Room temperature magnetic refrigerator using both metal Gd or/and Gd-Si-Ge alloys and a permanent magnetic field source

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A room temperature magnetic refrigerator using both metal Gd or/and Gd-Si-Ge alloys and permanent magnetic field source was introduced in the present paper. The permanent magnet was assembled in a shape of cylinder in which there are 1.4 Tesla uniform magnetic fields. A temperature span of 25 K was reached for the alloys when environment temperature was about 290 K. But if the alloys are short of Ga, the less temperature range could be reached at the same temperature. In addition, the magnetic refrigerator was also filled with metal Gd as the refrigerant; a temperature span of 26 K was reached.

INTRODUCTION

Since the discovery of magnetic-caloric effect of some materials, the great effort has been made to make use of it in refrigeration. To utilize it cooling in low temperature of liquid helium has been quite successful. Compared with this cooling refulgence of low temperature range, the use in near room temperature is not gratifying. But there was still much progress in room temperature magnetic refrigerator. Brown [1], for example, designed a demonstration experiment of magnetic refrigeration around room temperature in 1976 which shown us the possibility of room temperature magnetic refrigeration (RTMR) and realization clue. Zimm group[2] in 1997 made the 1st magnetic refrigeration unit around room temperature, which is of high heat efficiency. But there is a common character that they all used the superconductor-coils to generate the magnetic field. Since room temperature superconductors has not been found so far, say nothing of using them in practice, maintaining a strong magnetic field by traditional superconductors-coils is quite expensive and inconvenient. Maybe it is a feasible method to substitute a permanent magnet for superconductor-coils, for it seems that enhancing the magnetic field intensity of permanent magnet by using new high-powered permanent magnetic materials and new assembling techniques is more hopeful than finding the room temperature superconductors these days. As a try, we used the assembled permanent magnet arrays to apply the working field and run the room temperature magnetic refrigerator in a reciprocating way.

As regards the magnetic refrigerant, we think that metal Gd may be suitable for a demonstrator for its large magnetocaloric effect. But using only Gd seems hard to gain an enough cooling power. We tried Ga-Si-Ge alloys [3] commended by Ames Lab to compare its performance with pure metal Gd in the demonstration device of magnetic refrigeration, the result was goodish although the alloys did not increase 30% cooling power as expected beforehand.

PRINCIPLE AND AN INTRODUCTION TO THE DEMONSTRATION DEVICE

For a general magnetic system, during the external magnetic field changes, the entropy of the system may be calculated according to the following expression (the Maxwell relation):

$$\Delta S = \mu_0 \int_{H_I}^{H_F} \left(\frac{\partial M}{\partial T} \right)_H dH \tag{1}$$

where T is the absolute temperature, S is the entropy of the system, μ_0 is vacuum magnetic conductivity, H is the external magnetic field, M is magnetic moment, H_i is the initial field, and H_f is the last field.

Expression (1) is a universal equation (e.g. for Gd) unless the first order magnetic phase transition occurs during the process. For the 1^{st} order phase transition, we have the following expression:

$$\Delta S = \mu_0 \Delta M \frac{\Delta H}{\Delta \Theta} \tag{2}$$

where $\Delta\Theta$ and ΔH are the changes of temperature and applied field ,respectively, along the phase equilibrium curve, and the value ΔS and ΔM are both the differences between the two phases.
It is of dissension [4] if expression (1) still keeps correct during the process of magnetic phase transition or does not. We think that in a common situation, when applied field, the system does not only undergo the first order transition, but also undergoes the changes within the respective certain phase. We suggest a new mixed processing method to deal with this sort of problem of $Gd_5Si_2Ge_2$ alloy and other materials of the first order magnetic transition. We will introduce the processing method in other paper. But the final result still keeps true for Ga-Si-Ge alloys as behaves by using Maxwell relations. Under such a consideration we chose the materials as the representative of giant magneto-caloric effect materials to circulate in the demonstration device.

Because we use the permanent magnet arrays, the magnetocaloric temperature effect is about 2 K/Tesla, if we want to accumulate a large temperature varying range. We took it for granted that the AMR (active magnetic regenerator)[5] cycle should be employed.

The above is a brief summary of the magnetic refrigeration principle, the following is a description about the demonstration device and magnetic refrigerant.

