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Experimental Performance Evaluation of a Solar Assisted Magnetic Heating-Cooling System

Orhan Ekren[a,1], Ahmet Yılancı[a,2], Murat Kara[b,3], Mehmet Akif Ezan[c,4], Çağrı Metin[d,5], Emrah Bıyık[e,6]

[a] *Solar Energy Institute, Ege University*
Bornova, Izmir, Turkey

[1]orhanekren@gmail.com

[2]ahmetyilanci @gmail.com

[b] *Electronics Engineering, Izmir Institute of Technology*
Urla, Izmir, Turkey

[3]muratkaratr@gmail.com

[c] *Mechanical Engineering, Dokuz Eylul University*
Buca, Izmir, Turkey

[4]mehmetezan@gmail.com

[d] *Mechanical Engineering, Ege University*
Bornova, Izmir, Turkey

[5]cagri.metin.ege@gmail.com

[e] *Energy Engineering, Yasar University*
Bornova, Izmir, Turkey

[6]emrah.biyik@yasar.edu.tr

Abstract

To reduce building energy usage, novel heating-cooling solutions and building integrated renewable energy systems are required around the worldwide. Recently, the magnetic cooling system as an alternative method for the conventional cooling system is one of the promising approaches in terms of energy efficiency and environmental impact. Therefore, in this study, an experimental magnetic heating-cooling system has been designed and investigated. The current system has a permanent magnet pair, a magnetocaloric material, a heat transfer fluid and a linear reciprocating system. In the system, 50 Gadolinium plates are used as magnetocaloric materials. Furthermore, temperature variations of Gadolinium for no fluid flow condition and different magnetization and demagnetization periods are investigated. It is obtained experimentally that the effective magnetization and demagnetization durations should not be less than 30 s.

Keywords - magnetic; magnetocaloric; solar energy; gadolinium; innovative heating-cooling

1. Introduction

Reduction of energy usage in heating, cooling systems has a crucial importance and recently, attracting a more attention from end-users to researchers. The main reason for that is heating-cooling uses the largest portion of overall energy consumption in domestic and industrial utilization. This rate is 45% of final energy consumption in EU. Furthermore, around 70% of the energy used in buildings is consumed for heating and cooling [1]. Since the heating and cooling strategy is essential for a successful European energy union, there are many strategies under evaluation regarding efficient and novel heating-cooling systems and also renewable energy usage.

There are two main problems in conventional heating-cooling systems; the first one is high energy consumption in compressors of the cooling systems. The second problem is fossil fuel usage in heating systems and also non-environmental (global warming and ozone depletion) refrigerant usage in the cooling systems. Therefore, alternative heating-cooling systems have been under research. Magnetic heating-cooling can be considered as one of the novel solutions for efficient and environmental friendly way of the heating-cooling in buildings. It is a method in which magnetocaloric material is being used. Temperature of the magnetocaloric material increases when it is placed in a magnetic field, on the other hand, its temperature decreases as the magnetic field is removed. Based on this principle, while the magnetocaloric material is inside and outside of a magnetic field, a heat transfer fluid can be heated up and cooled down, respectively.

Fundamentals of magnetic theory go back to 1800s. In1843, James Prescott Joule observed that under a magnetic field heat exposed in iron materials. In 1860, William Thomson (Lord Kelvin) revealed that when heating the ferromagnetic materials until a certain temperature (later it is known as Curie temperature) they lose their magnetic properties. In 1881, Emil Warburg [2] identified this effect as magneto caloric effect (MCE). Although the magneto caloric effect (MCE) was discovered in 1881, the first experimentally magnetic cooling system was established by Giauque and MacDougall in 1933 [3]. In this system, 250 mK temperature span by using paramagnetic salts was observed. Afterwards, the first magnetic refrigerator was constructed and tested by G.V. Brown in 1976. An important exploration on this topic was the active magnetic regenerator (AMR), introduced in [4]. AMR is known as the best efficient magnetic cooling system up to now. It is the way to increase the temperature span by applying a magnetocaloric thermodynamic cycle that includes regeneration. Another important development was to set up the first near room temperature magnetic cooling system mentioned in [5].

