Cooling Capacity Improvement of Magnetic Heat Pump for On-board Air Conditioner

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Present air conditioner systems are based on traditional vapor compression technology with usage of HCFC (Hydro Chloro Fluoro Carbon). The Kyoto Protocol has designated HCFC as one of the gases whose emissions are to be reduced. This requires the development of HCFC free systems or the usage of substances which have little greenhouse effect. Under these conditions, magnetic refrigeration technology, which has the potential for high efficiency without Freon gases, has become a focus of attention. The aim of this study is to develop a large-scale magnetic refrigerator which has a maximum kilowatt-class cooling power for air-conditioners mountable on railway vehicles to enable them to be free from Freon gases.

**Keywords**: air conditioner, saving energy, non-Freon, magnetic heat pump, Halbach

1. Introduction

Present air conditioner systems use traditional vapor compression technology. The Kyoto Protocol has designated HCFC (Hydro Chloro Fluoro Carbon) as one of the gases whose emissions are to be reduced. This requires the development of HCFC free systems or usage of substances which have little greenhouse effect.

Under the present circumstances, magnetic refrigeration technology which has the potential for high efficiency without Freon gases, is a focus of attention. Magnetic refrigeration technology has been developed in the cryogenic region. However in this paper, this technology is called “magnetic heat-pump” instead of “magnetic refrigeration” because magnetic refrigeration technology is usable for heating in the range of room temperature.

A kW-class magnetic heat pump system was developed in association with the Chubu Electric Power Co, Sendai Corporation, Santoku Corporation, Tokyo Institute of Technology, Kyushu University, Kobe University, in order to demonstrate the potential of magnetic heat pumps for large scale application. This paper describes the cooling capacity and cooling properties of the developed magnetic heat pump. The data in this paper was acquired in cooperation with the partners, mentioned above.

2. Principle of magnetic refrigeration

2.1 Magnetocaloric effect

Magnetic refrigeration is a method which utilizes the magnetocaloric effect, i.e. the entropy change when a magnetic material is magnetized or demagnetized.

Figure 1 illustrates the magnetocaloric effect. When the magnetic material is magnetized adiabatically, the magnetic material heats up and its temperature rises.

Atoms constituting magnetic material have the same magnetic entropy as magnetic moments originating from electronic spins and the same lattice entropy as crystal lattices.

During magnetization, magnetic entropy decreases because magnetic moments are oriented by the magnetic field.

However, the entropy of the crystal lattice increases and the material temperature rises because the entropy of the whole system remains constant.

Conversely, magnetic material cools and its temperature drops when it is demagnetized adiabatically.

Magnetic entropy increases during demagnetization because of the disorientation of magnetic moments. However, crystal lattice entropy decreases, and temperature drops because overall entropy of the system stays constant.

A refrigerant gas is called a working material (fluid) in gas refrigeration technology. Magnetic materials which possess a magnetocaloric effect are called magnetic materials.

2.2 Thermodynamic cycle of the magnetic heat-pump

Since magnetocaloric materials have large magnetic capacity at room temperature, there is only a small margin of temperature change available for refrigeration.

A refrigeration method called AMR (Active Magnetic Regenerator) has been developed to gain large cooling temperature spans even if the magnetic field change is relatively small.

Large temperature spans can be obtained with AMR using the material as a heat regenerator. AMR is thought to be the most effective method for building magnetic heat
pumps at room temperature, and therefore the AMR cycle was adopted for the refrigeration cycle featured in this paper.

Figure 2 shows the principle of the AMR cycle and illustrates the temperature profile of the magnetic material in the AMR.

The magnetic material is magnetized adiabatically and its temperature rises (Fig. 2 ①). The dotted line shows the temperature profile before magnetization and the solid line shows the temperature profile after magnetization. After magnetization, the gradient of the temperature line in the AMR is generated by exchanging cold heat transfer fluid (ex. water) (②).

Subsequently, the temperature of the material drops while maintaining the same temperature gradient in the third process (③).

Finally, the temperature gradient is increased by exchanging heat with hot fluid in the fourth process (④).

The AMR bed system effectively stores and transfers heat to the outside of the AMR through the heat transfer fluid.

3. kW-class heat pump test apparatus

3.1 Magnetic materials

Gadolinium (Gd) is a second-order phase-transition material with a Curie point of 293 K.

The important properties of the magnetic material are the magnetic entropy change (ΔSM), the specific heat (c) and the adiabatic temperature change (ΔTad). Figures 3 ~ 5 show these properties as a function of the temperature.

The magnetic entropy change of Gd peaks at 21℃ (Fig. 3).

The temperature change can be derived from the change in entropy and the specific heat, using the following formula:

$$\Delta T_{ad} = -\frac{\Delta S_M T}{c}$$  
(1)

$\Delta T_{ad}$: Adiabatic temperature change, $\Delta S_M$: Magnetic entropy change, $T$: Temperature, $c$: specific heat

Figures 3 ~ 5 show that the maximum adiabatic temperature change is no more than 6℃ and that the change in magnetic entropy and variation in adiabatic temperature change become smaller as the gap between operating temperature and peak temperature grows.