Working materials

At the beginning, we chose metal Gd to fill in the magnetic refrigerant beds as a test. The Gd is of commercial quality in purity. Because the heat transfer time for material Gd is a bit too long, when its size is not small enough, we hope the material to be smaller than 0.2mm in diameter. To meet the need, we cut the clump Gd into thin sheets about 0.2mm in thickness, and then get them to be grinded in a tin with a spheroidizing mill. At last the Gd articles are basically shaped small spheres after such a process.

The typical heat transfer time for such a size of Gd spheres is about 2 seconds. The period of the AMR cycle is 6 seconds or so when the Gd spheres are used in the magnetic refrigerator. The total weight of Gd spheres filled in the two beds is about 1 kilogram.

$Gd_5Si_2Ge_2$ alloy and $Gd_5Si_{1.985}Ge_{1.985}Ga_{0.03}$ alloy were also filled in the beds of the AMR to circulate. The sphere shape of Gd-Si-Ge alloys is more regular than that of Gd spheres. The total weight of the alloys is also about 1 kilogram. By the magnetizing curves of the alloys, the alloys quality was equivalent with that prepared by Ames Laboratory.

The permanent magnet arrays

The permanent magnet system is made of many small cubic magnet units (see Figure 1). Every magnet unit is shaped as a small sector in which the magnetic field orients to a certain direction regularly. The angle between the neighbor directions is 45 degrees. The integral magnet arrays are shaped like a cylinder whose diameter is 140 centimeters. There is a hole at the center position of the magnet arrays cylinder, the diameter of the hole is 3 cm. All the magnet arrays co-generate a quite uniform magnetic field about 1.4 Tesla in the hole. There is a well-ranged magnetic field distribution (see Figure 3). The length of the cylinder is 0.2 m and the magnetic working materials will be magnetized in the hole of working space and demagnetized outside of the hole.

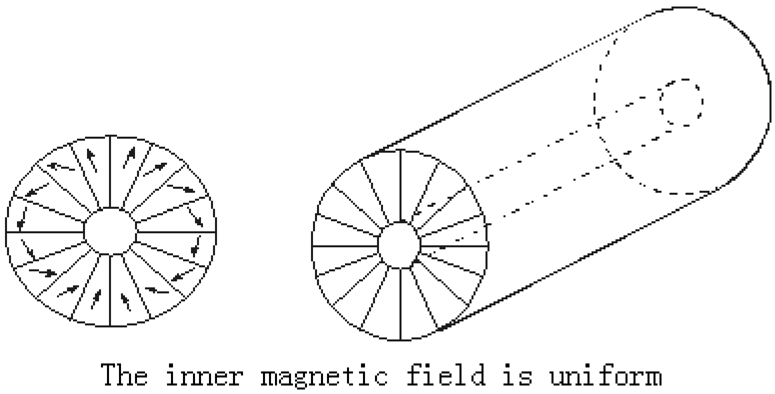

Figure 1 The field of O-shaped magnet arrays cylinder

Working style of the device

The room temperature magnetic refrigerator device works in a reciprocating way. There are two beds (see figure 2) in which the magnetic refrigerants such as small Gd spheres et. al.. We devised the magnetic refrigeration demonstration device using the above permanent magnet arrays, and the pneumatic drives are employed both for the movement of magnetic refrigerant beds and the flow of cycle water. The cycle water is sealed from the air and is confined between two chambers of a cylinder which is driven by another cylinder as the role of a pneumatic driver. The piston of the later drives that of the former to move to and fro, the air within the later is so compressed that the cycle water will be impelled to flow in the AMR. The connection tube between the cold sink and the cylinder is plastic. Because the heat transfer of the plastic tube and the air is much less than that of water and metal materials, the main heat loss of the system is from AMR. As for the heat transfer of the AMR, we did a simple estimation with the size of the AMR system. The AMR consists of a stainless tube and working particles in it. If the small particles are Gd, the calculating result shows that the size of the AMR is quite reasonable for the minimal heat loss.