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 [6] was applied Mean-Field-Theory (MFT) is used to predict the thermal properties of magnetocaloric materials. He evaluated the magnetic entropy variations of materials (Gd, Tb, Dy, Ho, Er, Ym, De, Ni and Co) with different Debye temperatures at different magnetic flux densities. A 1D transient numerical model of the active magnetic regenerator (AMR) with backed bed magnetic material was developed in [7], and they obtained adiabatic temperature change and specific heat of Gadolinium as an approximated function of temperature and magnetic induction. Sarlah *et al.* [8] designed a porous honeycomb regenerator and conducted a numerical analysis of different magnetocaloric material at different arrangements. Engelbrecht *et al.* [9]

compared 1D and 2D AMR models. Sarlah and Poredos [10] introduced a dimensionless model to determine the heat transfer coefficient of the regenerator and the operation of the AMR refrigerator (AMRR). Roudaut, *et al.* [11] developed a 1D transient numerical code of an AMR. The mean field theory was used to evaluate the magnetocaloric properties of Gadolinium. Chen *et al.* [12] experimentally and numerically investigated reciprocating AMR system with the micro channel. ANSYS-FLUENT software was used to simulate transient heat transfer of the AMR. Instead of calculating the adiabatic temperature change of the material as a function of temperature and magnetic flux density, they defined a constant source term as a function of temperature variation.

There are limited experimental studies in the literature. After the first room temperature magnetic cooling system by Brown in 1997, Ames Laboratory and the Astronautics Corporation presented an AMR system with the capacity of 500 W in 1998. For this room-temperature magnetic refrigeration system, COP was calculated to be 6.6 at the temperature span of about 12 K [13]. In 2001, the Astronautics Corporation proposed an AMR using permanent magnets for the magnetic refrigeration system [14]. Shir *et al.* [15] investigated room temperature magnetic refrigeration system and developed a computational model of the system. In the porous magnetocaloric bed, they reached 5 K of temperature span between hot and cold side, and the magnetic refrigerator produced 104 W cooling load. In another study, Engelbrecht *et al.* [16] investigated design and construction aspects of a high frequency rotary AMR system. In this study, they reached temperature span values of 25 K and 20.5 K for the unloaded and 100 W of cooling load cases, respectively. Lozano *et al.* [17] investigated an AMR type magnetic refrigerator prototype with a 2.8 kg packed sphere gadolinium. At 1.24 T with a permanent magnet and for 200 W cooling load, they reached 18.9 K temperature span in the system. These developments have revealed that magnetic refrigeration is an alternative method and a serious candidate for commercial/conventional near room-temperature refrigeration. However, finding a working material with a large magneto-caloric effect for different temperature regions is still a problem. Nearly 60 prototypes have been developed around the world, and today magnetic cooling is on its way towards the first market applications.

In this study, a near room temperature magnetic heating-cooling system has been experimentally investigated for no fluid flow condition. The current setup consists of a permanent magnet pair (about 0.7 Tesla with Gd bed in the air gap), magnetocaloric materials and a heat exchange bed, a heat transfer fluid and a linear reciprocating system. Inside the heat exchange bed, 50 Gadolinium plates are used as a magnetocaloric material.

2. Magnetic Heating-Cooling Fundamentals

A basic magnetic heating-cooling system consists of magnets for the magnetization/demagnetization processes, magnetocaloric materials, hot and cold heat exchangers, a heat transfer fluid and control/auxiliary equipment. In any magnetic heating-cooling system, the crucial part is the magnetocaloric material such as rare earth metals. 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. The total entropy of a magnetic material consist of three main components: $S_{magnetic}$, $S_{lattice}$ and $S_{electron}$.

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

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.

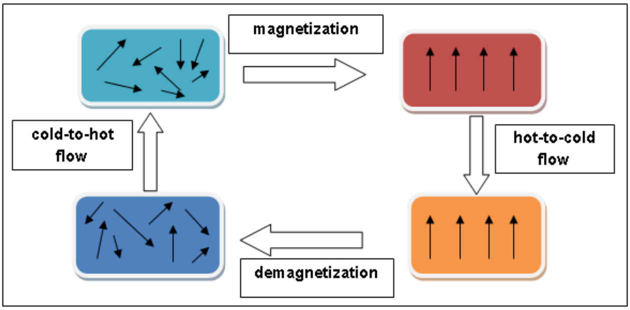
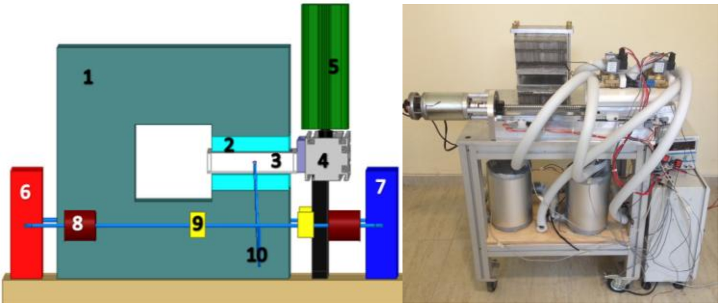


Fig.1 A principle view of magnetic cooling cycle.

