Design and development of rotary magnetic refrigeration prototype with active magnetic regeneration system

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Abstract. In the field of cooling system, a traditional vapor compression (VC) technology has been used over long time. The VC cooling is simple and cost effective, however, it raises global warming concern due to its relatively low energy efficiency and usage of ozone depletion substances. Magnetic refrigeration (MR) has been proposed as a potential cooling technology that can replace the VC cooling. MR can potentially be operated with efficiency closer to the theoretical efficiency, without using environmentally-harmful refrigerants. In the MR system, a magnetocaloric material (MCM) with magnetocaloric effect (MCE) is used as a refrigerant. The temperature of MCM can be increased and decreased under adiabatic magnetization and demagnetization, respectively. Water/ethylene glycol can be used as heat-exchanging fluid. In this work, a rotary MR prototype was designed and built. The prototype consists of the following main systems: 1. Flow distribution system, 2. Rotary magnetic field generator 3. Mechanic system, and 4. Temperature and pressure sensor system. Four beds of magnetocaloric gadolinium (Gd) particulates were used as an active magnetic regenerative cooling media. Fluid flow was controlled by pneumatic pump and solenoid valves. Rotary magnetic field generator was designed and built with maximum and minimum fields of 0.65 and 0 T, respectively. The overall setup and preliminary study showed that the pressure drop across the system was 2 bar when the flow rate was only 0.5 L/min. Increasing flow rate further resulted in too high pressure drop causing the MCM bed to swell. Therefore, the flow rate was limited to 0.5 L/min resulting in insufficient heat transfer rate by the slow heat exchange fluid flow. Consequently, the maximum temperature span was measured to be 0.5 K. The prototype must be improved to drive flow rate higher and to reduce the pressure drop of the system.

1. Introduction

Cooling technology is integral to human beings’ daily activities, i.e. home living, food storage, transportation, workplace, etc., with over 40% of the world's electricity applied to the cooling system. Currently, the most common cooling system is the vapor compression system. However, the vapor
compression system uses environmental-hazardous substances, i.e. Chlorofluorocarbons (CFC) or hydrofluorocarbons (HFC), etc., that can harm ozone layer and cause the greenhouse effect. Recently, the magnetic cooling system has gained a lot of attentions due to its several advantages including (i) potentially high energy efficiency, (ii) environmental-friendly solid refrigerant and heat exchange fluid [1]. The magnetic cooling system applies the magnetocaloric effect (MCE), which is a thermodynamics phenomenon in which the magnetization/demagnetization process can increase/decrease the temperature of a magnetocaloric material (MCM) under an adiabatic condition [2-3]. Active magnetic regenerator cycle (AMR) is commonly applied in most of the reported magnetic refrigeration (MR) prototypes. For AMR cycle, an MCM takes on two roles: (i) as a refrigerant to change temperature under magnetization/demagnetization, and (ii) as a heat-exchange regenerator to expand a temperature span with water as a heat-exchange fluid [4-5]. Therefore, many researchers have developed AMR magnetic cooling prototypes to be more effective and better performance. Tura and Rowe [6] developed an AMR rotary magnetic prototype, with rotating permanent magnet and 110 g Gd as AMR, and reported the cooling performance of 10 K temperature span at 50 W cooling power. Engelbrecht et al. [7] reported a rotary AMR prototype, with rotating AMR bed and stationary permanent magnet, exhibiting maximum temperature span of 25.4 K and maximum cooling power of 1,010 W (at 0.3 K temperature span). Lozano et al. [8] produced an AMR rotary magnetic refrigeration prototype, using 1.7 kg Gd as MCM, which exhibited maximum cooling power of 150 W and maximum temperature span of 12 K. In this work, an AMR rotary magnetic cooling prototype has been designed and built. The goal is to develop the magnetic-cooling prototype, which can be extensively used in future work for testing the performance of different MCM and varied MCM bed packing. The preliminary performance testing of this prototype using Gd particulates as MCM was reported herein.

2. Prototype design and setup
For the current AMR magnetic cooling system, three key components was designed and built, including (i) an AMR MCM beds, (ii) a rotating magnetic-field generator, and (iii) a flow system control of the heat-exchange fluid flow. The magnetic cooling prototype contains a rotating magnet assembly to generate cyclic magnetic field on the MCM beds, as shown in figures 1(a) and (b). The magnet field generator applied the design of a rotating magnetic field described in ref. [9]. 200 micron Gd MCM particulates were packed in a bed made of polyamide material (PA6) with the wall thickness of 3 mm and 8 cm in length, as shown in figure 2. Four MCM beds were inserted in a blue PA6 housing located in the gap between the rotating magnet rotor and stator, as illustrated in figure 1(b) and figure 2. The stationary packed beds were connected to the valves for heat-exchange fluids to flow through.

