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Performance characteristics of an irreversible regenerative magnetic Brayton refrigeration cycle using $Gd_{0.74}Tb_{0.26}$ as the working substance

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ABSTRACT

The cycle model of an irreversible regenerative magnetic Brayton refrigerator using $Gd_{0.74}Tb_{0.26}$ as the working substance is established. Based on the experimental characteristics of iso-field heat capacities of the material $Gd_{0.74}Tb_{0.26}$ at 0 T and 2 T, the corresponding iso-field entropies are calculated and the thermodynamic performance of an irreversible regenerative magnetic Brayton refrigeration cycle is investigated. The effects of the irreversibilities in the two adiabatic processes and non-perfect regenerative process of the magnetic Brayton refrigeration cycle on the cooling quantity, the heat quantity released to the hot reservoir, the net cooling quantity and the coefficient of performance are discussed in detail. Some significant results are obtained.

1. Introduction

Magneto-Caloric Materials (MCMs) are materials whose temperatures decrease when they are adiabatically demagnetized. Magneto-Caloric Effect (MCE) results from the magnetic entropy of a spin system: the spin order is toward the applied magnetic field which tends to decrease its entropy; and an adiabatic magnetization (or demagnetization) yields to an increase (or reduction) of temperature [1] of MCMs.

Though MCE was discovered in 1883, its potential as a room-temperature refrigeration technology was demonstrated only in 1976 by Brown [2]: under a 7 T magnetic field, he succeeded in cooling down a Gadolinium (Gd) sample with a temperature span of 47 K. This alternative refrigeration technology to the gas expansion/compression refrigeration is environmentally-friendly because the MCMs possess low Global Warming Potential or/and Ozone Depletion Potential. Moreover, magnetic refrigeration is also more efficient and compact. Since Brown's machine in 1976, more than 41 demonstrator systems have been designed up to 2010 [3]. This shows an increasing interest of the scientists and engineers in this technology. Looking for some new MCMs is also a current issue, because Gd is a rare-earth material with a too expensive price to be used in commercial devices. A review on recent research of some new MCMs is provided by Yu et al. [4]. In a recent article [5], a numerical calculation and comparison of the performances of magnetic Brayton refrigeration cycle have been performed using either Gd or $(Gd_{3.5}Tb_{1.5})Si_4$ or $Gd_{0.74}Tb_{0.26}$ as the working substance. The results show that among the three studied materials, $Gd_{0.74}Tb_{0.26}$ exhibits the largest cooling quantity. Therefore, it is necessary and important to further explore the thermodynamic performances of the working substance $Gd_{0.74}Tb_{0.26}$ in room-temperature magnetic refrigeration cycles. As described in reference [3], magnetocaloric regenerator materials had been used as metal ribbons, layered beds of grains, plates or packed beds. Rowe and Tura [6,7] have used crushed/irregular particles of $Gd_{0.74}Tb_{0.26}$ with an average diameter of 550 μm packed into a 40–45 g cylinder sample (Diameter 25 mm, length 25 mm with a 55% porosity) placed inside a test apparatus with 2 other cylinder samples which contained Gd and $Gd_{0.85}Er_{0.15}$ respectively. Tests were operated at 1.5–2 T, with frequencies ranging 0.65 to 1.0 Hz and Helium gas was used as heat transfer fluid with a 3, 6 and 9.5 bar mean pressure; a peak temperature span of 46.8 K was measured when operated at 301.5 K and 0.65 Hz, whereas at 0.8 Hz the temperature span was 50 K [6].

In the present paper, a regenerative Brayton refrigeration cycle using $Gd_{0.74}Tb_{0.26}$ as the working substance is established, in which the irreversibilities in the two adiabatic processes and non-perfect regenerative process are taken into account [8–10]. The effects of the irreversibilities in the magnetic Brayton refrigeration cycle on the cooling quantity, the heat quantity released to the hot reservoir, the net cooling quantity and the coefficient of performance are discussed in detail. The results obtained may provide some

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useful information for the design of actual magnetic refrigerators for room-temperature application.

2. A magnetic refrigeration cycle using $Gd_{0.74}Tb_{0.26}$ as the working substance

A magnetic Brayton refrigeration cycle (A → B → C → D → E → F → A) consists of two irreversible adiabatic processes (A–B and D–E) and two iso-field processes (C–D and F–A), as shown in Fig. 1. The magnetic Brayton refrigeration cycle set up here is operated between the applied fields $\mu_0 H_0$ = 0 T and $\mu_0 H_1$ = 2 T, the cold and hot reservoirs at temperatures T_{cold} and T_{hot} respectively.

In Fig. 1, the cycle A → B* → C → D → E* → F → A is a reversible magnetic Brayton refrigeration cycle, where A–B* and D–E* are the two reversible adiabatic processes. In the process A–B*, due to an adiabatic magnetization, the temperature of the working substance is increased from T_A (=T_{hot}) to $T_B^* = T_{hot} + \Delta T(\Delta H, T_{hot})$. In the process B*–C, the heat Q_h is released to the hot reservoir. Then, the iso-field process is carried out from C to D in which the working substance releases the heat Q_{sr} to the regenerator. On the other hand, in the process D–E*, due to the adiabatic demagnetization, the temperature of the working substance is cooled down to $T_E^* = T_{cold} - \Delta T(-\Delta H, T_{cold})$. Further, in the process E*–F, the working substance absorbs the heat Q_c from the cold reservoir (or cooled space). Finally, the heat Q_{rs} from the regenerator is transferred back to the working substance, bringing back the temperature of the working substance to the initial temperature T_A.