In the process, after magnetization of a magnetic material by applying magnetic field, molecular moments are forced to line up in the same direction and decreases the magnetic entropy. While the total entropy is constant, the reduction in the magnetic entropy then results an increase in the material's lattice entropy. Increase of lattice entropy results an adiabatic increase in magnetic material temperature. During the demagnetization, the molecules tend to be arranged randomly and increase the magnetic entropy. While the total entropy is constant, the increment in the magnetic entropy then results a decrease in the material's lattice entropy and temperature. In a magnetic refrigeration device, generation of the magnetic field requires electromagnets or permanent magnets. Parameters such as magnetic flux density, volume of the air gap have a great importance to create considerable MCE. In recent studies, permanent magnets are used to eliminate the need for any external energy source, and this increases the cooling efficiency [18]. Since the magnets with higher magnetic fields are very cost intensive and limited in their magnetic energy, researchers tend to apply moderate magnetic fields, mostly between 0.7 and 1.5 T [19].

3. Experimental Studies

The schematic and image of the current near room-temperature magnetic cooling system is shown in Figure 2. It consists of a Gadolinium bed (3), permanent magnets (2), hot and cold reservoir (6 and 7), DC pumps (8), pipes (10), valves (9), and a linear reciprocating system (4). A permanent magnet pair generates magnetic field about 0.7 T. Heat transfer fluid (HTF) is distributed between hot and cold side by solenoid valves and DC pumps. The Gadolinium bed has a linear reciprocating motion provided by a linear mechanism and a DC motor. To magnetize the bed, the linear mechanism carries the bed into the magnet pair at a certain frequency.



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

Fig.2 Experimental magnetic cooling system

In the setup, all required energy is supplied by photovoltaic (PV) panels. Daily energy consumption is seen in Table 1. PV panels are installed on the roof of a building at Ege University Solar Energy Institute, located on the coordinates, 38°27'48.1"N, 27°14'19.6"E.

Table 1 Maximum energy consumption of the system components for selecting PV panel numbers

Component	Power (W)	Voltage (V)	Current (A)	Daily current (A.h/day)	Daily energy consumption (kWh/day)
DC motor	133	24	5.54	55.42	1.33
Pumps	10x2	24	0.84	8.34	0.20
Tracker motors	60	24	2.50	25.00	0.60
Control system	10	24	0.42	4.17	0.10
Total					2.23

Installed power of the PV panels is calculated as 1 kWp to meet the total daily energy consumption, 2.23 kWh. Poly crystalline silicon (c-Si) PV panels with the capacity of 250 Wp each are selected in the current system. , A two-axis solar tracker is also used for maximum energy production from the 4 PV panels. Daily average energy production amounts for the months (Ed) and total monthly energy production amounts (Em) are presented in Table 2. As an off-grid application, batteries are used in the PV system. The batteries are selected as 4 pieces for energy needs of 3 days. Each battery has an energy storage capacity of 12V, 150 Ah (total 7.2 kWh).

Table 2 Daily average and monthly total energy production amounts

Month	Ed (kWh/day)	Em (kWh/month)
January	3.64	113.00
February	4.08	114.00
March	5.62	174.00
April	6.06	182.00
May	7.08	220.00
June	7.86	236.00
July	7.39	229.00
August	7.03	218.00
September	6.49	195.00
October	5.60	174.00
November	4.36	131.00
December	3.31	103.00
Yearly average	5.72	174.00
Total		2090

In Figure 3, the Gadolinium bed (or regenerator) is shown. The unit is designed as a parallel flow heat exchanger and 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. At the first tests, there is not any fluid (no flow) inside the bed.

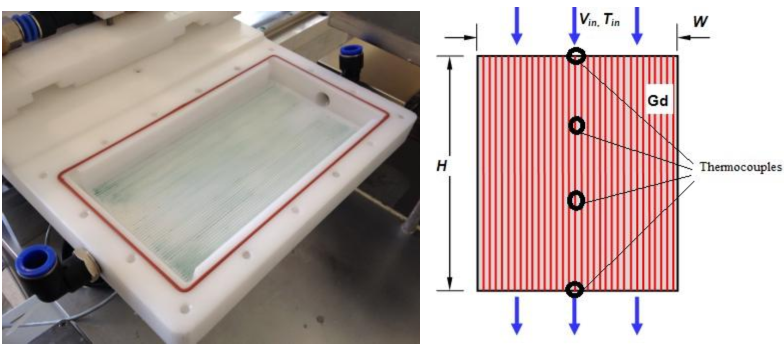


Fig.3 Gadolinium bed.

