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Hybrid Thermomagnetic Oscillator for Cooling and Direct Waste Heat Conversion to Electricity

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Abstract

Waste heat is an unavoidable and undesirable product of a huge number of industrially important processes. Cooling of such a heat load is of high interest. We developed a novel hybrid thermomagnetic oscillator (TMO) for cooling of the heat load as well as electricity harvesting. A bulk alloy, with a composition of $(\text{MnNiSi})_{0.7}(\text{Fe}_2\text{Ge})_{0.3}$ and Curie temperature of 144°C , was used as the thermomagnetic material. Heat load cooling by mechanical oscillation between the load and the sink by up to 70°C was achieved. Voltage of up to 10 V/cycle and a current of 15 mA was generated by the mechanical oscillation of this alloy and a coupled permanent magnet through solenoid type Cu coils. This energy was stored in a capacitor and used to light up a LED. The thermomagnetic material transferred heat from the heat load to the heat sink. A moving mesh based numerical model was developed to determine the role of various parameters on the performance. Our simulations are in good agreement with our experimental findings. Superior device performance can be achieved by higher magnetic field strength, sample mass, thermal conductivity of the sample, and optimum device height.

Keywords: thermomagnetic oscillator, energy harvesting, energy storage, thermomagnetic cooling, waste heat recovery

1. INTRODUCTION

Thermal energy is the most ubiquitous form of energy since other forms of energy, e.g., electrical, magnetic, mechanical, metabolic, etc. eventually degrade to thermal energy. The amount of energy consumption, especially electrical energy consumption has been rising dramatically, to 2.1×10^4 TWh in 2016[1]. The heat “wasted” from electricity use occurs in a wide range of energy applications. For example, computers with i7 processors and data centers dissipate 140 W and 400 MW energy, respectively as waste heat[2].

Between 20 to 50% of industrial energy consumption is discharged as waste heat [3]. For most automobiles, 55-80% energy is dissipated as waste heat[4]. Hence, there is high interest in waste heat harvesting electricity from waste heat [5]. Recent applications include electricity harvesting from human body heat [6] [7], heat from electronic devices [8] and solar energy [9] [10]. Recovery and conversion of waste heat to electricity[11] has been performed by piezoelectric [12, 13], pyroelectric [14-16], thermoelectric [4, 17-19], triboelectric [20, 21], thermoacoustic [22], and hybrid devices [23-27].

The thermomagnetic effect is the temperature-dependent change in the magnetic response of magnetic materials. This effect offers a method to harvest waste heat. Tesla [28, 29], Edison [30], and others [23, 24, 31-38] developed prototypes to convert waste heat to mechanical or electrical energy using this effect. The

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Seebeck effect was also utilized for thermoelectric conversion [39]. However, the practical applications of these devices were limited by the low efficiency of ~5% when the hot end temperature is below 200°C. Brown[40] reported a magnetic Stirling cycle utilizing the thermomagnetic effect for heat transfer from the hot end to the cold reservoir.

This thermomagnetic effect offers an attractive approach to harvest electricity from waste heat. Hence, we developed a thermomagnetic oscillator (TMO, **Fig. 1**) to convert waste heat to electricity while simultaneously accomplishing cooling of the heat load.

The single thermomagnetic oscillator (STMO) device (**Fig. 1**) utilizes a thermomagnetic alloy (TMA) cylinder which oscillates between a heat load (HL) and a heat sink (HS) due to the thermomagnetic effect. (a) Initially, the temperature of the TMA is below the Curie temperature (T_C), the TMA rises towards the heat load due to the attraction of the TMA by the permanent magnet (PM1) placed above the HL. The rapid movement of the TMA through the coil generates electricity. (b) When the TMA reaches the HL, heat is transferred from the HL to the TMA, resulting in cooling of the HL. The temperature of the TMA rises until it reaches T_C . (c) The TMA becomes paramagnetic at T_C and falls, due to gravity, towards the heat sink. (d) The TMA transfers heat to the heat sink and cools down below T_C . When it is sufficiently cool, the magnetic force between the TMA and the PM1 is sufficiently large to lift the TMA, repeating the cycle. These oscillations result in electricity generation and cooling of the heat load.

