Investigation on the performance characteristics of Ericsson refrigeration cycles based on $Gd_5Si_2Ge_2$ or Gd

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Abstract:

Based on the experimental characteristics of the iso-field heat capacity and the magnetic entropy changing with temperature for the room-temperature magnetic refrigeration materials $Gd_5Si_2Ge_2$ and Gd, the magnetic entropy versus temperature curves are presented and the Ericsson refrigeration cycles using these materials as the working substance are set up. The nonperfect regeneration quantity, net cooling quantity, released heat quantity, coefficient of performance and other parameters of the magnetic Ericsson refrigeration cycle are analyzed and calculated. Furthermore, the performance characteristics of the Ericsson refrigeration cycles employing the materials $Gd_5Si_2Ge_2$ or Gd as the working substance are evaluated and compared. Moreover, the influence of nonperfect regeneration on the performance of the magnetic Ericsson refrigeration cycle is revealed. The conclusions obtained may provide some theoretical references for the optimal design of room-temperature magnetic refrigerators.

Keywords:

Room-temperature magnetic refrigeration, Magnetocaloric material, Ericsson refrigeration cycle, Regeneration

1. Introduction

The conventional vapor compression refrigerator used widely in many fields has some disadvantages, especially in enhancing greenhouse effect and depleting Ozone layer and large energy consuption. Thus, many scholars and engineers have been searching for some new refrigeration technologies. Magnetic refrigeration, one of the alternative refrigeration technologies, has many merits including high efficiency, stabilization, environmental friendliness, easily control and maintain, and so on, and more and more attentions have been paid to it. In the recent decade, many works involving in magnetic refrigeration were focused on the searching for room-temperature magnetic refrigeration materials with large or giant magnetocaloric effect (MCE)[1-3]. The related experimental researches showed that Gd, GdSiGe, MnFe(P,As), La(Fe,Si), etc. [4-7] were all important candidates of room-temperature magnetic refrigeration materials. Note that most of the existing room-temperature magnetic refrigeration materials including those mentioned above possess nonperfect regeneration in an Ericsson refrigeration cycle and the performance characteristics of the magnetic Ericsson refrigeration cycles using these room-temperature magnetic refrigeration materials as the working substance depend, to a certian extent, on the degree of nonperfect regeneration of the cyclic working substance. Therefore, it is of great significance to investigate the performance characteristics of magnetocaloric materials in a regeneration room-temperature magnetic refrigeration cycle[8-10].

In the present paper, on the basis of the experimental characteristics of the iso-field heat capacity and the magnetic entropy changing with temperature for magnetic materials Gd [4] and $Gd_5Si_2Ge_2$[5], the related regeneration Ericsson refrigeration cycle employing these materials as the working substance are designed. By using thermodynamic analysis and numerical value calculation methods, the nonperfect regeneration quantity, net cooling quantity, *COP* of these magnetic Ericsson refrigeration cycles are analyzed and calculated. Moreover, the performance characteristics of the Ericsson refrigeration cycles using the magnetic material Gd or $Gd_5Si_2Ge_2$ as the working substance are evaluated and compared. At the same time, the effects of nonperfect regeneration on the performance charecteristics of these Ericsson refrigeration cycles are revealed.

2. Magnetic refrigeration materials and their iso-field heat capacities varying with temperature

The discovery of the giant MCE in $Gd_5Si_2Ge_2$ has led to a revival of the research dealing with magnetic refrigeration [5, 11]. This compound belongs to the pseudo-binary system, in which the magnetic properties change from anti-ferromagnetic to ferromagnetic upon increasing the Si content *x*. Usually, the heat capacity of a material at constant pressure behaves anomalously near the magnetic phase transition and hence the measurement of the heat capacity can be useful tool for studying the nature of a given magnetic phase transition. Figure 1 shows the temperature dependence of the heat capacity of $Gd_5Si_2Ge_2$, measured with increasing temperature under 0T and 2T [5].

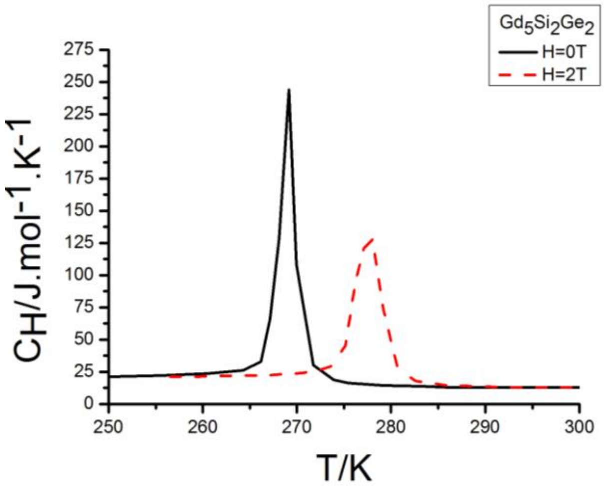


Fig.1 The C_H~T curve of $Gd_5Si_2Ge_2$ [5]

