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Construction of consistent magnetocaloric materials data for modelling magnetic refrigerators

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ABSTRACT

The simulation of magnetocaloric refrigerator behaviour needs a good description of the material properties. Magnetocaloric material data are often given as a function of few values of the external magnetic field applied on a sample, but active material reacts to its internal field. The simulating of the magnetocaloric effect using experimental data can then create some artefacts. In this paper we present an alternative way to obtain material data expressed as a function of the internal magnetic field. This characterization is built on the knowledge of the zero magnetic field heat capacity of second-order phase transition materials such as gadolinium, as well as on the direct measurements of magnetocaloric data. An inverse approach is performed to calculate the data as a function of the internal magnetic field with an improved level of detail. The obtained data allow a better modelling of the magnetocaloric effect in an active magnetic regenerator.

Elaboration de données pertinentes sur les matériaux magnétocaloriques pour la modélisation des réfrigérateurs magnétiques

Mots clés : Réfrigérateur magnétique ; Modélisation ; Cycle thermodynamique ; Exergie ; Gadolinium

1. Introduction

The Magnetocaloric Effect (MCE) achieved in various magnetic materials can be used to build magnetic refrigeration systems within different temperature ranges (Tishin and Spichkin, 2003). These systems are free of greenhouse gas and are also potentially interesting from the point of view of energy efficiency. Numerous prototypes have demonstrated the feasibility of such systems using an Active Magnetic Regenerator (AMR) for applications around room temperature (Vasile and Muller, 2006). These prototypes have indicated different configurations and performance levels that can be expected from pre-industrial devices (Zimm et al., 2006; Yu et al., 2010). The simulation of magnetic refrigeration systems is fundamental for optimizing their performances. This allows implementing efficiently the MCE in order to be

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Nomenclature

Symbols

B	induction (kg A^{-1} s^{-2})
C	heat capacity (J kg^{-1} K^{-1})
D	demagnetizing factor
H	magnetic field (A m^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
M	magnetization (A m^{-1})
n	shape function parameter (–)
S	entropy (J kg^{-1} K^{-1})
T	temperature (K)
x	position (m)
Q	energy density (J m^{-3})

Abbreviations

AMR	Active Magnetic Regenerator
AMRR	Active Magnetic Regenerative Refrigeration
COP	Coefficient Of Performance
MCE	Magnetocaloric Effect
MCM	Magnetocaloric Material

Greek symbols

Δ	difference
δ	variation
μ_0	vacuum permeability (V s A^{-1} m^{-1})
ρ	density (kg m^{-3})
τ	shape function or parameter (–)
κ	function of first order (–)
χ	shape parameter (–)

Subscripts

a	parameters for the shape function
b	parameters for the shape function
ad	adiabatic
c	Curie
d	demagnetizing
e	external
i	internal
k	summation parameter
$leak$	leakage
p	pressure
H	magnetic field
HT	heat transfer
M	magnetic
MC	magnetocaloric
0	close to zero
fus	at fusion temperature

economically competitive compared to conventional refrigeration systems. Therefore this leads to the emergence of numerical models increasingly detailed (Nielsen et al., 2011). Some of these models implement the magnetocaloric effect as an instantaneous process due to a varying applied magnetic field as a square. Consequently, it is necessary to distinguish magnetocaloric data, the adiabatic temperature change (ΔT_{ad}), according to the increasing or decreasing magnetic field to ensure a model respecting the thermodynamic principles (Nielsen et al., 2010).

2. Implementing progressive magnetization in a model

In order to perform a better description of the magneto-thermodynamic cycle covered by the Magnetocaloric Material (MCM), it is important to simulate the magnetization and the demagnetization as a progressive process and in a continuous manner using numerous steps of magnetic field values between the lower field and the higher field values (Risser et al., 2010). The equation of heat for an AMR with regular matrix, along the direction x of the thermal gradient from the cold side to the hot side is given by:

$$\rho \cdot C_{H,p} \cdot \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \cdot \left(k \cdot \frac{\partial T}{\partial x} \right) + \dot{Q}_{MC} + \dot{Q}_{leak} - \dot{Q}_{HT} \tag{1}$$

Where ρ is the density of the material, $C_{H,p}$ its heat capacity at constant magnetic field and pressure, T its temperature and k its thermal conductivity. $\dot{Q}_{leak}$ represents the heat leakages due to the imperfect thermal insulation and $\dot{Q}_{HT}$ is the heat transfer between the thermal fluid and the material. $\dot{Q}_{MC}$ is corresponding to the generation of heat or cold from the magnetocaloric effect. This term can be calculated from adiabatic temperature change ($\partial T_{ad}/\partial H_i$) or magnetic entropy change ($\partial S_M/\partial H_i$) due to the varying of the internal magnetic field H_i as it follows:

$$\dot{Q}_{MC} = \frac{\partial T_{ad}(T,H_i)}{\partial H_i} \cdot \frac{\partial H_i}{\partial t} \cdot C_{H,p}(T,H_i) \cdot \rho = -\frac{\partial S_M(T,H_i)}{\partial H_i} \cdot \frac{\partial H_i}{\partial t} \cdot T \cdot \rho \tag{2}$$

In the AMR of a device, the variation of the magnetic field is not instantaneous and it is not an adiabatic process either due to the contact with the coolant fluid. A high precision of the simulation, consistent with the principle of energy conservation for non adiabatic magnetization should be achieved without distinguishing magnetocaloric data as a function of the sense of the varying field. The discrete step of adiabatic temperature change is determined as:

$${}^{H_i+\delta H_i}_{H_i}\delta T_{ad}(T) = {}^{H_i+\delta H_i}_{0}\Delta T_{ad}(T) - {}^{H_i}_{0}\Delta T_{ad}(T) \tag{3}$$

where T is taken as the average temperature of the material between H_i and $H_i + \delta H_i$. The accuracy of the model is strongly dependant on the magnetic field step δH_i during the magnetization phase and the demagnetization phase.

3. Impact of the demagnetizing field

Another relevant problem is revealed by the demagnetizing field that requires making a difference between external applied magnetic field and internal field that causes the magnetocaloric effect. The demagnetizing field is depending on the geometry and on the orientation of the volume of MCM relatively to the magnetic field. Hence, for the same external