Effects of Magnetocaloric Wire on Increase in Magnetic Refrigeration Cycle

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We are working on the development of an environment-friendly, next-generation magnetic refrigerator focusing on magnetic refrigeration technology. Since conventional magnetic refrigerators have the problem of insufficient cooling, we aim to develop a new system with increased cooling power by increasing their cycle frequency. To achieve the goal, we have developed a magnetocaloric material (MCM) consisting of thin wires with the world's smallest diameter using wire drawing, which is one of Fujikura's core technologies. As a result of using the wire-shaped MCM in a magnetic refrigerator and operating this device at a cycle frequency of 10 Hz, the system achieved the world's top-level specific cooling power in a weak magnetic field of 0.6 T. This paper provides a summary of the results from experiments.

1. Introduction

In the conventional refrigeration technology for air conditioners and refrigerators, they often require refrigerant fluids which contain chlorofluorocarbons (CFCs) or hydrochlorofluorocarbons (HCFCs). On the other hand, the phase-out of these substances has been underway with greater awareness of the environment [1)]. Against this backdrop, new environment-friendly refrigerators are needed, and thus we have focused on magnetic refrigeration technology. Magnetic refrigeration systems based on the magnetocaloric effect (MCE) are more efficient in theory than vapor compression type refrigeration systems and are free of CFC and HCFC refrigerants. This report describes the study on the challenge in increasing cooling power in magnetic refrigeration technology.

2. Measures for increasing cooling power

In a near room temperature, temperature difference obtained by the magnetocaloric effect is small. To solve this challenge, an active magnetic regenerator (AMR) has been proposed [2)]. This AMR includes an MCM that serves for thermal energy storage and regeneration and thus can create a large temperature span.

Some prototype magnetic refrigerators for wine coolers and small-size refrigerators have recently been presented as an actual application example of magnetic refrigeration technology [3)]. However, these magnetic refrigerators have a cooling power of only several tens of watts. There are still challenges in developing magnetic refrigeration systems that enable high power cooling required of air conditioning systems. Increasing the cooling power of the magnetic refrigerator is one of the challenges for this new system to be put to practical use. There are several ways to solve these challenges, for example, by increasing the amount of the magnetocaloric material (MCM), the magnetic flux, and the frequency of the AMR cycle. Among these solutions, we have focused on the speed-up of the AMR cycle.

Speeding up the AMR cycle requires that temperature changes of MCM due to the MCE and heat exchanges between the MCM and the refrigerant occur in a short time. It was reported that the time response to temperature changes due to the MCE is as short as less than 2 ms [4)]. Therefore, it is necessary to speed up the AMR cycle by increasing the speed of the heat transfer between the MCM and refrigerant fluid.

MCMs are generally used in the form of about 0.3 mm particles [5)], which have large contact areas. However, the particles make the flow paths more complex and cause large pressure loss between the MCM and refrigerant [6)]. Pressure loss limits the flow rate and thus the speed-up of the AMR cycle as well. It has been studied based on simulation and reported that the shapes that can reduce pressure loss are plate, porous cube and wire [6)]. The results of the experiments that used a plate-shaped MCM have been reported [7) 8)]. However, there are problems that the thickness of each plate-shaped MCM needs to be thin to ensure a sufficient contact area, and that it is difficult to laminate and fix the plates.

We have focused on a wire-shaped MCM that is suitable to speed up the AMR cycle. If the wire-shaped

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Panel 1. Abbreviations, Acronyms, and Terms.

MCE—Magnetocaloric effect
MCM—Magnetocaloric material
Gd—Gadolinium
AMR—Active magnetic regenerator
ΔSm—Magnetic entropy change
Tc—Curie temperature

MCM is used, it will ensure a straight flow path. However, because the MCMs that were studied in the past had poor workability, none of them seem to have been formed into wire. No experimental report on a wire-shaped MCM has been published so far. Taking this situation into account, we have developed a wire-shaped MCM and an experimental AMR machine capable of operating at high frequency and measured the performance of the machine.

