Cooling Properties of Gd Alloys and $La(Fe,Si)_{13}$-Based Compounds in Active Magnetic Refrigeration for Environmentally-Friendly Cooling Systems

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***Abstract*—There is currently a global demand for highly-efficient and environmentally-friendly refrigeration techniques. The new concept of active magnetic regenerative (AMR) refrigeration has received much attention as a potential alternative to conventional gas expansion cooling. In the present study, Gd alloys and $La(Fe,Si)_{13}$-based compounds, both of which have been considered as likely candidates for solid magnetic refrigerants, were investigated in terms of their cooling properties in an AMR-cycle system. As a results, feature of the cooling properties with both materials were clarified. The Gd alloys are evidently suitable for the generation of large temperature differences, in contrast to the $La(Fe,Si)_{13}$-based compounds, which exhibit good heat-load properties. Numerical calculations support these experimental results and indicate that multi-layered structures composed of the $La(Fe,Si)_{13}$-based compounds with gradually varying Curie temperatures are effective at increasing the temperature difference and also demonstrate good heat-load properties. The optimization of magnetic refrigerants such as these is expected to result in new environmentally-friendly cooling systems.**

***Index Terms*—Environmentally-friendly, magnetic refrigeration, magnetocaloric effect, solid refrigerants.**

I. Introduction

Magnetic refrigeration based on the magnetocaloric effect has received significant attention as an environmentally friendly cooling technique, since the working substance is a solid magnetic refrigerant rather than a gas such as a chlorofluorocarbon (CFC), hydrochlorofluorocarbon (HCFC) or hydrofluorocarbon (HFC), as in conventional gas expansion cooling systems. Solid refrigerants have the advantage of higher energy density and are also retrievable and recyclable without the potential for the environmental release of ozone-depleting or greenhouse gases. Over the last few decades, new magnetic refrigeration systems and magnetic refrigerant materials have been actively investigated [1]-[10] for use in refrigerating and cooling systems for commodities. For practical applications, magnetic refrigerant materials must exhibit suitable cooling performance under the low magnetic fields that can be generated by permanent magnets. Several magnetocaloric materials, such as Gd and its alloys [1], [11] as well as $Gd_5Ge_2Si_2$ [2], Mn(As,Sb) [12], MnFe(P,As) [13], and $La(Fe,Si)_{13}$-based compounds [14]-[19], have been proposed as candidates for room temperature magnetic refrigeration (RTMR).

Gadolinium (Gd) is well-studied material that was used in the first successful work with RTMR in 1976 [1]. However, Gd is unfavorable for practical use because of concerns regarding sustainability, as it is a rare-earth element. Mn(As,Sb) or MnFe(P,As)-based compounds are also unfavorable for practical use because they contain arsenic and also because of their large thermal hysteresis in the magnetocaloric effect. In contrast, $La(Fe,Si)_{13}$-based compounds contain iron as the major element at more than 80% by atomic ratio, and show little thermal hysteresis [8]. Therefore, $La(Fe,Si)_{13}$-based compounds are considered to be the most-favored candidates for magnetic refrigerants in practical use. Despite this, there has been little research on the refrigeration properties obtained when using $La(Fe,Si)_{13}$-based compounds as the magnetic refrigerant.

To clarify the refrigeration properties of $La(Fe,Si)_{13}$-based compounds, it is important to develop new magnetic refrigeration technologies. In the present study, we fabricated spherical particles of Gd alloys and $La(Fe,Si)_{13}$-based compounds and characterized their magnetocaloric properties and specific heat values. Moreover, the cooling properties obtained from active magnetic regenerative (AMR) refrigeration using particle shaped refrigerants composed of $La(Fe,Si)_{13}$-based compounds were investigated and compared with that obtained when using Gd alloys. The differing characteristics of these materials when applied to AMR were clarified by both experimental study and numerical calculations.

