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Measuring the effect of demagnetization in stacks of gadolinium plates using the magnetocaloric effect

K.W. Lipsø [a], K.K. Nielsen [b,c,*], D.V. Christensen [b,d], C.R.H. Bahl [b], K. Engelbrecht [b], L. Theil Kuhn [b], A. Smith [b]

[a] Department of Physics, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
[b] Fuel Cells and Solid State Chemistry Division, Risø National Laboratory for Sustainable Energy, Technical University of Denmark, Frederiksborgvej 399, DK-4000 Roskilde, Denmark
[c] Department of Mechanical Engineering, Technical University of Denmark, Building 425, Niels Koppels Alle, DK-2800 Kgs. Lyngby, Denmark
[d] Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen, Denmark

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ABSTRACT

The effect of demagnetization in a stack of gadolinium plates is determined experimentally by using spatially resolved measurements of the adiabatic temperature change due to the magnetocaloric effect. The number of plates in the stack, the spacing between them and the position of the plate on which the temperature is measured are varied. The orientation of the magnetic field is also varied. The measurements are compared to a magnetostatic model previously described. The results show that the magnetocaloric effect, due to the change in the internal field, is sensitive to the stack configuration and the orientation of the applied field. This may have significant implications for the construction of a magnetic cooling device.

1. Introduction

Magnetic materials exhibit the magnetocaloric effect (MCE), which manifests itself as a change in temperature, ΔT_{ad}, when changing the magnetic field applied to the material under adiabatic conditions.

The MCE has been used since the 1920s as a tool to reach temperatures close to absolute zero [1]. It was later suggested to utilize it at near-room temperature by using thermal regeneration to increase the temperature span in a so-called active magnetic regenerator (AMR) [2,3]. In Refs. [4–6] extensive reviews of the application of the MCE in AMR devices are given.

One of the main components of a magnetic refrigerator based on the AMR is a regenerator made of a porous magnetic material in thermal contact with a heat transfer fluid. This component acts as a thermal regenerator that stores/releases heat and supports a temperature gradient in the flow direction, thus upholding a cold and a hot end, in close interaction with the heat transfer fluid (which is typically aqueous for room temperature applications). While working as a regenerator the AMR is exposed to a periodic change in applied magnetic field, H_{appl}. In this way the MCE in terms of the adiabatic temperature change provides the active work input to the refrigeration cycle [3].

The geometry of the regenerator may vary and typically either packed spheres [7,8] or parallel plates [9,10] are used. When numerical models of the AMR are considered the magnetic field is most often considered to be equal to the applied field, H_{appl} [11–16]. Recent material studies on a single rectangular plate subjected to conditions relevant for magnetic refrigeration show, however, that the internal magnetic field can differ significantly from the applied magnetic field [17,18]. This is due to the demagnetizing field created by the magnetization of the regenerator. This field is a function of the magnetization and the geometry of the regenerator [17,19–21]. The magnetization is in itself a function of the local field and temperature and given that the AMR is operating around the magnetic transition temperature of the material [22], which is where the largest MCE is achieved, the magnetization is generally far from being homogeneous in the material.

In this paper we consider stacks of parallel plates where the plates are identical and made of gadolinium. The resulting internal magnetic field of such a stack is found using a magnetostatic model previously published [17]. Experimentally, the adiabatic temperature change is measured directly on the surface of a single plate situated in various stack and magnetic field configurations.

2. Magnetostatic demagnetization model

It is well known that a magnetized body generates a magnetic field that, inside the body, tends to oppose the applied field. When

* Corresponding author at: Fuel Cells and Solid State Chemistry Division, Risø National Laboratory for Sustainable Energy, Technical University of Denmark, Frederiksborgvej 399, DK-4000 Roskilde, Denmark.
E-mail address: kaki@risoe.dtu.dk (K.K. Nielsen).

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the body is homogeneously magnetized this demagnetizing field may be expressed through a demagnetization tensor field, $\mathbb{N}(\mathbf{r})$, in the following way:

$$\mathbf{H}_{\mathrm{dem}}(\mathbf{r}) = -\mathbb{N}(\mathbf{r}) \cdot \mathbf{M}, \tag{1}$$

where $\mathbf{H}_{\mathrm{dem}}$ is the demagnetizing field and $\mathbf{M}$ is the magnetization. In general, $\mathbb{N}$ is a function of the shape of the magnetic body. For certain geometries, such as ellipsoids [23], infinite sheets, cylinders [24] and rectangular prisms [25] it may be found analytically.

When the magnetic body is not homogeneously magnetized, which is the case if, e.g., a temperature profile is present or the magnitude of $\mathbf{M}$ depends on the internal field, $\mathbf{H}$, Eq. (1) is not valid. The problem of finding the internal magnetic field given by

$$\mathbf{H} = \mathbf{H}_{\mathrm{appl}} + \mathbf{H}_{\mathrm{dem}} \tag{2}$$

is then coupled with finding the magnetization, which, in turn, is a function of the local field and temperature.