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. The specifications of measurement equipment are given in the Table 3. In the current study, temperatures are measured inlet and outlet of the Gadolinium bed and also at midpoint inside the bed as seen in Fig. 3.

Table 3 Specifications of measurement equipment

Equipment	Specifications
Flowmeter	Turbine type; Measuring range: 1-30 l/min at-20 and 120 ^{o}C; 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 <0.5^{o}
Thermocouple	T type; Measuring range: -200 and 350^{o}C; 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

4. Results and Discussion

Experimental results are discussed in this section. At the 0.7 T magnetic field and for no fluid flow condition, 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 are the same in these tests. Fig. 4-7 show time-wise variation of the Gadolinium (in the bed) temperature under a magnetic field of 0.7 T and 0 T for various durations of magnetization and demagnetization processes (t_{mag_demag}).

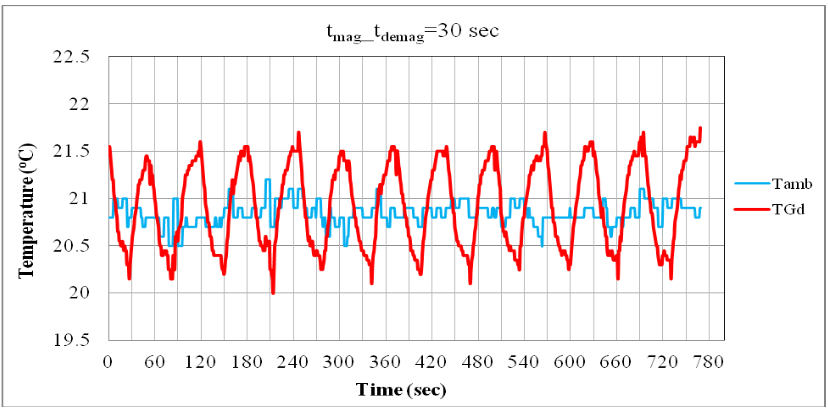


Fig.4 Temperature changes on Gadolinium at t_{mag_demag}= 30 s

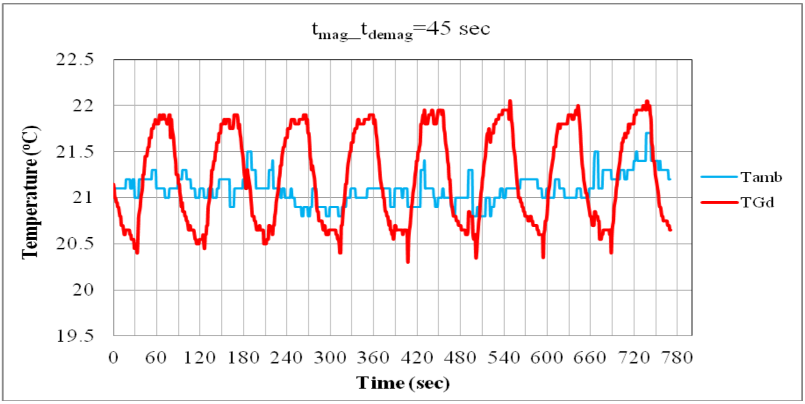


Fig.5 Temperature changes on Gadolinium at t_{mag_demag}= 45 s

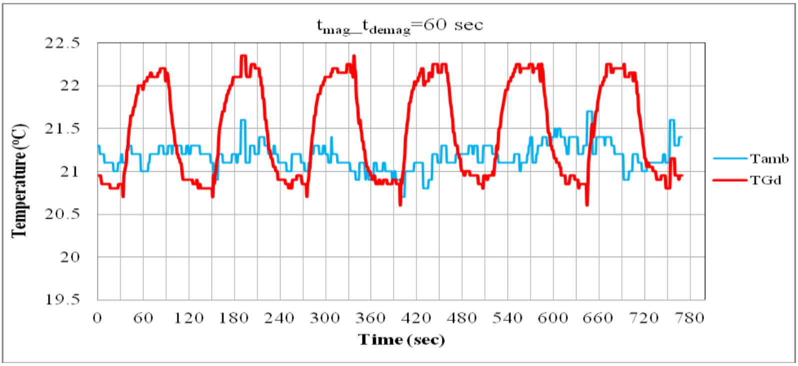


Fig.6 Temperature changes on Gadolinium at t_{mag_demag}= 60 s

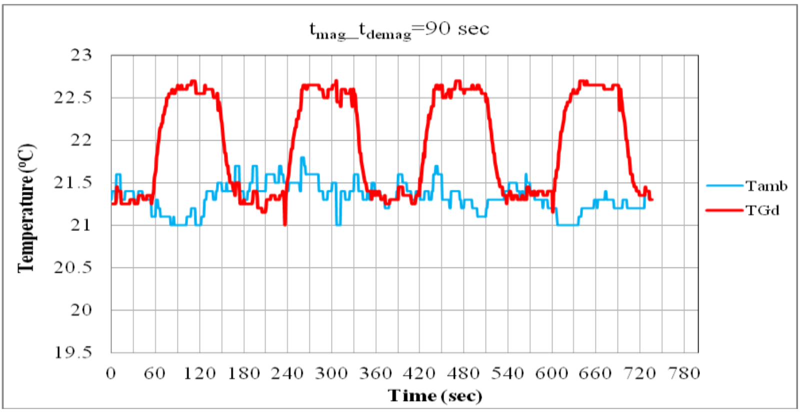


Fig.7 Temperature changes on Gadolinium at t_{mag_demag}= 90 s

As it is seen from the Fig.4-7, temperature change is enhanced at the higher magnetization-demagnetization periods. Lowering the t_{mag_demag} also decrease the heat transfer duration from Gadolinium to the heat transfer fluid (in Fig 4. see t_{mag_demag} =15 s). The tests show that asymmetric magnetization and demagnetization duration, such as t_{mag} =1 s and t_{demag} = 30 s, does not have any positive effect on the Gadolinium temperature change (Fig.8).

