Active transient cooling by magnetocaloric materials

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A setup for transient cooling using magnetocaloric effect (MCE) was developed. Thermal spikes of a resistor were actively cooled by exploiting the MCE of Gd. Cooling rate was enhanced ~85% for cooling by MCE compared to passive cooling. Our results establish that MCE cooling can efficiently cool thermal spikes.

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**Abstract**
The magnetocaloric effect (MCE) has been intensively studied for novel energy efficient thermal management systems. The present study demonstrates a proof-of-concept magnetic cooling setup for active cooling of the thermal spikes of a heated resistor. Using Gd as the MCE material, the device was capable of actively cooling thermal spikes within one cycle since the dynamics of magnetic phase transition in Gd (a second-order magnetic phase transition material) are favorable to effect a fast MCE response. Enhanced cooling rate of the heated resistor of up to ~85% for active cooling by MCE compared to passive cooling was achieved. The cooling curve of the resistor was found to follow an exponential decrease. Our results show that magnetic cooling systems can be an efficient solution to cool thermal spikes in active transient cooling systems.

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1. Introduction

Thermal management methods are required in an enormous range of applications, e.g., to heat and cool buildings [1–3], for electronic and photonic components [4–8], as well as refrigeration [9,10]. Cooling technologies in buildings account for ~40% of global energy consumption and are of high significance in reducing thermal discomfort in regions with a hot climate and high humidity [2,11–13]. This prompts for urgency to lower energy consumption using novel, energy efficient, active and passive cooling techniques. Since passive cooling involves thermal management of the load without utilization of a power-consuming mechanical apparatus, active cooling is a superior alternative in cooling buildings [2]. This is due to the operational inefficiencies resulted from the diverse energy demands in different climates or geological locations; active thermal management systems, which exploit phase change materials (PCM), display promising solution.

Thermal management techniques have also been proposed to cool electronic devices or mitigate transient local heat spikes resulting from “hot spots” in these devices [4–8]. Unavoidable heat generation, during the normal operation of electronic devices, when in excess can drastically reduce reliability and performance of these devices, as well as lowering the signal to noise ratio. Advances in technology demand improved power performance in electronic systems, consequently increasing with a challenging pace the performance requirements of cooling system needs. Hence, novel cooling systems need to be considered to cool future high power electronic systems [4–8]. Transient local heat spikes resulting from hot spots in these devices are not adequately mitigated by conventional steady state based cooling systems. Transient heat spikes should be thermally managed as and when they occur to allow the temperature to be maintained below a predefined maximum temperature, but this cannot be readily achieved by the usual heat transfer methods such as air fans or continuous liquid flows.
Heat absorption or discharge can be readily attained when a PCM undergoes a phase change [14]. PCM have shown promise for temperature control applications when integrated into thermal management system. However, the low thermal conductivities and losses associated with incongruent melting and solidification during phase transitions of conventional PCM are major limitations [3,14]. A potential solution to these pressing issues is magnetic cooling systems, based on the magnetocaloric effect (MCE) displayed during magnetic and/or structural phase transformations. The recent development of magnetic cooling devices provides a superior alternative to conventional vapor-compression refrigeration technology due to its high energy efficiency has been demonstrated to reach 60% of theoretical limit while only ~45% can be attained in the best vapor-compression refrigerators [15] and suggested it could attain up to 80% of Carnot limit using a single stage refrigerator with a magnetocaloric material (MCM) with negligible hysteresis etc. [17].

Magnetic cooling systems are based on the MCE, an intrinsic thermomagnetic phenomenon which describes a temperature change induced in magnetic materials when they are adiabatically subjected to a varying applied magnetic field (Fig. 1). The entropy of a magnetic material consists of contributions from its lattice as well as from its electronic and magnetic spins. Upon adiabatic application of an external magnetic field \(H\), the magnetic spins align parallel to \(H\), causing the magnetic component of the entropy to decrease. The lattice entropy consequently increases, leading to a temperature rise in the material. This induced heat can be expelled by a heat transfer medium, causing the material to return to the ambient temperature. When the material is adiabatically demagnetized, it cools below ambient temperature due to an increase in disorder of the magnetic spins, which results in lower lattice entropy. MCE based devices can offer improved energy efficiency, low noise, compact configuration \[18\], operational cost savings (it eliminates the compressor which is the most inefficient part of the refrigerator) \[15\] and environmental friendliness, absence of compressor etc. \[17\].