Generally, due to the high magnetic moment, heavy rare earth elements and their compounds are considered as good candidate materials for large MCE. Gd has a high MCE involving a second-order transition and has been frequently used as magnetic refrigerant by some engineers and experimenters. It was reported that melt-spun ribbons might have a relatively wider working temperature span, when it is used in magnetic refrigeration [4, 12]. The variation of iso-field heat capacity with temperature for Gd is shown in Fig. 2 [4].

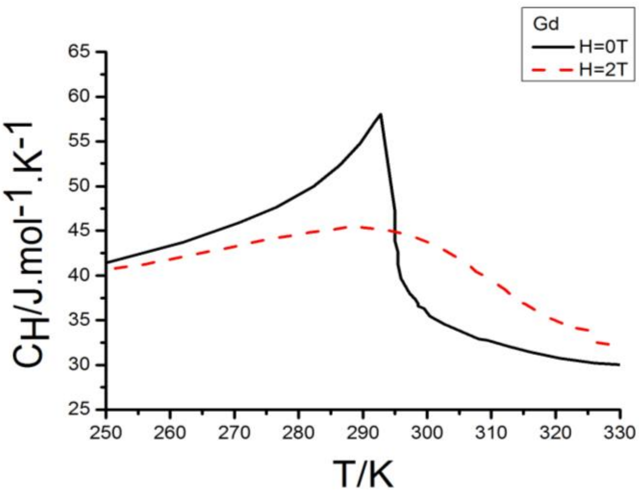


Fig.2 The C_H ~T curve of Gd [4]

3. The magnetic Ericsson refrigeration cycles using $Gd_5Si_2Ge_2$,Gd as the working substance

An Ericsson refrigeration cycle employing a magnetic material as the working substance consists of two isothermal processes and two iso-field processes [13] and may be represented by a field-temperature diagram, as illustrated schematically in Fig. 3, where T_1 and T_2 are the temperatures of the cold and hot reservoirs; Q_c and Q_h are the heats absorbed from the cooled space and releasing to the hot reservoir; and Q_{bc} and Q_{da} are the heats transferring into and out of the regenerator in the two iso- field processes, respectively.

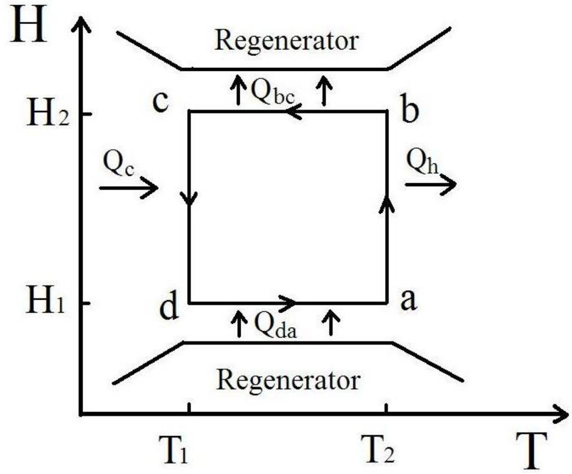
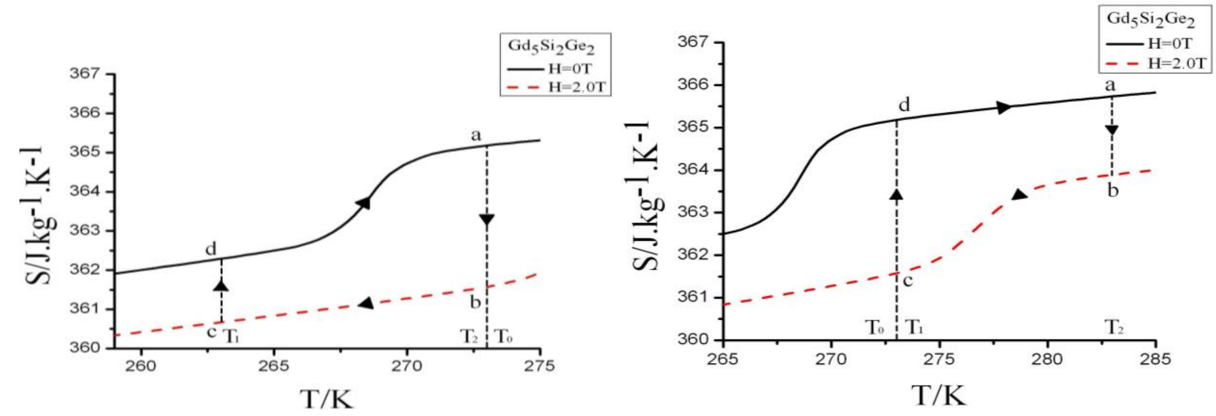