Figure 1. (a) Drawing of the magnet assembly; (b) The rotating magnet assembly with the blue MCM bed housing made of polyamide material (PA6) inserted in the gap between magnet rotor and stator.

The flow distribution of the heat-exchange fluid was controlled by solenoid valves, as schematically illustrated in figure 3(a). A reciprocating displacement pump, with maximum pressure
of 9 bar and maximum flow rate of 2.5 L/min, was used to drive fluid flow. A 3-phase motor was used to rotate the magnet rotor via the pulley and belt connection. Figure 3(b) shows the final assembly of the AMR magnetic cooling prototype. The temperature change across the MCM bed was measured by a RTD type PT-100 temperature sensor. Power consumption of the prototype, pressure drop across the system, and the flow rate were monitored for this preliminary testing of the prototype.

![Image](image1.png)

**Figure 2.** A packed bed of Gd MCM particulates that was placed in the PA6 assembly inside the gap between the magnet rotor and stator.

![Image](image2.png)

**Figure 3.** (a) Schematic diagram showing the solenoid-valve control of fluid flow direction between cold-sid heat exchange (CEX) and hot-side heat exchange (HEX); (b) the actual full assembly of the rotary AMR magnetic cooling prototype.

### 3. Results and discussion

The magnetic field generator assembly performance was shown in figure 4. As the magnet rotated, the magnetic field density on the MCM bed varied from 0 to 0.65 T. Therefore, under demagnetization state, the MCM bed was completely in zero field condition. Under the magnetization state, the MCM bed experienced maximum field of 0.65 T for this system.

![Image](image3.png)

**Figure 4.** Magnetic flux density (y axis) measured at the 0° bed location as the magnet rotor was rotating from 0 to 360 degree (x axis).
For the temperature span across the bed measurement, the temperatures were measured at 4 points across the MCM bed, as shown in figure 5. At location T1, the temperature of the fluid flowing from the HEX coil was measured. The temperature at T1 was controlled to be constant at temperature close to the Curie temperature of Gd (~21°C). T2 was the temperature of the fluid after flow through the demagnetized MCM bed (hence, adiabatically cooled down). T3 temperature was that of the fluid that returned from the CEX to the MCM bed. In this preliminary test, the thermal load at CEX was nearly zero (no heat exchange at CEX), therefore, T2 and T3 were close to one another. Finally, T4 temperature was the temperature of the fluid that passed through the magnetized MCM bed (adiabatically heated up) and returned to the HEX coil.

![Figure 5](image.png)

**Figure 5.** The location of temperature measurement across the MCM bed. The arrows indicate fluid flow direction from hot to cold sides and vice versa.

Before starting the magnetization/demagnetization process, the fluid was initially set by a chiller to be at 21°C and flowed throughout the system, so the temperatures in all locations were the same. Then, the magnet was rotated to generate alternating magnetic field from 0 T (demagnetization) to 0.65 T (magnetization). During the flow rate testing, it was found that the pressure drop across the system increased to 2 bar at a flow rate of only 0.5 L/min. Increasing flow rate further resulted in too high pressure drop that the MCM bed swelled and hindered the magnet rotor’s rotation. As a result, for this current 8-cm Gd-packed bed setup, the flow rate was limited to 0.5 L/min. The rotation of the magnet was in step motion with 10 sec interval to ensure that the fluid completely flowed through the system.

After the magnetic cooling system was active, the temperatures on the cold side (T2 and T3) slowly decreased from the set temperature of 21°C (set temperature from hot side) to 20.5°C. The temperature on the cold side remained at 20.5°C, while the hot-side temperature was constant at 21°C. The cold-side temperature returned to 21°C after the magnet rotation was stopped. Therefore, the maximum temperature span is 0.5°C. The temperature span was low, possibly due to too slow flow rate as well as the maximum field was 0.65 T. For the future work, the flow rate must be increased by reducing the pressure drop of the system. Moreover, the MCM materials with varying Curie temperature should be used to expand the operating temperature span.

4. Conclusion
The AMR magnetic cooling prototype was designed and assembled. The magnetic field generator produced cyclic field of 0 – 0.65 T using rotating magnet rotor. The maximum flow rate was limited to 0.5 L/min due to high pressure drop across the system. Therefore, the resultant temperature span was limited to 0.5°C at no thermal load. The pressure drop of the system must be decreased in the future to increase flow rate and performance of the prototype.

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