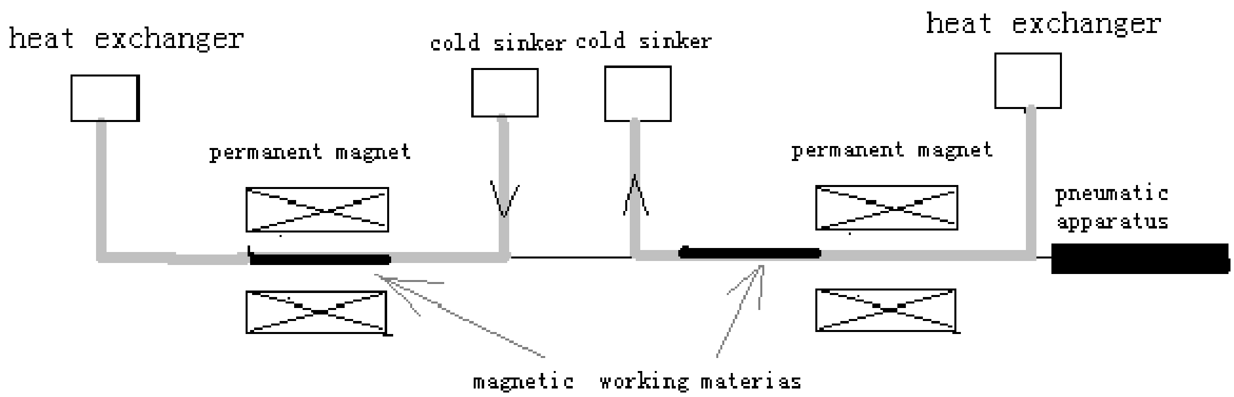

Figure 2 The sketch of a reciprocating magnetic refrigerator

RESULTS AND CONCLUSIONS

In real circulation, the system reached a temperature span more than 26 K when Gd spheres were used, and a temperature span of 25 K when $Gd_5Si_{1.985}Ge_{1.985}Ga_{0.03}$ spheres were used. When we substituted these two kinds of working materials as $Gd_5Si_2Ge_2$ alloy, the temperature span was less than 20 K. We refer the result about $Gd_5Si_2Ge_2$ to an ill-suited working temperature region.

We tried to couple using the working materials in the real cycle, the experiment did not go far, for there was something wrong with the equilibrium of forces applied on two beds. But the alloy $Gd_5Si_{1.985}Ge_{1.985}Ga_{0.03}$ worked well in the real circulating at any case. For there were some difficulties in shaping control of working materials, we did not succeed in preparing the three working materials exactly in the same shape of sphere. Although we cannot conclude that Gd-Si-Ge alloys have a better cooling effect than metal Gd, but the alloys are indeed valuable because of its optimal chemical stableness.

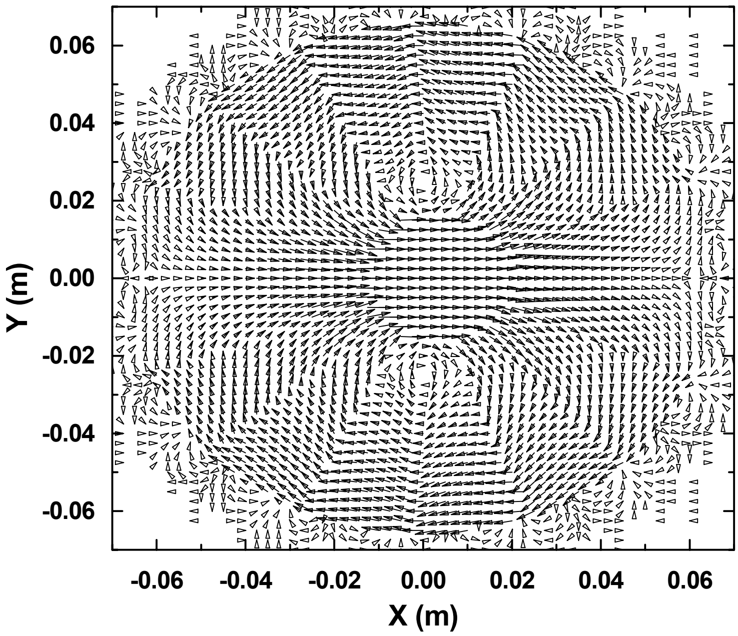

Figure 3 The magnetic field distribution in the hole of the cylinder

ACKNOWLEDGEMENT

This work was supported financially partly by the project of the Key Technologies of Research and Development (99-A30-01-03), and partly by the HTRDP(863) of P.R. China government, the serial number of the project is 2002AA324010.

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