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A simple magnetic refrigerator evaluation model

Wen-Nan Huang[a,b,*], Ching-Cheng Teng[a]

[a] Department of Electrical and Control Engineering, National Chiao-Tung University, Hsin-Chu, Taiwan
[b] ERL, Industrial Technology Research Institute (ITRI), Hsin-Chu, Taiwan

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Abstract

The simple evaluation model utilizing the selective parameters for the preliminary analysis for magnetic refrigerator (MR) development is proposed in this paper. The magnetocaloric effect and the related magnetic field applied for MR are also discussed. The model and system analysis following the algorithm expressions and the material characteristics required for MR are arranged and derived in related evaluation terms. The simulation results verify the feasibility and applicability for this simple evaluation model.
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Keywords: Magnetic refrigerator; Magnetocaloric effect

1. Introduction

The magnetocaloric effect (MCE), which indicates the mapping relation between the temperature and magnetic field by the description for the adiabatic temperature change of materials produced by the magnetic entropy change upon the application and removal of a magnetic field, introduced in Refs. [1–4]. MCE is generally largest in rare-earth elements, such as gadolinium (Gd), addressed in Ref. [5]. Besides that, the Curie temperature is also an important factor highly related to the MCE for the largest change of magnetic entropy.

Magnetic refrigerator (MR), the thermodynamics application device concept utilizing the MCE, is attracting considerable attention in possible market applications worldwide of late due to which the MR is environmentally benign and has a number of advantages while comparing with the conventional vapor-cycle refrigerator, which basically include the consideration for efficiency, mechanical vibration and size, described in Refs. [4–7]. A compound based on gadolinium, has previously been shown to work as a magnetic refrigerant, described in Refs. [8,9].

For the requirement of application, to obtain large MCE is the objective for material related research. Hence, the materials possess large magnetic moment and sharp magnetic transition are expected. Usually, the sharp magnetic transition is coupled with lattice change. Other than that, the applied material composition is also strongly involved, which brings the difficulty for

*Corresponding author. Department of Electrical and Control Engineering, National Chiao-Tung University, Hsin-Chu, Taiwan. Tel : +886-3-5914263; fax: +886-3-5820050.
E-mail address: wnhuang.ece88g@nctu.edu.tw (W.-N. Huang).

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the MR development, especially during the prototype evaluation phase.

No doubt that the evaluation methods for the MCE applied in the MR need to be developed for providing the preliminary analysis for clearly understanding in advance for system limitation and performance of integration. The research achievements will be useful for the material research and meeting the requirement for system integration considerations of MR.

2. Magnetic refrigerator concept

In recent years, the most important development achievement for putting MR into one of the acceptable practices in the near future is Astronautics demonstrated a 500 W near-room temperature magnetic refrigerator that operated at a competitive efficiency in 1997, which also described in Refs. [8,10–12]. We arrange the remarkable research results for MR, shown as Fig. 1. The heating and cooling that takes place in MR is related to the size of the applied magnetic field and the magnetic moments. As the magnetic moments of the atoms are aligned upon the application of a magnetic field, the MCE is a warming effect for MR for the ferromagnetic case. In the reverse way, the MCE is a cooling effect when the magnetic moments become randomly oriented upon removing the magnetic field. From Refs. [11,12], we can realize that the implementation for MR includes several categories: material studies, magnetic field supplying design, thermal transfer structure design, and system integration evaluation. Some models are also proposed for specific function described above in Refs. [13–16]. However, sophisticated assumptions and many unknown indexes required make them difficult to be utilized for the MR prototype concept research.

3. Evaluation method

In order to keep moving toward the future research phase, the evaluation for the related feasibility indexes, such as efficiency, electromagnetic effect, and temperature difference achievement of the developing magnetic refrigeration device is needed. Therefore, we try to elaborate a simple model for the evaluation of MR-related research requirements and it is the motivation for proposing this method.