A large temperature span is obtained when using the AMR cycle. However the temperature span which one material can generate is limited.

Therefore, a cascade method was proposed, whereby several magnetic materials can be used in order to obtain still larger temperature span.
3.2 Ring-shaped Halbach arrayed permanent magnet

The magnetic entropy change in the Gd was highest at around the Curie point of 21°C. The higher the applied magnetic field is, the larger the magnetic entropy change becomes.

Therefore a magnetic circuit was designed using the Halbach array to apply a high magnetic field.

Figure 7 (a) shows the basic structure of the Halbach array of permanent magnets.

The magnetic fields of magnets ②, ③ and ④ strengthened when the magnetized directions of the neighboring magnets indicated by empty arrows were at right angles to each other, as shown in Figure 7 (a). Therefore the magnetic field was higher than that with just a single magnet, and the leak in magnetic field to the back of the magnetic pole was smaller.

A ring-shaped Halbach arrayed permanent magnet was designed for the magnetic heat pump system. Then a pair of magnets were set facing each other, in order to reduce the leak in the magnetic field.

The ring-shaped Halbach arrayed permanent magnets used for the magnetic heat pump system are shown in Figure 7 (b).

The magnetic heat pump was equipped with 2 AMR units and 4 Halbach arrayed magnets. Each unit was sandwiched between 2 Halbach arrayed magnets. Each magnet was rotated by a single motor.

A peak field of 1.5 T was obtained for the developed ring-shaped Halbach arrayed magnets (Fig. 8).

3.3 Magnetic heat pump test apparatus

Figure 9 shows a photograph of the magnetic heat pump equipped with the ring-shaped Halbach arrayed magnets. The AMR bed was designed in the form of a V shape to ensure the flow passed through the AMR bed (Fig. 9).

The AMR bed was divided into twelve units arranged in annular fashion (Fig. 10).

The two AMR units were labelled “Unit A” and “Unit B” respectively.

Figure 11 shows the magnetic poles of the ring-shaped Halbach arrayed magnets when used with 12, 1, 6 and 7
During the cooling stage, and the temperature reached and was transferred to the cold stage. AMR beds, the fluid temperature dropped to pump to the 3, 4, 9, 10 AMR beds (demagnetized).

The fluid for the heat exchange at the temperature of In these cases the 12, 1, 6, 7 AMR beds were magnetized, and the 3, 4, 9, 10 AMR beds were demagnetized.

Because of the heat exchange in the demagnetized AMR beds, the fluid temperature dropped to $T_h$. After the heat exchange, the fluid was collected in the rotary valve 2 and was transferred to the cold stage.

The fluid absorbed the heat load “$Q_s$” of the heater during the cooling stage, and the temperature reached $T_w$.

The fluid was then transferred from the rotary valve 3 to the 12, 1, 6, 7 AMR beds during the magnetization process. After the fluid absorbed the heat from the magnetic material in the magnetized AMR beds, it was transferred from the rotary valve 4 to the hot stage. The temperature of the fluid was reset to $T_w$ after a heat exchange $Q_s$ through the chiller.

As the rotary valves are synchronized with the rotation of the magnet, the rotary valves change the flow, when 1, 2, 7, 8 AMR beds are magnetized and 4, 5, 10, 11 AMR beds are demagnetized.

2 AMR units were connected in series to evaluate the temperature spans, in what is called ‘a series mode’ . 2 AMR units connected in parallel were used to evaluate cooling capacity, in what is called ‘parallel mode’.

The cooling capacity is defined as the heat load of the heater shown in Fig. 11. The temperature span (ΔT) is defined as $T_w - T_c$.

4. Result of cooling performance

4.1 Cooling capacity

In order to assess the maximum cooling capacity, the cooling capacity was measured Unit A packed with Gd A and Unit B packed with Gd-GdY-GdDy in parallel mode.

The cooling capacity depends operational temperature because magnetic entropy change also depends on operational temperature.

Figure 12 shows the result of the cooling capacity as a function of $T_w$ when the magnetic heat pump is operated in parallel mode.

A maximum cooling capacity of 1.4 kW was obtained when the temperature of $T_w$ was 23°C.

It is thought that the temperature dependence of the magnetic entropy change in Gd influences the cooling capacity of the whole system because approximately 70% of all the magnetic materials packed in unit A and unit B are Gd which has a Curie point of 21°C.
4.2 Temperature span

Tests on the temperature spans were carried out by changing the magnetic materials packed in the unit, as shown in Table 1 (Case 1 ~ Case 3).

The numerals in ( ) in the table are the Curie points of the respective materials.

In Case 1, only Gd was packed in unit A. In Case 2, Gd, GdY and GdDy were packed in unit B. In Case 3, Gd was packed in unit A, and GdDy was packed in unit B.