II. Experimental

A. Material Preparations and Method for the Evaluation of Cooling Properties

Fig. 1 presents a conceptual diagram of the AMR-cycle refrigeration process. Magnetic refrigerant particles were packed into a cylindrical container (the AMR unit) filled with heat transfer fluid. The AMR-cycle process consists of the following four steps: 1) a magnetic field is applied to the AMR unit, causing the magnetic refrigerants to warm, 2) the

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heat transfer fluid flows from the cold to the hot end through the magnetic refrigerants, and warm heat is thus transported to the hot side by the flow, 3) the magnetic field is removed from the AMR-unit, causing the magnetic refrigerants to cool down, and 4) the heat transfer fluid flows from the hot to the cold end (in the opposite direction to step 2) through the magnetic refrigerants, and cold heat is transported to the cold side by the flow. After repeated cycles, a temperature gradient is generated in the AMR-unit because of heat accumulation in the refrigerant particles, which are inhibited of thermal flow by their point-contact.

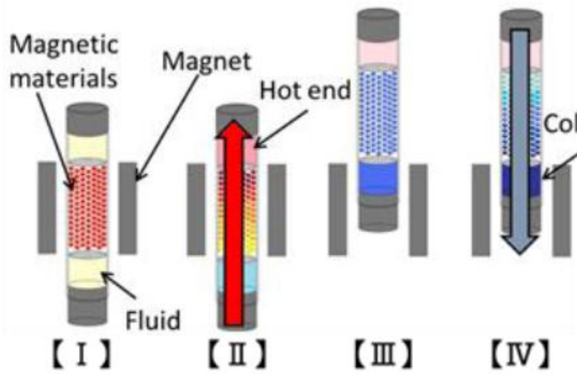

Fig. 1. Conceptual view of the AMR-cycle process.

To obtain magnetocaloric materials for use in AMR-cycle trials, spherical particles of Gd alloys and $La(Fe,Si)_{13}$-based compounds were prepared from their respective mother alloys by means of the rotating electrode process (REP). The resulting particle diameters varied from 0.2 to 1.2 mm in accordance with rotational speed of the mother alloy electrode. In the case of the $La(Fe,Si)_{13}$-based compounds, the spherical particles were subjected to heat treatment at 1050 ℃ for 10 days to obtain a $NaZn_{13}$-type crystal structure by atomic interdiffusion between mutual phases. The crystal structures of the particles were confirmed by X-ray diffraction (XRD) and magnetic properties were identified using a superconducting quantum interference device (SQUID) magnetometer (Quantum Design).

Two g samples of each type of magnetic refrigerant particle were packed into a mini-tube and the temperature changes resulting from the magnetocaloric effects within the mini-tube were measured in dry air under a magnetic field of $\mu_0 H_{ext} = 0.8$ T (hereafter referred to as simple magnetocaloric test). In addition, approximately 100 g samples of each type of magnetic refrigerant particle (approximately 12.5 cc in volume) were packed into a cylindrical AMR-unit, after which the cylinder was filled with heat transfer fluid. The heat transfer fluids were either water or a 20% ethylene glycol solution. The $La(Fe,Si)_{13}$-based compound particles were coated with copper to prevent corrosion by the fluids. The reciprocating motion of the heat transfer fluid was heat controlled by pistons movement attached to the top and the bottom sections of the AMR-unit. The strength of the applied magnetic field was approximately 1.1 T. The temperatures at the hot and the cold ends of the AMR-unit were monitored by type K thermocouples during the AMR-cycle operation. A heat load could be applied to the cold end of the AMR-unit using an electrical heater attached to the tip of the bottom piston. The cooling characteristics during the AMR-cycle were evaluated with magnetic refrigerant particles composed of either Gd alloys or $La(Fe,Si)_{13}$-based compounds under a variety of conditions, as shown in Table I. The specifications of the AMR-unit are given in Table II.