In Refs. [17,18] a numerical model of the demagnetizing field of rectangular prisms is presented. The model assumes a discretization into small rectangular sub-prisms, where the magnetization and temperature inside each sub-prism are assumed constant and homogeneous. In this way the analytical solution to Eq. (1) may be applied to each individual sub-prism and the solution of the entire system is then a superposition of the individual solutions. This is formulated mathematically as

$$\mathbf{H}_{\mathrm{dem}}(\mathbf{r}) \approx -\sum_{i=1}^{N} \mathbb{N}(\mathbf{r}-\mathbf{r}'_i) \cdot \mathbf{M}_0(\mathbf{H}(\mathbf{r}'_i, T_i), \mathbf{r}'_i, T_i), \tag{3}$$

where $\mathbf{r}$ and $\mathbf{r}'_i$ are the position vectors of the point at which the demagnetizing field is evaluated and the point contributing with the magnetization, $\mathbf{M}_0$, respectively. The index i denotes the respective sub-prism, or grid cell, and N denotes the number of grid cells. In this way the sum in Eq. (3) is taken over all the contributions to the resulting demagnetizing field at the location $\mathbf{r}$. The components of $\mathbb{N}(\mathbf{r})$ may be found in Ref. [17]. Eqs. (2) and (3) are combined with an appropriate state function for $M(T,H)$ and the direction of the magnetization is assumed to be along $\mathbf{H}$[19]. The model is then solved through iteration until it converges; see Ref. [17] for further details.

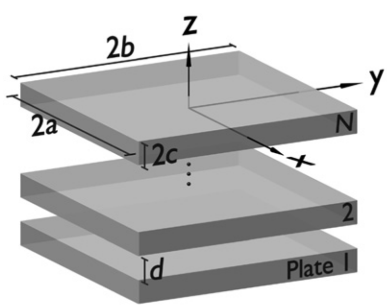

Fig. 1. The coordinate system of the stack of rectangular plates. The dimensions of each plate, $2a \times 2b \times 2c$, are indicated in the figure as are the number of plates, N, and the distance between adjacent plates, d.

Magnetization data is that of commercial grade Gd and are taken from the experimental determination of the magnetization as a function of internal magnetic field and temperature published in Ref. [26]. The adiabatic temperature change is found through interpolation from a table where it is given as a function of the internal magnetic field and temperature also published in Ref. [26].

The coordinate system employed for the stack of rectangular prisms is indicated in Fig. 1. The distance between the prisms is assumed constant and the prisms are assumed flat and uniform, i.e. plates. The distance between two adjacent plates is denoted d and the thickness of a single plate is $2c$. The stacking of rectangular plates will, in the case of magnetic refrigeration considered as an application, be as depicted in Fig. 1. Considering a single plate, application of a field along the x- or y-direction will thus maximize the internal field due to the resulting minimized demagnetizing field [17]. Application of the field along the z-direction will maximize the demagnetizing field and thus decrease the resulting internal field in a single rectangular plate. It follows qualitatively from Fig. 2 that application of the field along the x- or y-direction will tend to create an opposing magnetic field outside the individual plates, thus lowering the field in neighboring plates. In the case of magnetizing along the z-direction, the field external to the individual plate will tend to align with the internal field of neighboring plates thus increasing their total internal magnetic field.

It may therefore be concluded that it is not a priori obvious which configuration is optimal. This must be expected to be dependent on the number of plates in the stack, their relative dimensions and their spacing. It is thus of importance to investigate this in detail, which is the topic of the remainder of this paper.

3. Experimental

A plastic housing is used to make the different stack configurations. Thirteen grooves of 1 mm have been machined with a spacing of 0.8 mm. In this way various combinations of the number of plates and their positioning may be used.

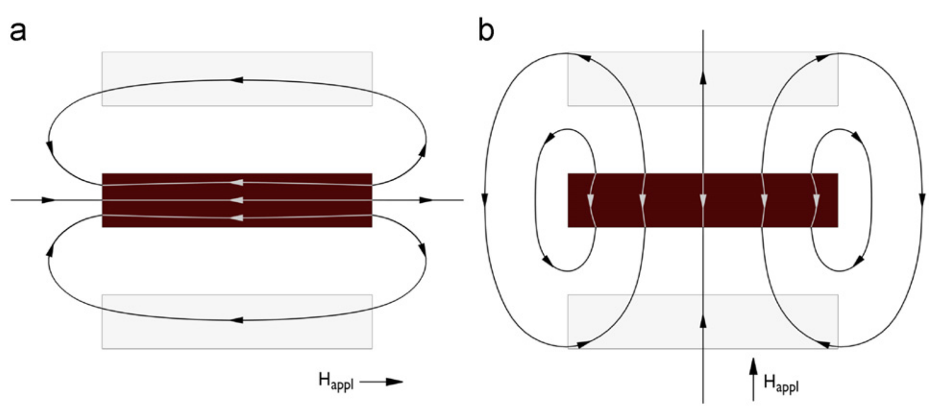

Fig. 2. Illustration of the magnetic field resulting from the magnetization of a single rectangular plate. In (a) The field is along the x-direction and thus parallel to the largest face of the plate. The resulting stray- or interaction field tends to oppose the applied field in the adjacent plates. In (b) the field is along the z-direction. The demagnetizing field inside the body is larger than in (a), however, the stray field tends to enhance the applied field in adjacent plates.