Available online at www.sciencedirect.com
ScienceDirect

International Journal of Refrigeration 29 (2006) 1358–1365

REVUE INTERNATIONALE DU FROID
INTERNATIONAL JOURNAL OF
refrigeration

www.elsevier.com/locate/ijrefrig

Effect of material hysteresis in magnetic refrigeration cycles

Vittorio Basso[a,*], Carlo Paolo Sasso[a], Giorgio Bertotti[a], Martino LoBue[b]

[a]*Istituto Nazionale di Ricerca Metrologica (INRIM), Strada delle Cacce 91, I-10135 Torino, Italy*
[b]*SATIE UMR CNRS 8029, IFR d'Alembert, ENS de Cachan, 61 Avenue du Président Wilson, 94235 Cachan, France*

Received 27 January 2006; received in revised form 7 August 2006; accepted 8 August 2006
Available online 7 November 2006

Abstract

In this paper we make use of the concepts of out-of-equilibrium thermodynamics applied to systems with hysteresis in order to model the magnetic material employed as a working substance in magnetic refrigeration cycles. The approach developed leads to a detailed description of heat fluxes as well as the entropy production connected with hysteresis. As an example we discuss Carnot and AMR refrigeration cycles where hysteresis effects are included.

Keywords: Magnetic refrigeration; Preisach model; Thermodynamic cycle

Effet de l'hystérésis du matériau dans les cycles frigorifiques magnétiques

Mots clés : Froid magnétique ; Modèle de Preisach ; Cycle thermodynamique

1. Introduction

The magnetocaloric effect has been studied for a long time for its potential use in refrigeration cycles. Recent progresses in material science, notably with the development of new materials exhibiting magnetocaloric effect (see the reviews of [1,2]), have generated a renewed interest in the development of magnetic refrigeration systems working around room temperature. Materials of interest include rare-earth-based ferromagnets, like Gd, Y–Fe and Gd–Fe, with a Curie point around room temperature, and alloys like Gd–Si–Ge [1], which display the so-called giant magnetocaloric effect connected to the presence of a first-order phase transformation induced by magnetic field.

The technological outlook promised by the introduction of this new family of materials has been accompanied by a growing interest in their physical properties including, temperature changes and entropy changes achievable by magnetic field. In this context, the fact that the working material displays hysteresis [3] calls for a better physical understanding of the role of irreversibility in the magnetization process.

Within the limits of equilibrium thermodynamics all the machinery of classical Gibbs thermostatics may be successfully used to describe the materials and to derive the performance of thermodynamic cycles. For example, the temperature change or entropy change due to a magnetic field

* Corresponding author. Tel.: +39 011 3919 842; fax: +39 011 3919 834.
E-mail address: basso@inrim.it (V. Basso).

0140-7007/$35.00 © 2006 Elsevier Ltd and IIR. All rights reserved.
doi:10.1016/j.ijrefrig.2006.08.001

Nomenclature

s	specific entropy
T	absolute temperature
M	magnetization
μ_0	permeability of vacuum
H	magnetic field
δs	variation of the specific entropy
$\delta_e s$	variation of the exchanged specific entropy
$\delta_i s$	variation of the specific entropy production
M_s	saturation magnetization
Δm	magnetic moment of the Preisach unit
h_u	local interaction field of the Preisach unit
h_c	local coercive field of the Preisach unit
$p(h_c, h_u)$	Preisach distribution
$b(h_c)$	state line
z_u	normalized local interaction field of the Preisach unit
z_c	normalized local coercive field of the Preisach unit
Q_u	h_u scaling factor
Q_c	h_c scaling factor
$\tilde{p}(z_c, z_u)$	normalized Preisach distribution
$\tilde{b}(z_c)$	normalized state line
$\tilde{H}$	normalized magnetic field
g_M	specific Gibbs free energy of the magnetic subsystem
f_M	specific free energy of the magnetic subsystem
s_M	specific entropy of the magnetic subsystem
s_B	specific entropy of the non-magnetic subsystem
s_R	specific entropy of the regenerative fluid
v_B	volume of the magnetic material
v_R	volume of the regenerative fluid

H may be derived from the graphical representation of the specific entropy $s(T, H)$ constitutive relation in the $s-T$ plane [4]. The performance of different kinds of cycles (Carnot, Ericsson, Bryton, AMR) can be directly derived from these diagrams.

However, if the material displays hysteresis, the equilibrium $s-T$ diagram is no longer sufficient to describe the material behavior. Internal entropy production takes place during the magnetization process and a specific out-of-equilibrium approach to the material behavior is needed.

The aim of our study is to develop a modelling approach permitting one to represent the out-of-equilibrium properties of the magnetic material. The constitutive relation is replaced by the entropy balance equation $\delta s = \delta_i s + \delta_e s$, in which the measurable quantity, i.e. the heat flux $T\delta_e s$, is proportional to the exchanged entropy $\delta_e s$ and the internal entropy production term $\delta_i s$ is present.

The model we describe in this paper is far from being a general theory of hysteretic systems. However, it has the merit of working out in detail a case for which both the system entropy s and the entropy production $\delta_i s$ can be expressed in closed analytical forms. Furthermore, the equations of state describing the magnetization as a function of the field and temperature have been shown to be an excellent tool for the description of ferromagnetic materials behavior [5,6]. In addition, the formalism of our approach bears strong similarities with a well known approach to out-of-equilibrium systems which is known as thermodynamics of materials with memory [7].

Irreversible thermodynamics is the appropriate context to study dissipation phenomena associated with hysteresis. In recent papers (see Ref. [8] for a review) the thermodynamics of hysteresis was studied for a system made of the superposition of non-interacting two-level systems (TLS) using an internal variables thermodynamic approach. When the magnetic field H and the temperature T are externally controlled quantities, explicit expressions for the magnetization M, the entropy s and the entropy production $\delta_i s$ were derived. One of the merits of this approach is that the isothermal constitutive relation $M(H;T)$ is equivalent to the very well known Preisach model of hysteresis [8] whose applications to magnetic materials have been extensively studied.

A common way to describe systems characterized by long-living non-equilibrium states consists in the introduction of a proper set of additional variables, vanishing when the system reaches equilibrium, which are assumed to still enable the use of state functions, like Gibbs free energy, when the system is not at equilibrium. One of the main properties of these non-equilibrium variables is that they appear in the constitutive relations, but not in the work expression of the first law. For this reason they are called internal variables [7]. In our case internal variables account for dissipative processes taking place along hysteresis curves. This approach is extensively discussed in Ref. [8].

In Section 2 we make use of the internal variable approach in order to formulate the thermodynamics of hysteresis for a system consisting of the superposition of two-level subsystems (Preisach model) [8]. The approach gives the explicit expressions for the magnetization, the entropy and the entropy production for a system with hysteresis [8]. The resulting model is an appropriate description of the magnetic part (M) of a ferromagnetic body.

In Section 3 we discuss how this approach can be employed to model the thermodynamic behavior of a ferromagnetic body in order to predict the exchanged heat along a thermodynamic transformation [9,10].

In Section 4 we employ the same model to compute thermodynamic transformations in refrigeration cycles. Due to the conceptual difficulties associated with constitutive laws with hysteresis, the literature dealing with the design and optimization of thermodynamic cycles for magnetic