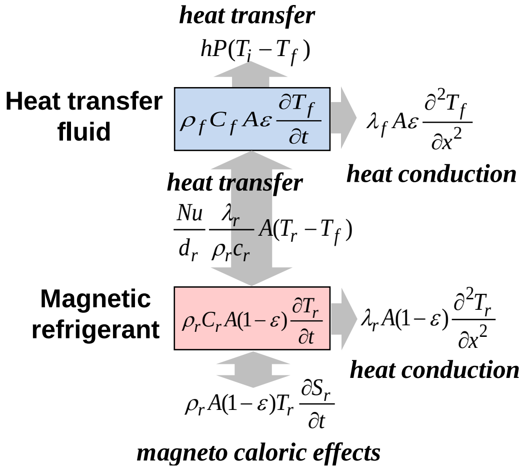

Fig. 2. Schematic of heat flow in the AMR-cycle.

TABLE I: AMR-CYCLE OPERATING CONDITIONS

Parameters	Ranges
Ambient temperature T_i (℃)	5 to 35
AMR cycle frequency f (Hz)	0.3, 0.4
Heat load input power Q (W)	0 to 3.6

TABLE II: AMR-UNIT SPECIFICATIONS

Material	Particle size (μm)	Fluid
Gd	710 to 850	Water
$Gd_{0.985}Y_{0.015}$	710 to 850	20% ethylene glycol solution
$La(Fe_{0.86}Si_{0.14})_{13}H_{1.2}$	500 to 850	Water
$La(Fe_{0.85}Co_{0.07}Si_{0.08})_{13}$	500 to 850	Water

B. AMR Model for Numerical Calculations and Method of Evaluating Cooling Properties

A one-dimensional model of the heat flow during the AMR-cycle is presented in Fig. 2. The governing equations for the magnetic *refrigerant* and the heat transfer fluid are as follows, respectively:

$$\rho_r c_r A(1-\varepsilon)\frac{\partial T_r}{\partial t} = \lambda_r A(1-\varepsilon)\frac{\partial^2 T_r}{\partial x^2} + \frac{Nu}{d_r}\frac{\lambda_r}{\rho_r c_r}A(T_f - T_r) - \rho_r A(1-\varepsilon)T_r\frac{\partial S_r}{\partial t} \quad (1)$$

and

$$\rho_f c_f A\varepsilon\frac{\partial T_f}{\partial t} + \dot{m}c_f\frac{\partial T_f}{\partial x} = \lambda_f A\varepsilon\frac{\partial^2 T_f}{\partial x^2} + \frac{Nu}{d_r}\frac{\lambda_r}{\rho_r c_r}A(T_r - T_f) + hP(T_i - T_f) \quad (2)$$

Here T is the temperature, C is the specific heat, S is the entropy, ρ is the density, λ is the thermal conductivity, and the subscripts r and f indicate refrigerant material and fluid, respectively. The Nu term is the Nusselt number, m is the mass flow rate of the heat transfer fluid, d_r is the diameter of the refrigerant material particles, A is the cross-sectional area of the flow and ε is the porosity in the AMR-unit cylinder body. The heat flow in an AMR-cycle procedure was calculated in four sequential steps, considering the heat exchange between the refrigerant material and the fluid over a number of small elements along the flow direction. The temperature variations in the AMR-unit were obtained as functions of time and one-dimensional position. After repeating the calculation of AMR-cycle, the temperature gradient of the AMR-unit was obtained. Moreover, the calculation takes into account the additional effect of heat load.

