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Performance Assessment of a Near Room Temperature Magnetic Cooling System

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Abstract

In this study, performance of a near room temperature magnetic cooling system was investigated experimentally in terms of temperature span. The current setup has a permanent magnet pairs (0.7 Tesla), a magnetocaloric material (Gadolinium) and a heat transfer fluid (water, ethylene glycol and 10% ethanol-water mixing) furthermore solar energy was used as a power source of liner motion of the magnetic system. The obtained results showed that ethanol-water was the best heat transfer fluid and also that optimum magnetization-demagnetization period for the system was found 10 s.

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Keywords: Clean energy, gadolinium, heating-cooling,magnetic, magnetocaloric

1. Introduction

Recently, reduction of energy utilization for heating and cooling has crucial importance. The main reason for that is heating and cooling occupy the largest portion of overall energy consumption in buildings. According to the EU energy strategy plan this rate is more than 40% of final energy consumption [1]. Conventional cooling systems use compressor which is the main component of energy consuming and also non-environmental (global warming and

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ozone depletion) refrigerants are another problem for the conventional systems. Therefore, different alternative heating and cooling methods have been under research. Magnetic cooling can be a promising solution for cooling also has opportunity for renewable usage in buildings.

In a magnetic cooling system, a magnetocaloric material which is the most important part is being used. When magnetic material enters into the magnetic field its temperature rises and decreases out of the magnetic field. Based on this principle a fluid can be cooled (or heated under magnetic field) while the magnetocaloric material is out of the magnetic field. In the literature, there are many studies on magnetic cooling but most of them are theoretical. The most important studies are given as following in this part; Tishin [2] was applied Mean-Field-Theory (MFT) is used to predict the thermal properties of magnetocaloric materials. The first near room temperature magnetic cooling system development was a mile stone in this area [3]. An important exploration on this topic was the active magnetic regenerator (AMR) which is known as the best efficient magnetic cooling system up to now [4]. Therefore, numerical and experimental studies are mostly related AMR for instance Engelbrecht *et al.* [5] compared 1D and 2D AMR models. Sarlah and Poredos [6] introduced a dimensionless model to determine the heat transfer coefficient of AMR regenerator. In another AMR study, a 1D transient numerical code was developed by Roudaut, *et al.* [7]. In this study, the mean field theory was used to evaluate the magnetocaloric properties of Gadolinium. Engelbrecht *et al.* [8] investigated design and construction aspects of a high frequency rotary AMR system.

They reached 25 K, 20.5 K and 18.9 K temperature span values for the unloaded, 100 W and 200 W of cooling load cases, respectively. Lozano *et al.* [9] developed a prototype which was AMR type magnetic refrigerator. In the AMR they used 2.8 kg packed sphere gadolinium and magnetic field (1.24 T) provided with a permanent magnet. In the current study, magnetic system was analyzed for different design aspects such as type of heat transfer fluid, flow rate, magnetization-demagnetization period. Experimental and theoretical results have been compared.

2. Principle of magnetic cooling

All magnetic materials exhibit magneto caloric effect (MCE) and this effect peaks at Curie temperature. Curie temperature is the magnetic phase change temperature of a magnetic material. The MCE is a physical phenomenon that occurs in magnetic materials under the influence of a varying magnetic field. The temperature of magnetic material is increased when magnetic field is applied; this is known as magneto caloric effect [10]. The total entropy of a magnetic material consists of three main components [10]: $S_{magnetic}$, $S_{lattice}$ and $S_{electron}$.

$$S_{total}(B,T) = S_{magnet}(B,T) + S_{lattice}(T) + S_{el}(T) \tag{1}$$

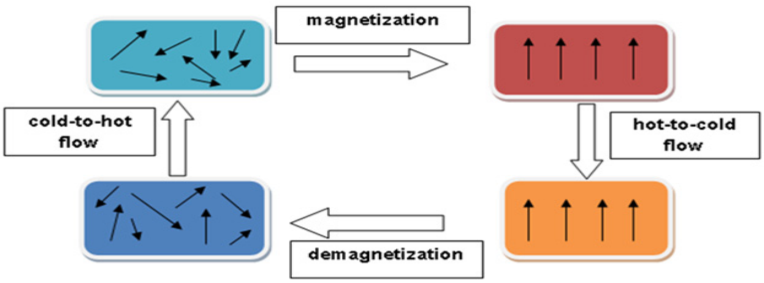
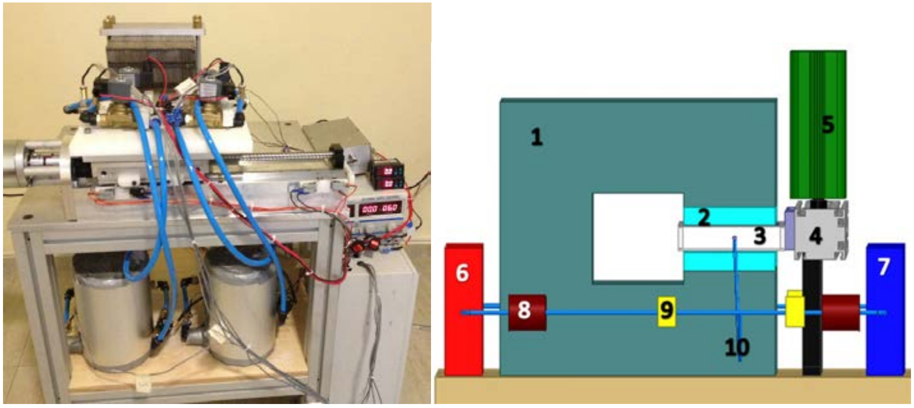