MCE, which is the phenomenon governing magnetic cooling \[19–23\], has been recently proposed to exhibit good potential for use in computer cooling systems \[24,25\]. The transient response of magnetic refrigeration systems has rarely been reported \[26,27\] and active cooling by MCE has not been reported so far. Since MCE exploits the adiabatic temperature change accompanying a magnetic phase transition of a magnetic material to induce temperature change, it can overcome some of the limitations of conventional PCM used in thermal management systems. In this paper, we show that active transient magnetic cooling can be achieved.

To demonstrate active transient cooling of a heated electrical resistor by MCE, a proof-of-concept setup was designed and developed. The setup consists of a resistor (heater), Gd block, thermocouples and polystyrene insulation (Fig. 2). The magnetic field was applied by an electromagnet, providing a maximum magnetic field of 16 kOe. Active cooling of thermal spikes using a benchmark MCE material (Gd) was investigated. To study conduction cooling by MCE, the resistor and Gd block were mounted in direct contact using nonmagnetic thermocouple wires to measure the time dependence of temperatures of the resistor, Gd and their interface. The influence of different heating power inputs of the resistor (1 W–5 W) on the cooling behavior was studied.

In actual systems, the magnetic cooling system will be placed away from the electronic devices and cooled by airflow from the magnetic cooling systems to the device. The device is represented in the setup by the resistor with various power dissipation values.

2. Experimental procedure

A setup for transient magnetocaloric cooling was designed and assembled. A schematic diagram of the device and the magnetocaloric cooled resistor cell is presented in Fig. 2. An electromagnet (EM) was used as the magnetic field source. The magnetic field change was provided by changing the current supplied to the EM with a slew rate limit of 10 A s\(^{-1}\), reaching a maximum field of 16 kOe. The magnetocaloric material (MCM), which is Gd (Alfa Aesar, 99.99%; 11 × 11 × 14 mm; 10.41 g) was placed in contact with the thermocouple (Type T bare wires, model number: TT-T-36; 36 AWG, \(\phi = 0.13\) mm; Neoflon-PFA insulation), denoted as tc1 in Fig. 2, and another thermocouple with the same specs (denoted as tc2) was also placed in contact with a thick-film planar resistor (BPC10–100 J; 10 Ω; standard tolerance; 27.7 × 25.4 × 2.54 mm) and Gd. Another thermocouple (denoted as tc3) was placed in

Fig. 1. Schematic representation of a magnetic cooling cycle (after ref. [28]).
contact only with the resistor. The resistor and tc1 were connected to a temperature controller which was then connected to the EM power supply. To perform data acquisition, a USB-serial-I/O adaptor was used to communicate the commands written in LabView 8.5 to the temperature controller. The software performed conversion from thermocouple voltage to temperature. The other thermocouples, tc2 and tc3, which recorded the temperatures of the resistor and Gd were connected to a temperature logger.

The results of the time dependence of temperature, magnetic field and power dissipation the setup are presented in Fig. 3. The magnetic field (H) was initially increased (Fig. 3a). This increase in H resulted in an increase in temperature (Fig. 3c) recorded by the interface thermocouple (Tinf). H was switched off when Hmax was attained, leading to a decrease in the temperature measured by tc2, Tinf (blue curve in Fig. 3c). Our results demonstrate the feasibility of using MCE in this setup. The resistor was programmed to heat to 1 W for ~10 s upon reaching Hmax causing a temperature spike (see red curves in Fig. 3b and c). Switching off H resulted in reduction of Tinf and the temperature of the resistor.

3. Results and discussion

3.1. Variation in magnetic field ramp rates

The variation of H is an important factor in controlling the temperature change of Gd during magnetization or demagnetization due to MCE. During magnetization, heating can be observed due to the MCE of Gd as well as from heating of the electromagnet (EM) coils. As this initial temperature increase is undesirable, the rate of magnetization was optimized to minimize heating from the EM and MCE. With slow ramp rates, MCE heating can be minimized but at the expense of EM heating. The number of steps to increase H is denoted as N_i, with each step having duration of 0.5 s. N_i was varied from 200 to 3000. The difference between initial starting temperature (Tstart) and that of the N_i step (T(N_i)) was determined (ΔT(N_i)). The ramp rate for decreasing H (demagnetization rate) was

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**Fig. 2.** Schematic representation of transient cooling setup. The cross-section of the magnetocaloric cooled resistor cell is also schematically highlighted in the yellow region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