III. Results and Discussion

Temperature dependence of magnetic entropy change, ΔS_m in spherical particles of Gd, $La(Fe_{0.86}Si_{0.14})_{13}H_{1.2}$ [17] and $La(Fe_{0.85}Co_{0.07}Si_{0.08})_{13}$ (these $La(Fe,Si)_{13}$-based compounds are referred to collectively as LaFeSi) under an external field of $\mu_0 H_{ext}$ = 0.8 T are summarized in Fig. 3. The magnetic entropy changes were estimated from magnetization curves using the Maxwell relation: $(\partial S/\partial H)_T = (\partial M/\partial T)_H$. Each plot exhibits a peak in the vicinity of the material's Curie temperature (T_C); 21, 24 and 13 °C for Gd, $La(Fe_{0.86}Si_{0.14})_{13}H_{1.2}$, and $La(Fe_{0.85}Co_{0.07}Si_{0.08})_{13}$. The ΔS_m peak values in these materials are approximately equal, although the peak widths are different. Fig. 4 shows the results from a simple magnetocaloric test with Gd or $La(Fe_{0.86}Si_{0.14})_{13}H_{1.2}$ particles at various ambient temperatures in an external magnetic field $\mu_0 H_{ext}$ = 0.8 T. Both samples exhibit a peak around their T_C value. The peak value of ΔT in the case of the $La(Fe_{0.86}Si_{0.14})_{13}H_{1.2}$ is less than half that generated by the Gd, whereas both materials exhibit approximately equal ΔS_m peak values. Taking into account the relation $T\Delta S = C\Delta T$ and the two times greater specific heat of $La(Fe_{0.86}Si_{0.14})_{13}H_{1.2}$ compared with that of Gd (inset to Fig. 4), the lower ΔT value observed for the $La(Fe_{0.86}Si_{0.14})_{13}H_{1.2}$ is consistent with the ΔS_m data.

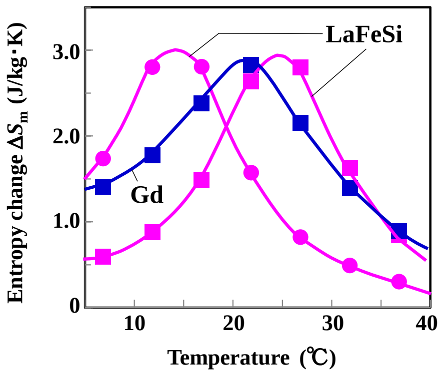

Fig. 3. Temperature dependence of magnetic entropy change, ΔS_m, in spherical particles of Gd and LaFeSi compounds in an external field $\mu_0 H_{ext}$= 0.8 T. Blue squares, pink squares and pink circles indicate Gd, $La(Fe_{0.86}Si_{0.14})_{13}H_{1.2}$, and $La(Fe_{0.85}Co_{0.07}Si_{0.08})_{13}$.

The refrigeration properties of the different AMR-units listed in Table II were subsequently investigated. Fig. 5 shows the temperature changes at the hot and the cold ends of the AMR-unit during AMR-cycle operation with Gd or LaFeSi particles at a cycling frequency of f = 0.3 Hz. The steady state temperature difference between both ends is defined as the temperature span, ΔT_{span}. The variations of ΔT_{span} with temperature observed for the various AMR-units listed in Table II are shown in Fig. 6. Broad peaks are observed for each refrigerant material. The ΔT_{span} peak values obtained when using the Gd and $Gd_{0.985}Y_{0.015}$ refrigerants are almost equal and also significantly larger than those observed when employing the $La(Fe_{0.86}Si_{0.14})_{13}H_{1.2}$ and $La(Fe_{0.85}Co_{0.07}Si_{0.08})_{13}$ refrigerant. These represent reasonable results considering that ΔT_{span} results from the heat accumulation, ΔT, as measured during the simple magnetocaloric test. As described above, the smaller ΔT associated with the $La(Fe_{0.86}Si_{0.14})_{13}H_{1.2}$ in the simple magnetocaloric test is attributed to its greater specific heat compared to that of Gd. The higher specific heat should lead to the larger permissible heat load. Therefore, the AMR-cycle properties with heat-load were investigated to clarify the effects of this higher specific heat.