Fig. 1. A principle view of magnetic cooling cycle.

The electron entropy is disregarded since its effect is quite small comparing to the others. Fig. 1 shows the two basic processes of the magnetocaloric effect when a magnetic field is applied or removed in a magnetic system: the isothermal process, which leads to an entropy change, and the adiabatic process, which yields a temperature variation. When the magnetic material is exposed to a magnetic field, molecular moments are forced to align in the same direction resulting in a decrease in the magnetic entropy [10]. As the total entropy is constant, the reduction in the magnetic entropy then is compensated by an increase in the material's lattice entropy. Increase of lattice entropy causes an adiabatic increase in magnetic material temperature. During demagnetization on the other hand, the molecules tend to be arranged randomly causing an increase the magnetic entropy [10]. In an opposite manner to the magnetization phase, the increase in the magnetic entropy results in a decrease in the material’s lattice entropy and thus a decreased temperature.

3. Description of magnetic cooling system

In Fig. 2 experimental setup is given. The system consists of a Gadolinium (Gd) bed (3), permanent magnets (2), hot and cold fluid tank (6 and 7), pumps (8), flexible pipes (10), valves (9), and a linear motion system (4). A permanent magnet pair generates 0.7 T average magnetic field. Heat transfer fluid (HTF) is distributed through the Gd bed by solenoid valves and DC pumps. The Gadolinium bed has a linear motion provided by a linear mechanism and a BLDC motor.



1-Yoke, 2-Magnet, 3- Gd bed, 4- Linear system, 5- BLDC motor, 6- Hot reservoir, 7- Cold reservoir, 8-Pump, 9- Valve, 10- Flexible pipe

Fig. 2. Experimental magnetic cooling system

Performance of a magnetic cooling system mostly depends of the magnetic bed or regenerator (Gd bed). In Fig. 3, Gd bed (regenerator) is shown. Gd bed is designed as a parallel flow heat exchanger also inside the regenerator Gd plates are used. The thickness of each Gadolinium plate is 1 mm. The length and the width of the unit are L = 200 m and W = 100 mm, respectively. The unit consists of 50 Gadolinium plates. Experimental setup also includes measurement equipment for obtaining and logging temperature, flow rate values at different points, power consumption of the magnetic cooling system, and solar energy production amount from PV panels.

Table 1. Specifications of measurement equipment

Equipment	Specifications
Flowmeter	Turbine type; Measuring range: 1-30 l/min at-20 and 120 oC; Measuring error: ±%2
PV system	Charge Controller: Xantrex MPPT 60-150. XANBUS communication via computer
	Inverter: Tommatech 2kVA pure sine wave. RS232 communication via computer
	Sun Tracker: 4 panels dual axis tracking by accuracy <0.5o
Thermocouple	T type; Measuring range: -200 and 350 oC; Measuring error: ±%1.5
Control and data acquisition	Siemens S7-1200 1214C DC/DC/DC PLC and Wintr SCADA ; 12bit SM 1231 Analog input module; 16 bit RTD and TC module; Digital input/outputs

The specifications of measurement equipment are given in the Table 1. In the current study, temperatures are measured inlet and outlet of the Gd bed also from Gd surface as seen in Fig. 3. Daily energy consumption of the system is 2.23 kWh/day which is included linear motion motor, pumps, tracker motors, control system.

In the setup, required energy has been supplied by solar energy system. PV panels are installed on the roof of a building at Ege University Solar Energy Institute. Installed power of the PV panels i s calculated as 1 kWp (four Poly crystalline silicon (c-Si) PV panels with the capacity of 250 Wp each) to meet the total daily energy consumption, 2.23 kWh. Also a two-axis solar tracker has been used for maximum energy production from the PV panels. Since the PV system is an off-grid application, for the energy needs of 3 days (total 7.2 kWh) 4 pieces of batteries (each has an energy storage capacity of 12V, 150 Ah) has been used.

