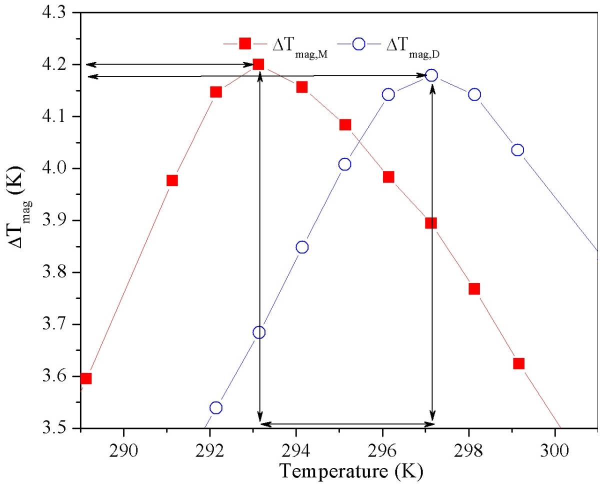

Figure 4. Reversibility analysis considering the magnetization and the demagnetization curves

An alternative experimental analysis that confirms the reversibility of the MCE is presented in Fig. 5. In this test, the material is firstly magnetized and then demagnetized a few seconds later. In both cases, the temperature variation is the same, which characterizes a reversible process.

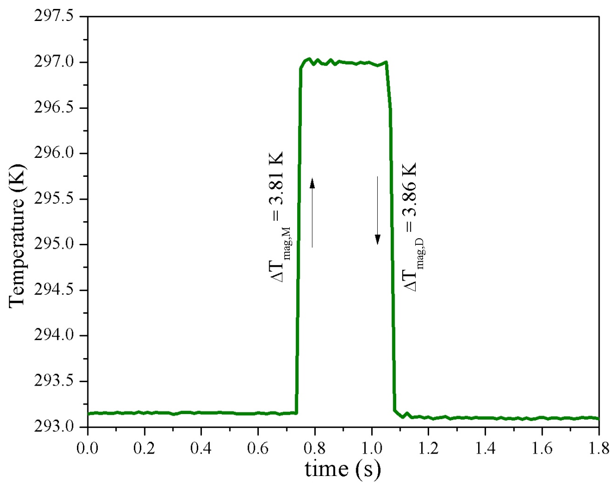

Figure 5. Temperature measurement after successive magnetization and demagnetization

Bahl and Nielsen (2009) and Nielsen *et al.* (2010) presented a thorough discussion concerning the reversibility of the MCE. They point out that the temperature shift between the magnetization and demagnetization curves, for a fixed ΔT_{mag}, is equal to ΔT_{mag}. For example, if the material is magnetized at 293.15 K, then ΔT_{mag} = 4.2 K, which is the same amount by which the sample temperature is decreased if it is demagnetized at 297.35 K. Therefore, the temperature difference, ΔT = 297.45 - 293.15, is equal to 4.2 K, i.e., the ΔT_{mag}. Nielsen *et al.* (2010) proposed a theoretical estimation to $\Delta T_{mag,D}$ based on the $\Delta T_{mag,M}$ measurement as follows,

$$\Delta T_{mag,M}(T_0, H) = \Delta T_{mag,D}(T_0 + \Delta T_{mag,M}(T_0, H), H) \tag{3}$$

where a comparison between the experimental $\Delta T_{mag,D}$ and that computed via Eq. 3 is presented in Fig. 6.

3.2 Impact of the reversibility of the MCE on the thermal performance of an AMR

In this section, the influence of the reversibility of the MCE on the cooling capacity of an AMR will be studied on the basis of two different scenarios (tests) as follows:

- Test 1: This is a situation which is typical of the majority of papers published in the literature, i.e., the simulations consider only the $\Delta T_{mag,M}$ curve for the magnetization and the demagnetization processes;

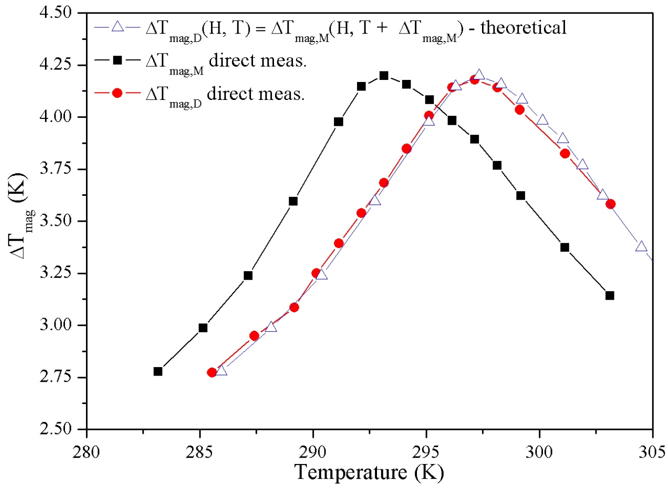

Figure 6. Comparison between the experimental and the theoretical values of $\Delta T_{mag,D}$