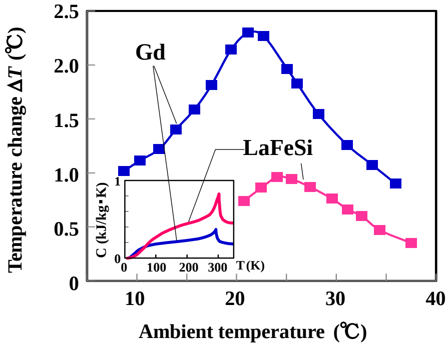

Fig. 4. Temperature change, ΔT, during simple magnetocaloric tests with Gd or $La(Fe_{0.86}Si_{0.14})_{13}H_{1.2}$ particles at various ambient temperatures in an external field change $\Delta\mu_0 H_{ext}$= 0.8 T. The insert shows the specific heats of these materials.

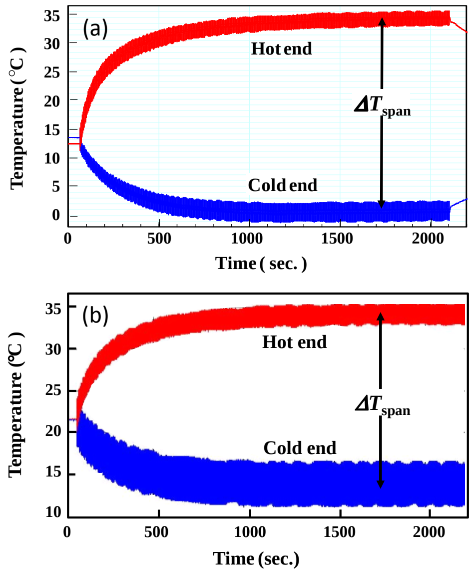

Fig. 5. Temperature changes at the hot and the cold ends of the AMR-unit during AMR-cycle operation with (a) Gd particles at the ambient temperature T_i= 13℃, and (b) LaFeSi particles the ambient temperature T_i= 21℃ where the cycle frequency f = 0.3 Hz.

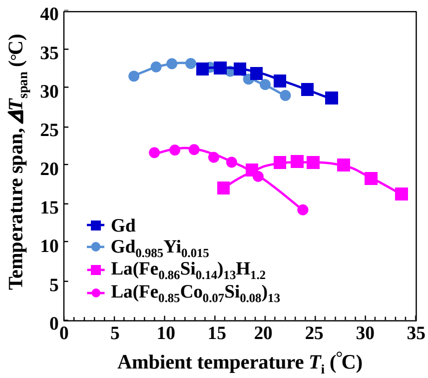

Fig. 6. Temperature span, ΔT_{span} as a function of ambient temperature when using Gd, $Gd_{0.985}Y_{0.015}$, $La(Fe_{0.86}Si_{0.14})_{13}H_{1.2}$, and $La(Fe_{0.85}Co_{0.07}Si_{0.08})_{13}$ as refrigerants.