**Fig. 3.** Time dependence of the programmed experimental run for MCE cooling demonstration: (a) magnetic field profile, (b) heating profile of the resistor and (c) interfacial temperature measured. Two experiments are shown: without (blue curves) and with (red curves) power dissipated at the resistor. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).
also optimized by varying the number of steps while decreasing the magnetic field \((N_f)\). \(N_f\) was varied from 14 to 100 steps. The experimental data for different magnetization and demagnetization rates are shown in Fig. 4a and b, respectively. For simplicity, the plots of number of steps to ramp \(H\) versus \(\Delta T(N_f)\) and the temperature measured are presented in Fig. 4c and d respectively. The lowest \(\Delta T(N_f)\) was observed for \(N_f = 1000\), which indicates a compromise between the two contributions to heating. To optimize magnetization rates, this value of \(N_f\) was used in subsequent experiments. Demagnetization rates were also optimized: the decrease in \(T_{\text{inf}}\) due to MCE for \(N_f \geq 50\) was less abrupt than for \(N_f \leq 20\) (Fig. 4b) and the lowest \(T_{\text{inf}}\) was attained with the fastest demagnetization rate (Fig. 4d). This is the lowest limit of \(N_f\) for the setup due to the slew rate limit in the power supply unit of the EM. Hence, \(N_f = 14\) was used as the demagnetization rate.

### 3.2. Active cooling

The behavior for different configurations was investigated for the following conditions (Fig. 5):
- Heating and passive cooling of only the resistor
- Temperature change of Gd block due to the MCE
- Temperature change of Gd block in contact with the resistor during cooling due to the MCE
- Heating and passive cooling of resistor in contact with Gd block (no MCE)
- Heating and MCE cooling of resistor in contact with Gd block

The cooling profiles \((T_R(t)\text{cooling})\) and temperature behavior of the resistor \((T_R)\) are the main parameters of interest. When 1 W power is supplied to the resistor with only the resistor present in the cell, it is passively cooled to near its starting temperature \((T_{\text{start}})\) within \(\sim 750\) s (Fig. 5a). To determine MCE of Gd, only the Gd block was placed in the cell, the temperature profile \((T_{\text{Gd}})\) is presented in Fig. 5b. The initial increase in \(T_{\text{Gd}}\) was due to the heating of Gd during magnetization. Subsequently when Gd demagnetized upon attaining \(H_{\text{max}}\), an abrupt decrease in \(T_{\text{Gd}}\) was observed. \(T_{\text{Gd}}\) was subsequently observed to return to the starting temperature \((T_{\text{start}})\). The change in temperature \((\Delta T)\) of the Gd block was found to be \(\sim 3.4\) °C and this temperature change was achieved in \(\sim 17\) s.

With the resistor in contact with Gd, the temperatures of both bodies during the MCE experiment are plotted in Fig. 5c. \(T_R\) increased initially due to MCE heating of the Gd block during magnetization. When the Gd block was demagnetized, \(T_R\) decreased to \(\sim T_{\text{start}}\) within \(\sim 82\) s, attaining \(\Delta T_R = \sim 0.88\) °C. With the same configuration of the cell, passive cooling of the heated resistor for 1 W heating (without MCE of Gd) is shown in Fig. 5d. It takes \(\sim 560\) s for the resistor to cool passively to \(\sim T_{\text{start}}\). For active cooling of the heated resistor (1 W heating) by MCE, it took \(\sim 87\) s for the resistor to cool, showing that MCE can actively cool the resistor (Fig. 5e).

#### 3.2.1. Active cooling of resistor

To study active cooling of various power dissipations of the resistor, the difference between \(T_{R_{\text{max}}}\) and \(T_R\), denoted as \(\Delta T_R\), was plotted against time in Fig. 6 for various heating dissipations of the resistor (1–5 W). Active cooling rate of the resistor by MCE (green curves) showed steeper slopes than those of passive cooling (red curves). For 1 W heating of the resistor, the time taken to cool the resistor was reduced \(\sim 85\%\) by MCE active cooling (Fig. 6a). For 3 W heating, it requires \(\sim 45\) s and \(\sim 95\) s to attain \(\Delta T_R = 1.03\) °C for cooling the resistor actively by MCE and passively, respectively (Fig. 6b), a \(\sim 53\%\) faster cooling rate due to MCE cooling. In addition, MCE cooling achieves \(\Delta T_R = 1.42\) °C in \(\sim 95\) s. For 5 W heating, the resistor passively cools by \(\Delta T_R = 3.95\) °C within \(\sim 407\) s (Fig. 6c). A similar magnitude of \(\Delta T_R\) was attained in \(\sim 65\) s for MCE cooling, which was \(\sim 84\%\) faster. Moreover, MCE cooling resulted in a \(\Delta T_R\) equal to 4.25 °C in \(\sim 132\) s.