However, for an actual magnetic Brayton refrigeration cycle, owing to internal multi-irreversibilities such as the eddy-current flow, hysteresis, etc., the entropy generation of the working substance in the adiabatic processes are unavoidable and consequently the reversible adiabatic processes A–B* and D–E* should be replaced by the irreversible adiabatic processes A–B and D–E respectively, as shown in Fig. 1.

For a complete cycle, the first law of thermodynamics is written in the integral form as:

$$\oint dU = \oint dW + \oint dQ = 0. \quad (1)$$

And, the heat Q_h released to the hot reservoir and the heat Q_c absorbed from the cold reservoir are given by:

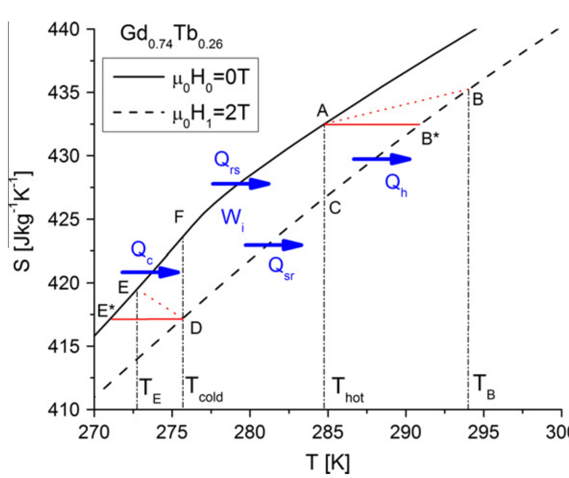

Fig. 1. An irreversible regenerative magnetic Brayton refrigeration cycle using $Gd_{0.74}Tb_{0.26}$ as the working substance. Irreversible adiabatic processes are indicated by red dotted lines and reversible adiabatic processes are indicated by red solid lines.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$Q_h = \int_{T_B}^{T_{hot}} TdS(H_1, T). \quad (2)$$

$$Q_c = \int_{T_E}^{T_{cold}} TdS(H_0, T). \quad (3)$$

The exchanged heats during the two regenerative processes are:

$$Q_{sr} = \int_{T_{hot}}^{T_{cold}} T\,dS(H_1, T), \quad (4)$$

$$Q_{rs} = \int_{T_{cold}}^{T_{hot}} T\,dS(H_0, T). \quad (5)$$

The isothermal entropy change is defined as $\Delta S(\Delta H,T) = S(H_1,T) - S(H_0,T)$ and a maximal entropy change is obtained at the temperature T_0, i.e., $|\Delta S_{max}| = \Delta S(\Delta H, T_0)$. The temperature T_0 is a crucial parameter in the regeneration magnetic Brayton refrigeration cycle. The net cooling quantity Q_L is an effective heat absorbed from the cold reservoir after reckoning the redundant heat Q_r transferred to the cold reservoir in the regenerative processes. Thus, one has:

$$Q_L = Q_c - Q_r. \quad (6)$$

Due to the dependence of the iso-field heat capacity $C_H(H,T)$ on the magnetic field, the heat transferred from the working substance to the regenerator (at $H = H_1$) is usually different from the heat transferred from the regenerator to the working substance (at $H = H_0$). Moreover, if the heat transferred from the working substance to the regenerator is larger than the heat transferred from the regenerator to the working substance, the redundant heat has to be released to the cold reservoir, which will reduce Q_c, otherwise the regenerator would not operate properly. Similarly, if the heat transferred from the working substance to the regenerator is smaller than the heat transferred from the regenerator to the working substance, the regeneration heat difference can only be compensated from the hot reservoir, which will reduce Q_h but without any impact on Q_c. The two iso-field heat capacities (at $H = H_0$ and $H = H_1$) are such as: for $T < T_0$, $C_H(H_1,T) < C_H(H_0,T)$ and for $T > T_0$, $C_H(H_1,T) > C_H(H_0,T)$; so, the heat Q_r has to be calculated according to the relative positions of the temperatures T_{cold}, T_{hot} with T_0 [5,11–13]:

- $T_{cold} < T_{hot} < T_0$,

$$Q_r = 0. \quad (7)$$

- $T_{hot} \geqslant T_0 \geqslant T_{cold}$,

$$Q_r = \int_{T_0}^{T_{hot}} \left[T\frac{\partial S(H_1,T)}{\partial T} - T\frac{\partial S(H_0,T)}{\partial T} \right] dT. \quad (8)$$

- $T_{hot} \geqslant T_{cold} \geqslant T_0$,

$$Q_r = \int_{T_{cold}}^{T_{hot}} \left[T\frac{\partial S(H_1,T)}{\partial T} - T\frac{\partial S(H_0,T)}{\partial T} \right] dT. \quad (9)$$

The coefficient of performance COP is then obtained as:

$$COP = \frac{Q_L}{W_i} = \frac{Q_L}{-(Q_h + Q_c + Q_{rs} + Q_{sr})}. \quad (10)$$

Now, we introduce dimensionless parameters α and β to describe the irreversibilities in the two adiabatic processes, which are, respectively, defined as:

$$\alpha = \frac{T_{cold} - T_E}{T_{cold} - T_{E^*}}, \quad (11)$$

$$\beta = \frac{T_{B^*} - T_{hot}}{T_B - T_{hot}}. \quad (12)$$