Fig.3 A magnetic Ericsson refrigeration cycle

It is well known that for a magnetic refrigeration cycle, the calculation and evaluation of nonperfect regeneration of a material are of importance because it obviously affects the cooling quantity and coefficient of performance [14]. In reference [14], Yan and Chen discussed several different cases of nonperfect regeneration for the ferromagnetic Ericsson refrigeration cycle and pointed out that the T_0, which is the temperature corresponding to the maximum entropy change between the two different magnetic fields, is an important parameter. When $T_0 \geq T_2 > T_1$, $Q_r = Q_{bc}\text{-}Q_{da} < 0$ such that the inadequate heat can only be compensated from the hot reservoir. When $T_0 \leq T_1 < T_2$, $Q_r > 0$ and the redundant heat Q_r can only release to the cold reservoir. Otherwise, the regenerator cannot be operated normally.

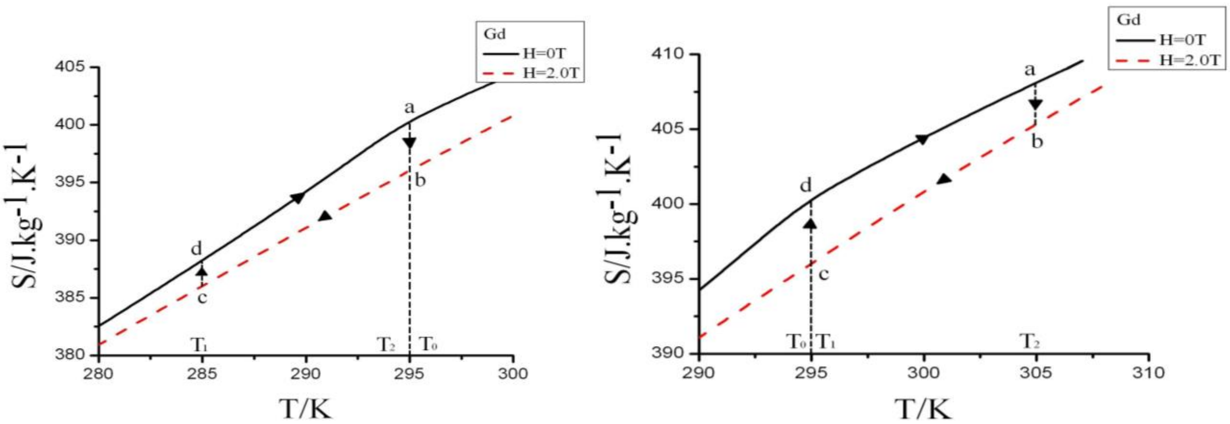
Though Yan's research took many kinds of complicate nonperfect regeneration of materials into account, the related results are true only for some ferromagnetic materials like some rare earth based compounds and so on. In fact, for the other concrete ferromagnetic materials, their regeneration characteristics are complicate. Thus, it is a new and significant work to discuss and evaluate the regeneration characteristics of individual magnetic material. For this reason, we select two kinds of important room-temperature magnetic refrigeration materials, $Gd_5Si_2Ge_2$ and Gd as refrigerants. According to their iso-field heat capacity characteristic curves varying with temperature under 0T and 2T, the corresponding magnetic entropy versus temperature curves are generated by means of numerical calculation. Furthermore, based on the magnetic entropy versus temperature curves under 0T and 2T, some magnetic Ericsson refrigeration cycles are designed, as shown in Figs. 4 and 5, where the temperatures of two isothermal processes are, respectively, T_1=263K and T_2=T_0 =273K for Fig. 4(a); T_1=T_0=273K and T_2=283K for Fig. 4 (b); T_1=285K and T_2=T_0=295K for Fig. 5(a); T_1=T_0=295K and T_2=305K for Fig. 5 (b).

Obviously, the Ericsson refrigeration cycles employing the materials $Gd_5Si_2Ge_2$, Gd as the working substance are established beside the left or right side of T_0, as shown in Figs. 4 and 5. It should be pointed out that two isothermal processes of Ericsson refrigeration cycles may be located on both sides of T_0. The performance of such magnetic Ericsson refrigeration cycles will be discussed later.