3.1. Entropy

As MR working, the status for the gadolinium mass or its compound being magnetized or demagnetized at any moment decides the action

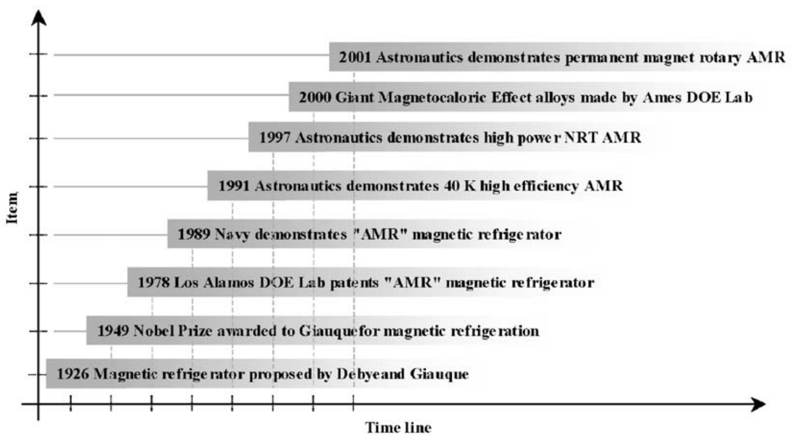

Fig. 1. The remarkable achievements for MR.

of MR. Entropy is the most important parameter that has to be concerned and observed for the thermal and succeeding heat transfer status evaluations. According to the related definition, the entropy equation could be expressed as Eq. (1)

$$s(B,T) = s_M(B,T) + s_L(T) + s_E(T), \tag{1}$$

where s, s_M, s_L, and s_E are respectively the total entropy, the magnetic entropy, the lattice entropy, and the electron entropy. B and T denote the magnetic flux density and the temperature.

We arrange the related calculation equations and methods to be part of the preparation, in Table 1, for the proposed model. The computation results are conformed to the known material properties and shown as Fig. 2 for the related information of the magnetic entropy and the total entropy, respectively.

3.2. Analysis strategy

The simple MR evaluation model is derived from basic thermodynamic opinions, such as

Table 1
The entropy calculation method

Magnetic entropy model	Lattice entropy model	Electron entropy model
$S_M(B,T) = R\left[\ln\sinh\left(\frac{2J+1}{2J}\chi\right) - \ln\sinh\left(\frac{1}{2J}\chi\right) - \chi B_J(\chi)\right]$	$S_L = \int_0^T \frac{C_L}{T}\,dT$	$S_E = \gamma T$
$B_J(\chi) = \frac{2J+1}{2J}\operatorname{ctnh}\left(\frac{(2J+1)\chi}{2J}\right) - \frac{1}{2J}\operatorname{ctnh}\left(\frac{\chi}{2J}\right)$	$C_L = 9Nk\left(\frac{T}{\theta_D}\right)^3 \int_0^x \frac{x^4 e^x}{(e^x-1)^2}\,dx$	
$\chi = \frac{g_J J \mu_B B}{kT} + \frac{3\theta_c J B_J(\chi)}{T(J+1)}$	$x = \theta_D/T$	

J is the total angular momentum quantum number, R is the the universal gas constant, $B_J(\chi)$ is the the Brillouin function, g_J is the Lande' factor, k is the the Boltzman's constant, μ_B is the Bohr magneton, θ_c is the Curie temperature, B is the external magnetic field, T is the temperature, N is the atomic number, θ_D is the Debye temperature, γ is the electron constant.
The definitions are referred to solid-state physics-related books and published lectures. However, the summation of change for the two entropy values, both not change by the magnetic field, is fewer portion in our developing phase MR system evaluation conditions.