- Test 2: The simulations consider the $\Delta T_{mag,M}$ curve for magnetization and $\Delta T_{mag,D}$ for the demagnetization.

The simulations parameters are presented in Table 1. The temperature difference between the hot and cold sources was set as 12 K due to the fact that, in this temperature region, the magnetization and the demagnetization curves present the maximum MCE, as can be seen from Fig. 3. The numerical results are presented in Fig. 7, which exhibits the instantaneous cooling capacity as a function of time for the hot-to-cold blow. The average cooling capacities of the two tests are compared in Table 2.

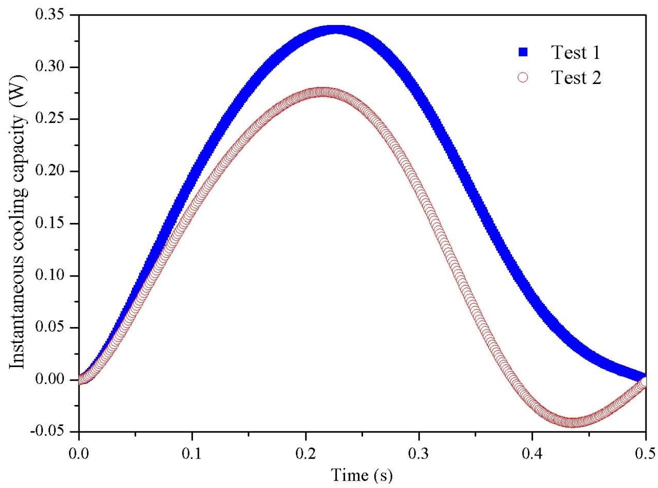

Figure 7. Instantaneous cooling capacity as a function of time for Test 1 and Test 2

Table 2. Average cooling capacities for Tests 1 and 2.

Test	**Average cooling capacity**
Test 1	4.59 W
Test 2	3.08 W

The results show that the consideration of the reversibility of the MCE reduces the cooling capacity. The average cooling capacity decreases by 33% in Test 2. To understand this result, one can refer to Figs. 8 and 9 to analyze how the MCE is distributed along the regenerator after the magnetization and demagnetization process.

To compare the results presented in Figs. 8 and 9, an arbitrary value of $\Delta T_{mag} = 3.3$ K was taken as a reference. This value represents a ratio of 2 K/T for a magnetic field of 1.65 T, which is considered an acceptable limit for applications in cooling systems (Rowe *et al.*, 2005). Values of $\Delta T_{mag} > 3.3$ K are desirable in the biggest part of the regenerator, and