Fig. 7 shows the experimental results obtained from heat load trials during AMR-cycle operations with the $Gd_{0.985}Y_{0.015}$ and $La(Fe_{0.86}Si_{0.14})_{13}H_{1.2}$ refrigerants along with theoretical results calculated based on the one dimensional heat flow model in AMR cycle. In these trials, the AMR cycle frequency was set to 0.4 Hz. In the case of the AMR-unit with the $Gd_{0.985}Y_{0.015}$ refrigerant, the ΔT_{span} is seen to decrease sharply with increasing heat load, although the ΔT_{span} obtained at no load is about twice as large as that seen for the $La(Fe_{0.86}Si_{0.14})_{13}H_{1.2}$ refrigerant. It should be noted that the derivative of ΔT_{span} at the intercept (corresponding to the no load point) obtained when using the $La(Fe_{0.86}Si_{0.14})_{13}H_{1.2}$ was considerably larger than that seen for the $Gd_{0.985}Y_{0.015}$. These results are in good agreement with the model calculation results, indicating that a large specific heat value improves the heat load properties. Precipitous drops are observed in ΔT_{span} in the heat load range of 3 to 4 W, derived from the bottleneck in the ΔS_m decrease arising from its peak shape. The ΔS_m peak width for the LaFeSi is narrower than that observed in the case of the Gd alloy. Subsequently, we calculated the cooling properties of the AMR-unit assuming the use of multi-layered materials exhibiting gradual variations in T_C. The resulting values of ΔT_{span} as functions of heat load are shown in Fig. 8(a) and Fig. 8(b) for the Gd-based alloy and the LaFeSi. In the case of the Gd alloy, a slight improvement in the derivative of ΔT_{span} at the ΔT_{span}-intercept (corresponding to the no-load point) was observed when modeling a five-layered structure or when increasing the AMR cycle frequency from 0.4 to 1 Hz. In contrast, a remarkable improvement in the ΔT_{span} derivative was obtained when employing a three- or nine-layered structure composed of LaFeSi at $f = 1$ Hz. Therefore, in the present study, increasing the number of layers is an effective means of increasing ΔT_{span}, while raising the AMR cycle frequency over the range from $0.4 \le f \le 1$ improves the heat-load properties. The significant improvement in the derivative of ΔT_{span} in the case of the LaFeSi should be also affected by the high specific heat of this material. Model calculations also indicated the critical ΔT_{span} drop down points were extended to 20 W in both multi-layered structures at $f = 1$ Hz.

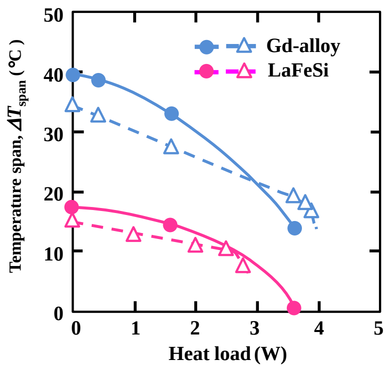

Fig. 7. Temperature span, ΔT_{span}, as a function of heat load. Closed circles show the experimental results obtained with $Gd_{0.985}Y_{0.015}$ and $La(Fe_{0.86}Si_{0.14})_{13}H_{1.2}$ refrigerants. Open triangles show the calculation results.