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**Fig. 4.** Variation of the number of steps for optimization of the setup: during (a) magnetization \((N_f)\); (b) demagnetization \((N_f)\), and their influence on (c) \(\Delta T(N_f)\) and (d) \(T_{\text{start}}\) obtained at \(N_f^p\) step.
3.2.2. Modeling

From the configuration of the setup assembly of the resistor and Gd, assuming that the assembly was well insulated, it can be considered that heat from the resistor is transferred to Gd in one direction (yellow region in Fig. 2). The heat flow from the resistor to Gd can be described by Fourier’s Law:

\[
\frac{dQ}{dt}_{\text{cond}} = -k_T A \frac{dT}{dD}
\]  

where \( k_T \) is the thermal conductivity, \( A \) is surface area, \( d \) is thickness. \( k_T \) was assumed to be the effective thermal conductivity between the resistor, Gd and the thermocouple.

The heat modeled by the resistor and the MCE heating of Gd will change the temperature of Gd and the resistor, this temperature change depends on the specific heat capacity (\( c_p \)) and mass (\( m \)):

\[
dQ = m c_p dT.
\]

Substituting Eqs. (1) and (2):

\[
C_p \frac{dT}{dt} = -k_T A \frac{dT}{dD} = -k_T A \left( T - T_f \right)
\]

\[
\frac{dT}{dt} = -k_T \frac{A}{R_p} dT = -k_T \frac{A}{R_p} dt
\]

\[
T(t) - T_f = \left( T_{R(\text{max})} - T_f \right) e^{-k_T t} = \left( T_{R(\text{max})} - T_f \right) e^{-k_T L}.
\]

Eq. (3) shows that \( T_k \) should decrease exponentially to a final temperature \( T_f \) which is dependent on an experimental constant \( K \). This constant is a combination of materials properties (thermal conductivity, \( c_p \) and geometry) and the thermal properties of the resistor and Gd.

The experimental \( T_k(t) \) data for the cooling profile of the resistor for different power dissipation is shown in Fig. 7. The profile of the passively cooled resistor with heat pulse of 1 W...
(Fig. 7a) could be matched with Eq. (3) for $K = 0.0027 \, \text{s} / \text{C} \cdot \text{A}$.

Similar exponential fits to Eq. (3) are observed for active cooling profiles of heated resistor by MCE in Fig. 5b–d. Similar values of $K$ were determined for different power inputs (1, 3 and 5 W in Fig. 5b, c and d respectively), showing the validity of the above model. For the passively cooled resistor, $K$ was smaller than that of the MCE-cooled resistor. This is in agreement with the previously observed steeper slopes in the $\Delta T(t)$ plots for active cooling. The faster cooling rate of the resistor due to active cooling by MCE demonstrates the capability of MCE for active cooling applications.

The examples of applications in microelectronics for the power loads used in the experimental setup are light emitting devices (LED), Zener diodes, audio amplifiers, and high-brightness diode-laser devices used in communications, industry and medicine. In addition, according to the Eq. (1), heat transfer is directly correlated to the cross-sectional area while it is inversely proportional to the thickness of the material. Hence, it is evident that more Gd material is necessary for larger heat loads. To maintain good heat transfer, only the cross-sectional area of the Gd refrigerant material should be increased. An estimation of the scaling up of the system for higher heat loads is shown in Table 1.

### 4. Conclusions

A proof-of-concept setup demonstrating transient cooling by exploiting the magnetocaloric effect of Gd was designed and developed. Active cooling of thermal spikes of a resistor within one cycle using Gd as the magnetocaloric material was demonstrated.

- ~85% faster cooling rate of the thermal spike of a resistor was achieved by active cooling by MCE compared to passive cooling for 1 W power heating. For power dissipation values of 3 W, the resistor was actively cooled ~53% faster, while a cooling rate of ~84% faster was attained for power dissipation of 5 W.
- The rate constant for passive cooling was found to be smaller than that for active cooling, in agreement with theory.
- Our results show that MCE cooling can be an efficient solution to cool thermal spikes.

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