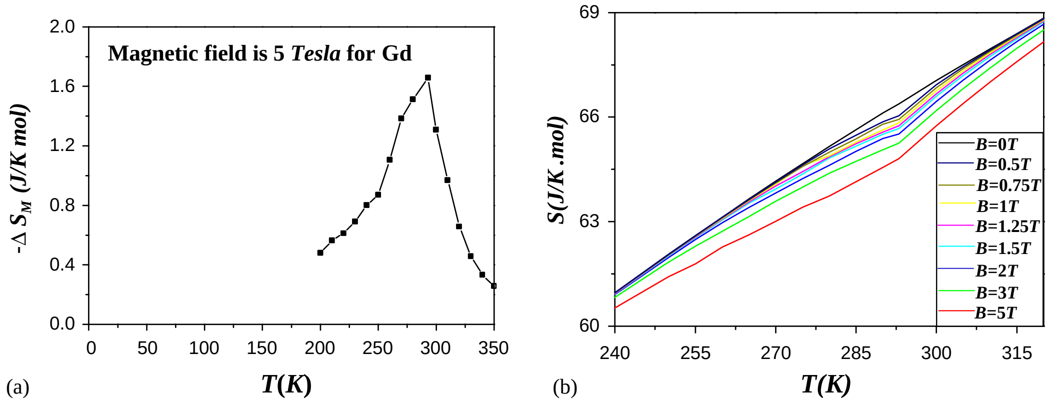

Fig. 2. The entropy computational results for Gd. (a) Magnetic entropy, (b) sum of the entropy.

Table 2
The derivation remark of the evaluation model

Magnetism related term	Entropy related term	Free energy term
$\mu_0 H\,dM$	$T\,ds$	$-s\,dT + \mu_0 H\,dM + T\,ds$
Main derivation:		*Obtain:*
1st step	2nd step	
$dF = dU - T\,ds - s\,dT$	$dU = dF + T\,ds + s\,dT$	$dT = \frac{T\,ds}{s} + \frac{\mu_0 H\,dM}{s} - \frac{(dF + T\,ds)}{s}$
$dU = dQ - dW = T\,ds + \mu_0 H\,dM$	$dF + T\,ds + s\,dT = T\,ds + \mu_0 H\,dM$	
	$s\,dT = T\,ds + \mu_0 H\,dM - dF - T\,ds$	

Q is the heat, W is the work.

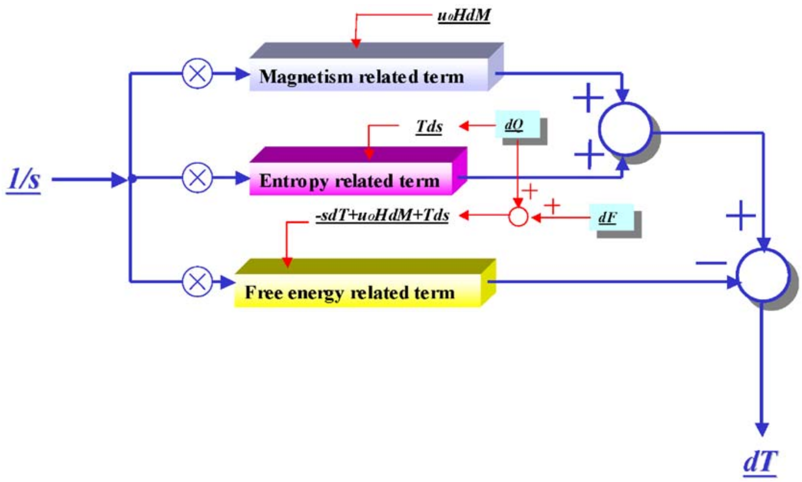

Fig. 3. The simple evaluation model analysis scheme.

enthalpy, Helmholtz free energy and Gibbs free energy, expressed as Eqs. (2)–(4), respectively.

$$h = U + PV, \tag{2}$$

$$G = h - Ts, \tag{3}$$

$$F = U - Ts, \tag{4}$$

where h denotes enthalpy; U, P, and V, say, internal energy, pressure and volume of the