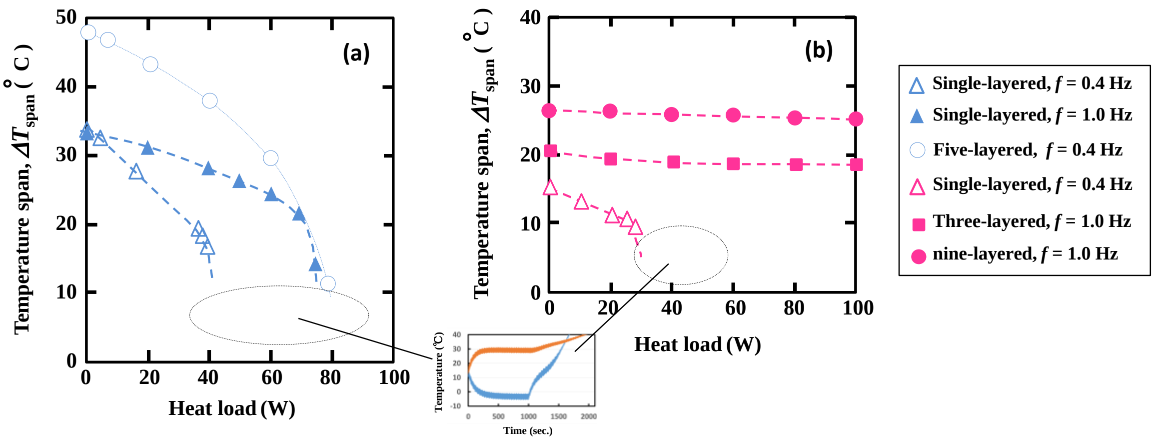

Fig. 8. Calculation results of temperature span, ΔT_{span}, for the steady-state during AMR-cycle operation as a function of heat load assuming the 1 kg of refrigerant of (a) Gd-based alloys, and (b) LaFeSi compounds. Triangles show the results with a single refrigerant material layer in the AMR-unit, circles and squares show multi-layered structures. In the case of five-, three-, and nine-layered structures, the Curie temperature of the materials gradually varied by 10 degrees. In the three- and nine- layered structures, the Curie temperature of the materials varied by 10℃, 10℃ and 2.5℃, respectively.

IV. Conclusion

Spherical particles composed of Gd alloys and $La(Fe,Si)_{13}$-based compounds with diameters ranging from 0.2 to 1.2 mm were fabricated by means of REP and their magnetocaloric properties were characterized. Moreover, the cooling characteristics obtained from the AMR-cycle using particles of $La(Fe,Si)_{13}$-based compounds were investigated and compared with the results generated by Gd alloys. It was found that the $La(Fe,Si)_{13}$-based compounds generate a AMR-cycle temperature span approximately half that obtained from the Gd alloys. At the same time, the $La(Fe,Si)_{13}$-based compounds exhibit better heat-load properties than the Gd alloys. These results are primarily attributed to the greater specific heat of the $La(Fe,Si)_{13}$-based compounds. The numerical calculations supported these experimental results and indicated that multi-layered structures composed of the $La(Fe,Si)_{13}$-based compounds having a gradual variation in T_C effectively increase the temperature span and demonstrate good heat-load properties. $La(Fe,Si)_{13}$-based compounds are thus promising candidates for magnetic refrigeration, and their use may lead to new, environmentally-friendly cooling systems. multi-layered structure by the $La(Fe,Si)_{13}$-based compounds gradually-varied T_C are effective to enlarge the temperature span and demonstrate good heat-load properties.

$La(Fe,Si)_{13}$-based compounds is promising candidate for magnetic refrigeration, and will lead to the new environmentally friendly cooling systems.

REFERENCES

[1] G. V. Brown, "Magnetic heat pumping near room temperature," *J. Appl. Phys.*, vol. 47, pp. 3673-3680, 1976.

[2] V. K. Pecharsky and K. A. Gschneidner, "Magnetocaloric effect and magnetic refrigeration," *J. Magn. Magn. Mater*, vol. 200, pp. 44-56, 1999.

[3] C. B. Zimm, A. Jastrab, A. Sternberg, V. Pecharsky, K. A. Gschneidner, Jr., M. Osborne, and I. Anderson, "Description and performance of a near-room temperature magnetic refrigerator," *Adv. Cryog. Engin.*, vol. 43, pp. 1759-1766, 1998.

[4] X. Bohigas, E. Molins, A. Roig, J. Tejada, and X. X. Zhang, "Room temperature magnetic refrigerator using permanent magnets," *IEEE Trans. Magn.*, vol. 36, pp. 538-544, 2000.

[5] N. Hirano, S. Nagaya, M. Takahasi, T. Kuriyama, K. Ito, and S. Nomura, "Development of magnetic refrigerator for room temperature application," *Adv. Cryog. Engin*, vol. 47, pp. 1027-1034, 2002.

[6] P. Colt, D. Viallet, F. Allab, A. Kedous-Lebouc, J. M. Fournier, and J. P. Yonnet, "A magnet-based device for active magnetic regenerative refrigeration," *IEEE Trans. Magn.*, vol. 39, pp. 3349-3351, 2003.

[7] M. Balli, O. Sari, C. Mahmed, C. H. Besson, P. H. Bonhote, D. Duc, and J. Forchelet, "A pre-industrial magnetic cooling system for room temperature application," in *Proc. the 4th IIF-IIR International Conference on Magnetic Refrigeration at Room Temperature*, 2010, pp. 313-322.