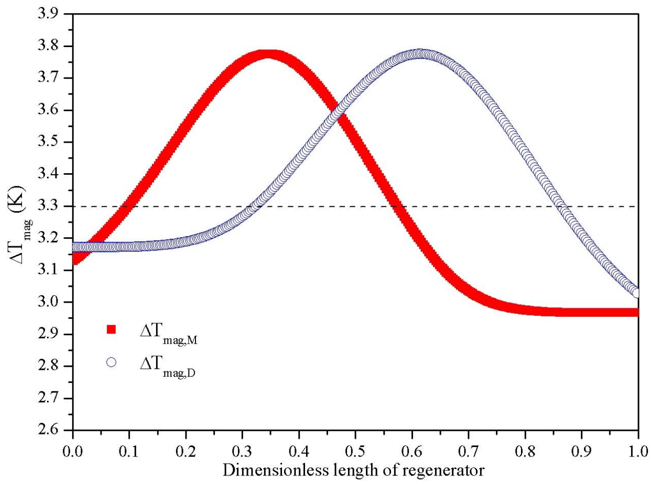

Figure 8. MCE distribution along the regenerator for the Test 1 conditions

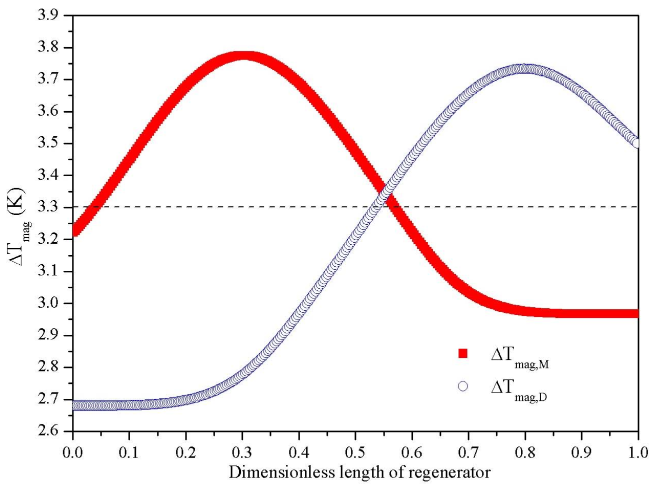

Figure 9. MCE distribution along the regenerator for the Test 2 conditions

this condition is observed in Fig. 8. Thus, if only the magnetization curve existed, the MCE would be better distributed along the regenerator and, consequently, this would improve the system performance. However, in reality, the demagnetization curve is followed when the magnetic field is removed, so the fact is that the reversibility of the MCE reduces the performance of the AMR.

4. CONCLUSIONS

The present paper analyzed experimentally the reversibility of the magnetocaloric effect via direct measurements. The results are in agreement with the work published by Nielsen *et al.*, 2010. Therefore, it can be concluded that the MCE is reversible and this has a negative impact on the cooling performance of the active magnetic regenerator, reducing the cooling capacity by 33%.

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6. REFERENCES

Bahl, C.R.H. and Nielsen, K.K., 2009, "The effect of demagnetization on the magnetocaloric properties of gadolinium", Journal of Applied Physics, Vol. 105, p. 0139161-0139165.

Christensen, D.V., Bjørk, R., Nielsen, K.K., Bahl, C.R.H., Smith, A. and Clausen, S., 2010, "Spatially resolved measurement of the magnetocaloric effect and the local magnetic field using thermography", Submitted to Journal of Applied Physics.

Nielsen, K.K., Bahl, C.R.H. and Smith, A, "Constraints on the adiabatic temperature change in magnetocaloric materials", Physical Review B, Vol. 81.

Oliveira, P.A., Trevizoli, P.V., Barbosa Jr., J.R. and Prata, A.T., 2009(a), "Numerical analysis of a reciprocative active magnetic regenerator - Part I", Proceedings of the 3rd International Conference on Magnetic Refrigeration at Room Temperature, Des Moines, USA.

Oliveira, P.A., Trevizoli, P.V., Barbosa Jr., J.R. and Prata, A.T., 2009(b), "Numerical analysis of a reciprocative active magnetic regenerator - Part II", Proceedings of the 3rd International Conference on Magnetic Refrigeration at Room Temperature, Des Moines, USA.

Pecharsky, V.K. and Gschneidner, Jr., K.A., 1999(a), "Magnetocaloric effect and magnetic refrigeration", Journal of Magnetism and Magnetic Materials, Vol. 200, p. 44-56.

Pecharsky, V.K. and Gschneidner, Jr., K.A., 1999(b), "Magnetocaloric effect from indirect measurements: magnetization and heat capacity", Journal of Applied Physics, Vol. 86, p. 565-575.

Pecharsky, V.K., Gschneidner Jr., K.A., Pecharsky, A.O. and Tishin, A.M., 2001, "Thermodynamics of the magnetocaloric effect", Physical Review B, Vol. 64, p. 1444061-14440613.

Rowe, A., Tura, A., Dikeos, J., Chahine, R., 2005, "Near room temperature magnetic refrigeration", Proceedings of the International Green Energy Conference.

Tishin, A.M. and Spichkin, Y.I., 2003, "The magnetocaloric effect and its applications", IoP Institute of Physics Publishing.

Trevizoli, P.V., Barbosa Jr., J.R., Oliveira, P.A., Prata, A.T. and Ferreira, R.T.S., 2009, "Direct measurements of the magnetocaloric effect of gadolinium samples at near room temperature", Proceedings of the 20th International Congress of Mechanical Engineering, Gramado, RS, Brazil.

Trevizoli, P.V., 2010, "Experimental analysis of an active magnetic regeneration test device", M.Sc. diss. (in Portuguese), Federal University of Santa Catarina.

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