3. Method of measuring performance of each material

3.1 MCMs in different shapes

We used pure gadolinium (Gd) to draw a wire because this metal is an MCM widely used for magnetic refrigeration research and probably the optimum choice to verify the effect by shape. We succeeded in fabricating the wire-shaped MCM by applying wire drawing technology, which is one of our core technologies. Figure 1 shows the appearance of the Gd wire. In this study, we used two types of Gd wires with a diameter of 0.5 mm and 0.25 mm and, for comparison, 0.3 mm dia Gd particles.

3.2 Properties of Gd Wire

We determined magnetic properties of the Gd wire with a diameter of 0.25 mm. The ΔSm and Tc of the wire at 1 T were measured with a magnetic property measuring system (MPMS), and the measured values were compared with those of Gd particle with a diameter of 0.3 mm. Figure 2 shows the results. The ΔSm of the Gd wire at the Tc (−2.6 J/kg·K) was lower than that of the particle (−2.8 J/kg·K). The Tc of the wire was lower than that of the particle. In the range of temperatures lower than the Tc, the ΔSm of the wire was −0.2 to −0.6 J/kg·K higher than that of the particle. We think that the shape of the Gd wire may have exerted an influence on its demagnetizing field.

3.3 Porosity Control

When single wires are cut into the same length and arranged side by side in the AMR bed, the porosity of the wires is smaller than that of Gd particles with a diameter of 0.3 mm. This could cause an increase in pressure loss. To solve this challenge, three-twisted wires were fabricated, and the AMR bed was filled with these wires (Fig. 3). We thought that the use of

Fig. 1. 0.25 mm dia. Gd wires.

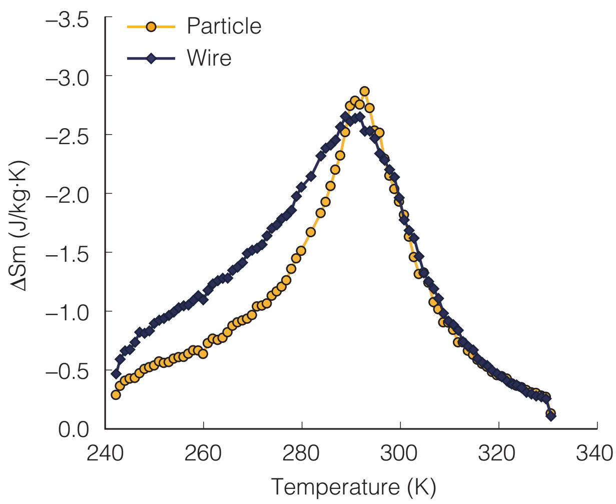

Fig. 2. ΔSm of Gd wire and Gd particle.

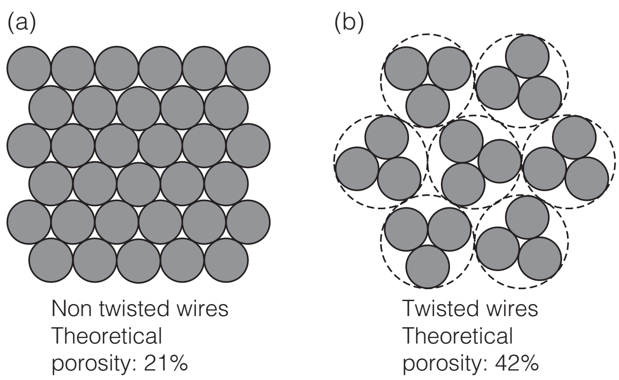

Fig. 3. Porosity (a) non twisted wires. (b) twisted wires.

the twisted wires would allow the securing of the flow paths between the wires and refrigerant and the control of the porosity. We measured the flow rate of the fluid into each MCM beds filled with particles, wires, or twisted wires after setting the pressure difference between both ends of the beds at 0.3 MPa. Figure 4 shows the comparison results of the nominal contact area and the flow rate of each configuration of the MCM. There was no significant difference in the flow rates between the Gd particles and the single Gd wires. On the other hand, the flow rates of three-twisted wire are higher than those of the particles and the single Gd wires despite the same contact area.