[8] C. R. H. Bahl, K. Engelbrecht, D. Eriksen, J. A. Lozano, R. Bjork, J. Geyti, K. K. Nielsen, A. Smith, and N. Pryds, "Development and experimental results from a 1 kW prototype AMR," in *Proc. the 5th IIF-IIR International Conference on Magnetic Refrigeration at Room Temperature*, 2012, pp. 53-60.

[9] J. M. Gatti, C. V. Muller, G. Brumpter, and P. Haegel, "Magnetic heat pumps – Configurable hydraulic distribution for a magnetic cooling system," in *Proc. the 5th IIF-IIR International Conference on Magnetic Refrigeration at Room Temperature*, 2012, pp. 341-348.

[10] J. A. Lozano, K. Engelbrecht, C. R. H. Bahl, K. K. Nielsen, J. R. Barbosa Jr., A. T. Prata, and N. Pryds, "Experimental and numerical results of a high frequency rotating active magnetic refrigerator," in *Proc. the 5th IIF-IIR International Conference on Magnetic Refrigeration at Room Temperature*, 2012, pp. 373-380.

[11] S. A. Nikitin, A. S. Andreyenko, A. M. Tishin, A. M. Arkharov, and A. A. Zherdev, "Magnetocaloric effect in rare earth alloys Gd–Ho and Gd–Er," *Phys. Met.Metall.*, vol. 59, no. 2, pp. 104-108, 1985.

[12] H. Wada and Y. Tanabe, "Giant magnetocaloric effect of $MnAs_{1-x}Sb_x$," *Appl. Phys. Lett.*, vol. 79, pp. 3302-3304, 2001.

[13] O. Tegus, E. Bruck, K. H. J. Buschow, and F. R. Bore, "Transition-metal-based magnetic refrigerants for room-temperature applications," *Nature*, vol. 415, pp. 150-152, 2002.

[14] X. X. Zhang, G. H. Wen, F. W. Wang, W. H. Wang C. H. Yu, and G. H. Wu, "Magnetic entropy change in Fe-based compound $LaFe_{10.6}Si_{2.4}$," *Appl. Phys. Lett.*, vol. 77, no. 19, pp. 3072-3074, 2000.

[15] S. Fujieda, A. Fujita, and K. Fukamichi, "Large magnetocaloric effect in $La(Fe_xSi_{1-x})_{13}$ itinerant-electron metamagnetic compounds," *Appl. Phys. Lett.*, vol. 81, no. 7, pp. 1276-1278, 2002.

[16] A. Fujita, S. Fujieda, Y. Hasegawa, and K. Fukamichi, "Itinerant-electron metamagnetic transition and large magnetocaloric effects in $La(Fe_xSi_{1-x})_{13}$ compounds and their hydrides," *Phys. Rev.* B., vol. 67, p. 104416, 2003.

[17] A. Fujita, S. Koiwai, S. Fujieda, K. Fukamichi T. Kobayashi, H. Tsuji, S. Kaji, and A. T. Saito, "Active magnetic regeneration behavior of spherical hydrogenated $La(Fe_{0.86}Si_{0.14})_{13}$ fabricated by rotating electrode process," *J. Jpn. Appl. Phys*, vol. 46, no. 8, pp. 154-156, 2007.

[18] A. T. Saito, H. Tsuji, and T. Kobayashi, "Magnetocaloric effects and magnetic properties in intermetallic compounds $La(Fe_{1-x-y}Co_xSi_y)_{13}$," presented at the 2005 INTERMAG Conference, GU-15, 2005.

[19] A. T. Saito, T. Kobayashi, and H. Tsuji, "Magnetocaloric effect of new spherical magnetic refrigerant particles," *J. Magn. Magn. Mater.*, vol. 310, pp. 2808-2810, 2007.

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