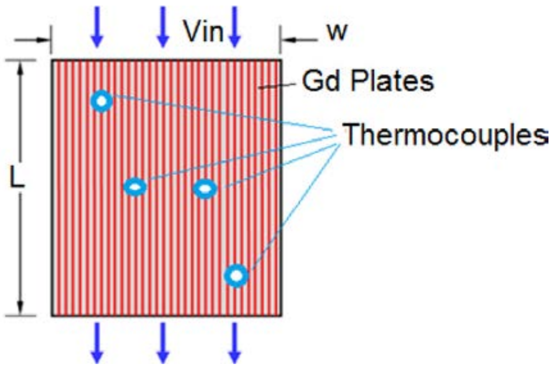


Fig. 3. Gadolinium bed.

4. Results and discussion

Experimental results are discussed in this section. For the magnetic field of 0.7 T different periods of the magnetization and demagnetization have been investigated. For this aim, magnetization periods were changed from 5 to 90 s by a 5 s-interval, and temperature variations of the Gadolinium are compared to each other. Both the magnetization and demagnetization periods(tmag_demag) are the same in these tests. Fig. 4 shows time-wise variation of the Gd (in the bed) temperature under a magnetic field of 0.7 T and 0 T. There is about 1.3 ^{o}C temperature span for no-flow cycle.

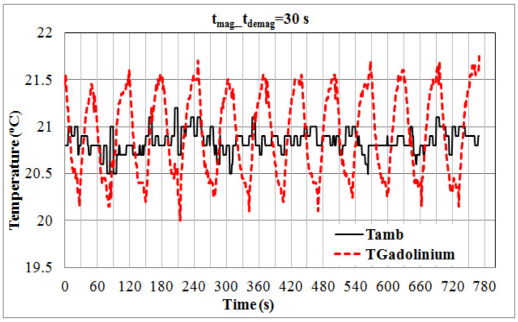


Fig. 4. Temperature changes on Gadolinium at t_{mag_demag}= 30 s

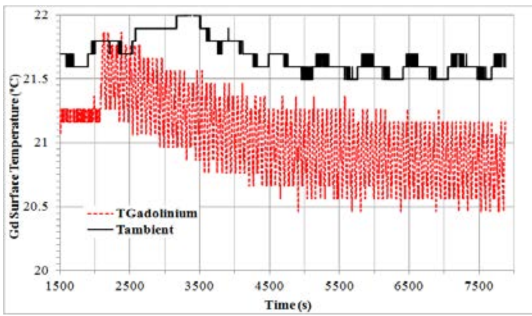


Fig. 5. Temperature changes on Gadolinium at t_{mag_demag}= 30 s

On the other hand, in Fig. 5 with the HTF flow, Gd surface temperature change versus time has been given. Experiments with the HTF should be realized at lower flow rates and higher magnetization-demagnetization period since delay at the heat transfer mechanism. Because of the fact that, heat conduction value of the Gd is to low (10 W/mK).

As seen from Fig. 5 temperature decreases about 1.5 ^{o}C for the 30 s magnetisation-demagnetisation period and 0.5 l/min HTF flow rate. In this study, three different heat transfer fluids are investigated in numeric analysis; water (W), ethanol-water (EW) and ethylene glycol (EG). Performance of the magnetic cooling is given by coefficient of performance (COP) and for the current magnetic cooling system the COP can be defined as in Eq. (2),

$$COP = \frac{\dot{Q}_C}{\dot{W}} \quad (2)$$

where $\dot{Q}_C$ is the cooling capacity and $\dot{W}$ is the electrical energy consumption of the magnetic cooling system including pumps, linear motion motor, control etc. In the current system, average electrical energy consumption is 51.6 W, cooling capacity is 52.3 W (for 1.5 ^oC temperature span and 0.5 l/min flow rate of HTF). By the help of these values COP of the current system for experimental studies is1.6.

5. Conclusions

In the current study, a near room temperature magnetic cooling system was investigated both numerical and experimentally. According to the numerical results the best HTF is ethanol-water mixture and the best operational parameters are 10.2 s magnetization-demagnetization period and 0.0046 m/s HTF fluid velocity. Furthermore, at the Gd bed 5 ^oC temperature decrease (under 0.7 T) has been observed according to the numerical results. On the other hand, experimental studies resulted only 1.5 ^oC temperature decrease under 0.7 T magnetic field. This difference from the numerical study is related the heat transfer mechanism at the Gd bed. The best magnetization-demagnetization period is 30 s at the same velocity of HTF and the COP of the system is 1.68.

As a result, efficient heating and cooling solutions in buildings need to be investigated. For this purpose alternative methods such as magnetic cooling can be solution in the future. However currently magnetic cooling systems have very limited capacity for building scale cooling applications. In this regard, solar energy powered magnetic heating and cooling must be investigated since it has potential to help energy efficiency, environmental problems also has an advantage of being powered by green energy technologies especially for household heating and cooling systems.

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