3.4 Experimental Methods

Figure 5 shows a schematic diagram of the experimental machine, and Figure 6 shows a photograph of the machine. The AMR has mechanisms of reciprocating magnet and a reciprocating refrigerant pushed by reciprocating pistons in accordance with the magnet movement. Table 1 shows the configuration of the AMR bed, and each MCM packed into the bed, and Table 2 shows the measurement parameters. The Gd particles packed into the AMR bed had a diameter of 0.3 mm on average. The porosity of the particles calculated from the weight was 40%, which was higher than the theoretical value (26%). We think that this is because of the shape of the granular material, which is not a true sphere, and variations in particle diameter. Similarly, the porosity of the twisted wire was calculated from the weight. The theoretical value of the porosity of three-twisted wire is 42%, but actually measured values were 57% for 0.25 mm dia and 49% for 0.50 mm dia, both of which were higher than the

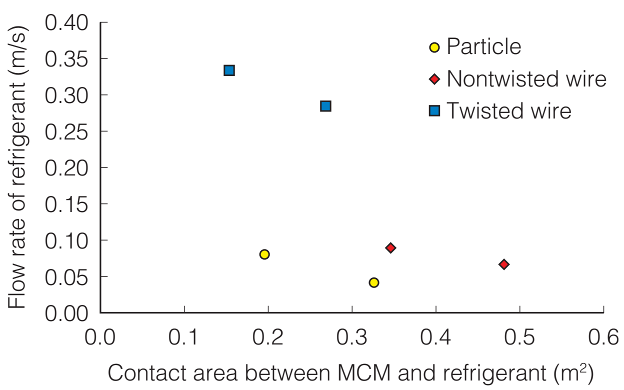

Fig. 4. Comparision of flow rate among MCMs in each configuration at 0.3 MPa.

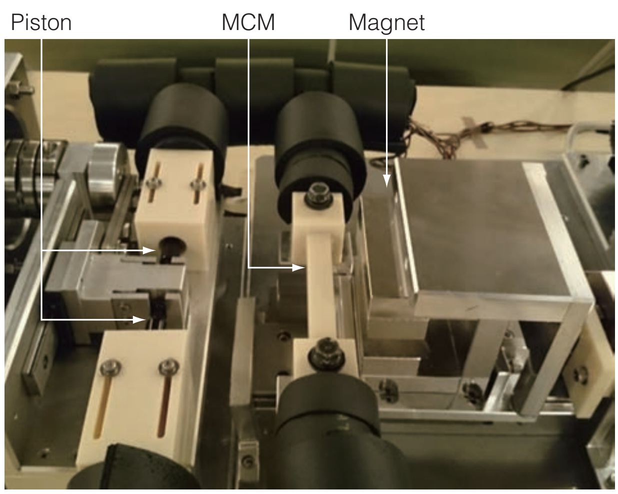

Fig. 6. Photograph of experimental apparatus.

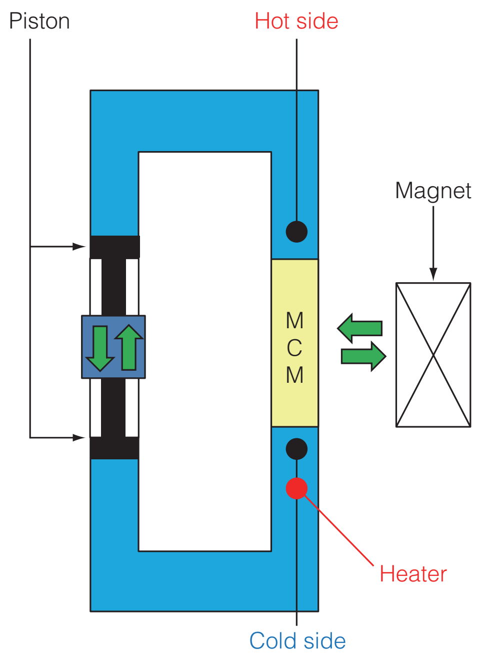

Fig. 5. Schematic diagram of experimental apparatus.