In Case 3, tests were carried out in series mode.

| Case   | Unit A       | Unit B       |
|--------|--------------|--------------|
| Case 1 | Gd (21)      | ※ left unused|
| Case 2 | ※ left unused| Gd, GdY, GdDy (21, 15, 10) |
| Case 3 | Gd (21)      | GdDy (10)    |

4.2.1 Comparison between Case 1 and Case 2

Temperature spans ($\Delta T$) dependent on the fluid flow rate ($q_v$) are shown in Fig 13 (Case 1) and Fig. 14 (Case 2).

The temperature ($T_{hi}$) of the heat transfer fluid from the pump was set at 20 ℃. In these figures, the empty circles show $\Delta T$ when the number of magnet rotations was 10 min$^{-1}$, and the black dots mark $\Delta T$ when the number of magnet rotations was 30 min$^{-1}$.

In both the Cases, $\Delta T$ had a tendency to increase up to the flow rate of the heat transfer fluid of 5 litter/min, followed by a decrease.

When the number of magnet rotations was 30 min$^{-1}$, the maximum value of $\Delta T$ exceeded that obtained when the number of magnet rotations was 10 min$^{-1}$. The rate of decrease in $\Delta T$ at 30 min$^{-1}$ was lower when the flow rate was over 5 litter/min.

The maximum temperature span was 8.7 ℃ in Case 1 and 8.2 ℃ in Case 2.

Results from Case 2 implied that the cascade method did not work effectively even if 3 magnetic materials with a different $T_c$ were packed in the AMR bed.

The change in Gd entropy peaked at around the Curie point, however, the specific heat became smaller at temperatures above the Curie point, as shown in Figs. 5 ~ 7.

Therefore the peak adiabatic temperature change increases in the temperature range above the Curie point.

4.2.2 Comparison between Case 1 and Case 3

In Case 3, when the operational mode was in series, a maximum temperature span of 21.3 ℃ was obtained at the operational temperature of $T_{wo} = 28$ ℃ (Fig. 16).

This indicates that the temperature span was drastically improved compared to the temperature span of 12.5 ℃ obtained in Case 1, with an operational temperature of around 30 ℃. These results verified the cascade effect.

The maximum temperature span dependent on the operational temperature was measured with the change in temperature “$T_{wo}$” of unit A, as shown in Fig. 15.

A maximum temperature span of 12.5 ℃ was obtained when the operational temperature was around 30 ℃, in the higher temperature range above the Curie point.

The following tests were carried out at the operational temperature of around 30 ℃.
4.3 Improvement of the AMR bed

A maximum cooling capacity of 1.4 kW was obtained. However in Case 2, the cascade method which consisted of 3 materials packed into one AMR bed was not effective. On the other hand, in Case 3, the cascade method which consisted of a Unit A bed and a Unit B bed was effective. These results implied that the V shaped AMR bed did not bring out the potential of the magnetocaloric effect of the magnetic materials.

The velocity of the heat transfer fluid was not constant in the V shaped AMR bed. Therefore it is thought that there are areas where there is no effective heat transfer between the magnetic material and the fluid. Improvements were made to the AMR beds, changing the formation from a V shape to a rectangular shape.

At the same time, the AMR bed material was changed from stainless steel to other material. Given that the heat capacity of the AMR bed is as large as that of the magnetic material, the AMR bed may incur a large cooling load. Therefore, instead of stainless steel, MC nylon was chosen as the AMR bed material which has a low specific heat and thermal conductivity.

The dead volume in the AMR bed where the magnetic material is not packed was decreased so that the heat transfer fluid is not stirred and the gradient of the temperature is not disturbed.

Figure 17 shows the improved AMR beds. The comparison of the temperature span between the V-shape bed and rectangular shape bed is shown in Fig. 18. The rectangular shape improved the temperature span, obtaining a maximum temperature span of 16.2 °C. The results show that the changes of the shape and the material of the AMR bed were effective.

5. Summary

A magnetic heat pump was designed, consisting of a ring-shaped Halbach arrayed magnet with a maximum magnetic flux density of 1.5 T and Gd-based alloys packed into the AMR beds, in order to evaluate the potential of a magnetic heat pump in a large scale application.

The maximum cooling capacity of the developed magnetic heat pump was 1.4 kW, which is the maximum value so far achieved in Japan.

A maximum temperature span of 21.3 °C was also obtained demonstrating the potential of the magnetic heat pump in large scale applications.

The maximum cooling capacity was obtained at an operational temperature of around 23°C, and it was found that the cooling capacity reaches a peak at around the point of Curie temperature of Gd.

Nonetheless, the temperature span in Case 3, which consisted of a Unit A and a Unit B bed was larger than in Case 2, which consisted of 3 materials in a single AMR bed. These results suggest that a V shaped AMR bed does not bring out the potential of the magnetocaloric effect from magnetic materials. Therefore, the shape of the AMR was changed from a V-shape to a rectangular shape. The change in shape and material of the AMR bed were effective because the maximum temperature span was then improved to 16.2°C from 12.5°C.

Based on these results, it is now planned to develop a high frequency system, with a special focus on downsizing the size and decreasing the weight of the system.

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