(a) (b)

Fig.4 The Ericsson refrigeration cycle with $Gd_5Si_2Ge_2$, (a) T_1=263K and *T_2= 273K, (b) T_1= 273K* and *T_2=283K.*



(a) (b)

Fig.5 The Ericsson refrigeration cycle with Gd, (a) T_1=285K and *T_2= 295K, (b) T_1= 295K* and *T_2=305K.*

4.Results and discussion

On the basis of the entropy change equations of the related materials and numerical calculation technology, the nonperfect regeneration quantity Q_r (redundant or deficient), net cooling quantity Q_L, released heat quantity Q_h, net work input *W*, *COP*, and so on, are calculated and listed in Table 1. From Table 1, we can conclude some results as follows:

(1) All the established Ericsson refrigeration cycles using the two kinds of materials as the working substance possess nonperfect regeneration such that the effects of the redundant heat $+Q_r$ or the deficient heat $-Q_r$ in the two iso-field processes on the net cooling quantity Q_L, the net work input *W* and *COP* are remarkable. This shows once again that it is necessary and important to take the effects of nonperfect regeneration into account in the performance analysis of actual magnetic refrigeration cycles.

(2) For those refrigeration cycles operating beside the right side of T_0 and employing the materials $Gd_5Si_2Ge_2$ or Gd as the working substance, both the net cooling quantity Q_L and *COP* are clearly larger than those operating beside the left side of T_0. As an example, one can obtain from Table 1 that $(Q_L)_{IV}=1.31(Q_L)_{III}$,$(COP)_{IV} = 1.56(COP)_{III}$,where the subscripts III and Ⅳ denote the cycles III and Ⅳ listed in Table 1 or Fig.5(a) and Fig.5(b). According to the actual needs of the temperature ranges of refrigeration, the magnetic Ericsson refrigeration cycle may be designed to be located beside the right or left side of T_0

(3) For the conditions of a same temperature span and similar cycle, the net cooling quantity of the Ericsson refrigeration cycle using Gd as the working substance are larger than those using $Gd_5Si_2Ge_2$ as the working substance, as listed in Table 1.

Table 1. The main thermodynamic quantities of Ericsson refrigeration cycles employing $Gd_5Si_2Ge_2$, Gd *as the working substance*

Material	Temperature span(K)	Q_c (J/kg)	Q_h (J/kg)	Q_r (J/kg)	Q_L (J/kg)	W (J/kg)	*COP*	*COP*/ (*COP*)$_{Carnot}$
$Gd_5Si_2Ge_2$	Ⅰ: 263-273	428.6	989.9	-536.3	428.6	25.1	17.1	0.65
Gd	Ⅱ: 273-283	989.9	528.3	+488.4	501.5	26.8	18.7	0.68
	Ⅲ: 285-295	628.6	1257	-588.8	628.6	39.9	15.8	0.55
	Ⅳ: 295-305	1257	855.6	+434.9	822.3	33.3	24.7	0.84

It should be pointed out that the cycles set up in the present paper are still some idealized ones. Actually, the irreversibilities and other irreversible effects including heat-transfer irreversibilities between the working substance and the heat reservoirs [15-19], internal dissipation of the working substance, thermal hysteresis, magnetic hysteresis, heat leak as well as the efficiency of the regenerator should be considered in the further performance analysis for Ericsson refrigeration cycles employing magnetic materials as the working substance [20-22]. If so, the net cooling quantity Q_L and *COP* of the cycles must decrease remarkably. For example, if one introduces an internal irreversibility parameter I [23] to describe synoptically all the internal irreversibilities of the working substance resulting from thermal hysteresis, magnetic hysteresis and other internal dissipation, we may re-calculate $Q_L' = Q_L/I$, $COP' = Q_L'/W$. On the other hand, there always exists the heat leak Q_{leak} between T_1 and T_2 and it is often thought to be proportional to the temperature difference $T_2 - T_1$ such that one may obtain $Q_{leak} = k(T_2 - T_1)$, where k is a proportional coefficient. In such a case, one may re-calculate $Q_L'' = Q_L - Q_{leak}$, $COP'' = Q_L''/W$.

5.Conclusions

Based on the experimental characteristic curves of the iso-field heat capacity varying with temperature for magnetic materials $Gd_5Si_2Ge_2$ and Gd, the corresponding entropy versus temperature curves are presented and some room-temperature magnetic Ericsson refrigeration cycles are established in different temperature regions, i.e., beside the right or left side of T_0. Furthermore, the effects of nonperfect regeneration on main thermodynamic performances are analyzed and discussed. Moreover, the other irreversible effects such as the heat-transfer irreversibility, internal irreversibility resulting from dissipation of working substance, thermal hysteresis, and so on, should be considered in the further investigation.

Acknowledgments

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