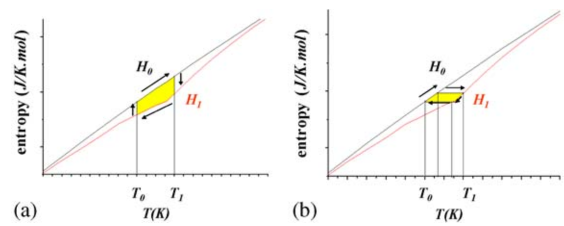

Fig. 4. The two cycles applied to consider. (a) Ericsson cycle, (b) Brayton cycle.

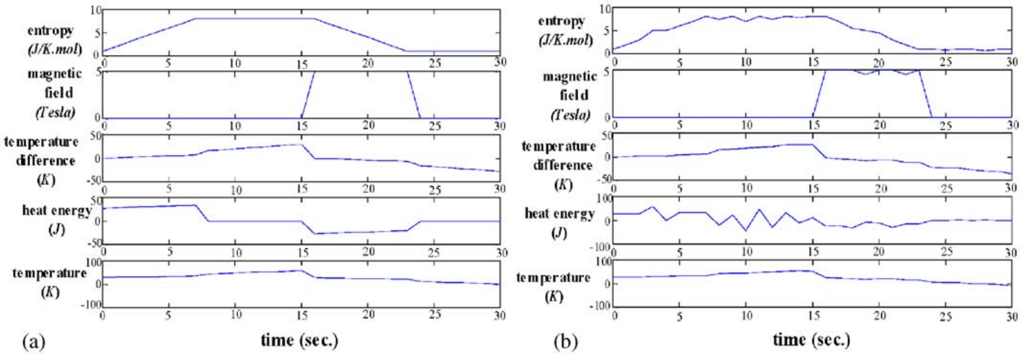

Fig. 5. The simulation results for MR evaluation. (a) For Ericsson cycle, (b) for Brayton cycle.

system; G and F mean Gibbs free energy and Helmholtz free energy, respectively.

For obtaining the simple analysis opinion among the magnetic field, entropy, and related thermal parameters, we make use of the magnetic moment related equation to be the basis for linking relation, as Eq. (5)

$$B = \mu_0(H + M/V_s), \tag{5}$$

where H denotes the magnetic field intensity; μ_0, M, and V_s mean, the coefficient of magnetic permeability, the magnetic moment, and the specific volume.

Then, by the work definition and derivation, we can analyze the MR related performance by Eqs. (2)–(5), depicted in Table 2. A basic evaluation opinion, based on Eq. (6), can be obtained as

$$dT = \frac{T\,ds}{s} + \frac{\mu_0 H\,dM}{s} - \frac{(dF + T\,ds)}{s}. \tag{6}$$

The simple model, shown as Fig. 3, is further divided into three terms: magnetism related term, entropy related term, and free energy related term, respectively. The input requiring parameter of this simple evaluation model is entropy related and then we can evaluate the temperature difference, which is the model output, by some magnetic parameter settings.

4. Simulation and case evaluation

The two applicable thermal cycles, Ericsson cycle and Brayton cycle, whose $T-S$ operation status are shown as Fig. 4, being taken into account to verify the proposed model evaluation capability. The simulation results, T_0 and T_1 are chosen to be 210 and 310 K, demonstrated the feasibility of the proposed evaluation model by the required temperature differences, shown as Fig. 5, and is also useful for the material research and meeting the magnetic field requirement for MR system integration considerations.

5. Conclusions

A simple MR evaluation model is developed from the algorithms derivation procedures. The Ericsson cycle and Brayton cycle are also applied for verifying the proposed evaluation model. The simulation demonstrated the feasibility of the proposed evaluation model. The simple MR evaluation model is easy to be utilized for the analysis and integration evaluation.

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