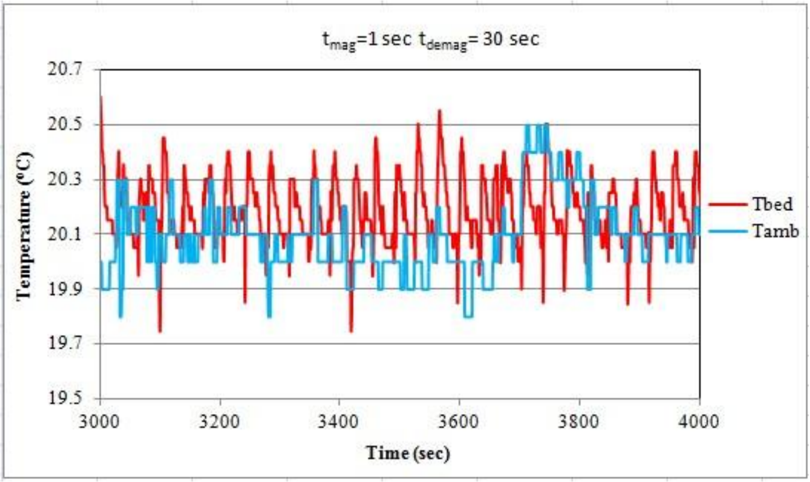


Fig.8 Temperature changes on Gadolinium at different magnetization-demagnetization periods (t_{mag} =1s and t_{demag}= 30 s)

5. Conclusion

In this study, near room temperature magnetic heating-cooling system with a permanent magnet pair (about 0.7 Tesla), and a Gadolinium bed having a linear reciprocating motion provided by a linear DC motor mechanism is investigated. In the magnetic cooling setup, all required energy is supplied by photovoltaic (PV) panels. In the bed, 50 Gadolinium plates which are designed as a parallel flow heat exchanger (regenerator) are used. The thickness of each Gadolinium plate is 1 mm and the length and the width of the unit are L = 200 m and W = 100 mm, respectively. The first tests are realized without heat transfer fluid and at different equal magnetization (t_{mag}) and demagnetization (t_{demag}) duration under 0.7 T. Experimental results show that at higher t_{mag_demag} temperature change and also heat transfer duration from Gadolinium increase, therefore, 30 s and higher t_{mag_demag} values seems to be better for the efficient operation of the current system. Furthermore, unequal (asymmetric) magnetization and demagnetization durations and lower magnetization or demagnetization durations such as t_{mag} =1 and t_{demag} = 30 sec affect temperature change and heat transfer mechanism from Gadolinium negatively. As a future study, water, ethylene glycol and %10 ethanol-water mixture will be used as heat transfer fluids for the cooling performance analysis of the experimental set-up.

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