Table 1. Experiment sample details.

Material configrations	Particle	Twisted wire	Twisted wire
Diameter of MCM (mm)	0.3	0.25	0.5
Mass of MCM (kg)	0.093	0.067	0.079
Dimentions of bed (mm)	14 (height) x 14 (width) x 100 (length)		
Porosity (%)	40	57	49
Contact area (m^2)	0.22	0.11	0.056

Table 2. Measurement parameters.

Operation frequency [Hz]	Max 10
Magnetic field [T]	0 - 0.6
Flow rate [l/min]	0.288 - 4.32
Refrigerant	Water
Ambient temperture [°C]	200 ± 0.5

theoretical value. We think that the three-twisted wire could not come in close contact with each other at the time of arrangement, leaving space between the wires. With practical application in mind, the magnetic flux density was set at 0.6 T, which enables the magnetic circuit size to be relatively small.

The measurement procedure and the calculation method of the cooling power are as follows: First, the AMR is operated to create a temperature span in the refrigerant on both sides of the MCM bed. After the temperature span becomes stable, the heater installed in the cold end is operated so that the heating power cancels the cooling power. The heating power is regarded the cooling power, and the cooling power divided by the weight of the MCM is regarded the specific cooling power. The maximum specific cooling power can be calculated using the temperature span and the cooling power plots.

4. Results and discussion

Figure 7 shows the relationship between specific cooling power and operation frequency. In the experiment of the 0.3 mm-dia particle, its specific cooling power peaked out at 3 Hz. The specific cooling power of the 0.5 mm-dia twisted wire peaked out at an operating frequency of 5 Hz. The measurement results of the 0.25 mm-dia twisted wires did not show the peak value in this measurement range. The largest specific cooling power in all the experimental data was 298 W/kg at an operating frequency of 10 Hz.

Although the contact area of 0.3 mm-dia Gd particle was more than twice the twisted Gd wire, the maximum specific cooling power of the Gd wire exceeded the results of the Gd particle by increasing the cycle frequency.

We conclude that this is because the Gd wire was able to reduce the pressure of the refrigerant on the wire and thus the wire stayed in the same place even though the frequency was increased. Therefore, we think that the refrigerant was able to flow uniformly to some extent and that the heat exchange was carried out efficiently.

On the other hand, we think that the Gd particle was moved by the pressure of the refrigerant, which caused the refrigerant to flow locally and thus the performance to decrease because of a less effective total contact area for heat exchange with the refrigerant.

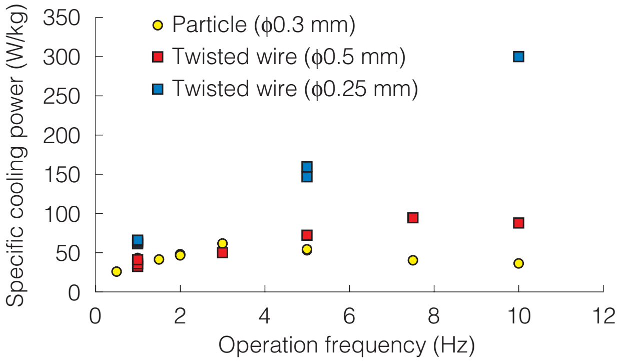

Fig. 7. Performance of Gd particle and wires in experimental device.

5. Conclusion

We examined the possibility of increasing the cooling power of our prototype magnetic refrigerator by increasing AMR cycle by using a wire shaped MCM. As a result of the testing using three-twisted Gd wires consisting of 0.25 mm-dia single wires, the specific cooling power achieved 298 W/kg at a cycle frequency of 10 Hz. In the future, we will examine the possibility of increasing the cooling power by further increasing the frequency for practical application.

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