Fig. 1: Single thermomagnetic oscillator (STMO) converts waste heat into electricity by the mechanical motion of thermomagnetic alloy (TMA). (a) The TMA rises towards the heat load (HL) when it is in the ferromagnetic state. (b) The stationary TMA cools the HL, consequently it is heated to TC. (c) The TMA falls when its temperature is above T_C , in the paramagnetic state. (d) The stationary TMA at the heat sink (HS) transfers heat to the HS and cools. TC is the Curie temperature of the TMA.

For a thermomagnetic oscillator (TMO), a change in the magnetization of the material with temperature is an essential requirement [41]. Magnetocaloric materials exhibit the desired temperature dependence of magnetization, hence are suitable as the working material of a TMO, such a material will be referred to as a thermomagnetic alloy (TMA). For a TMA exhibiting a second-order magnetic phase transition, the maximum rate of change of magnetization occurs near T_C . The transformation from the ferromagnetic state to the paramagnetic state results in large reduction in the attractive force of the TMA towards the permanent magnet. In a TMA exhibiting a first order phase transition (Table 1), there can be coupling between the magnetic transition and a structural transition, giving rise to a giant magnetocaloric effect at a transition temperature (T_t). To increase oscillation frequency, a steep magnetic phase transition over a small temperature range is preferred. High hysteresis in the magnetocaloric transition results in lower

oscillation rate [42], hence a material exhibiting a phase transition with low hysteresis may be preferable to increase the rate of energy harvesting [41, 42].

A higher value of entropy change as a result of the transition will favour greater cooling of the heat load. The magnetic entropy change (ΔS_M) is generally higher for first-order TMA [43] compared to benchmark materials, such as gadolinium [44]. In TMA exhibiting a second order phase transition, there is only a magnetic transition at the T_C , typically exhibiting small ΔS_M . On the other hand, first order TMA can exhibit higher efficiency in terms of power output and lower switching time between magnetic states compared to second order TMA [42] because of the steep variation of magnetization over a narrow temperature range.

Hence, we selected a thermomagnetic alloy with high ΔS_M for the oscillator (**Fig. 1**). Specifically, a $(\text{MnNiSi})_{0.7}(\text{Fe}_2\text{Ge})_{0.3}$ alloy having a high ΔS_M of $53 \text{ J kg}^{-1} \text{ K}^{-1}$ (for $\Delta H = 5 \text{ T}$) [45] was selected. The T_C of $(\text{MnNiSi})_{1-x}(\text{Fe}_2\text{Ge})_x$ alloys can be tuned over a wide range of temperature by changing the value of x , providing flexibility in selection of the service temperatures of the thermomagnetic oscillator. The magnetization versus temperature plot for $(\text{MnNiSi})_{0.7}(\text{Fe}_2\text{Ge})_{0.3}$ (**Fig. 2**) reveals a transition temperature of 144°C during heating (T_{CH}) and 129°C during cooling (T_{CC}).

Fig. 2: M vs T plot measured at 0.1 T magnetic field for $(\text{MnNiSi})_{0.7}(\text{Fe}_2\text{Ge})_{0.3}$ showing the transition temperature during heating (T_{CH}) and cooling (T_{CC}).

Electricity harvesting can be accomplished by either active or passive thermomagnetic actuation (**Table 2**). In passive systems, the magnetic material moves between the hot and cold reservoirs due to the thermomagnetic effect.

Table 1: First order thermomagnetic materials for various applications compared to the present work ($\mathcal{E}$). Notation: Not described (ND), thermomagnetic generator (TMG), alloys containing toxic elements are in bold. $\Delta S_{\max}$ ($\text{Jkg}^{-1}\text{K}^{-1}$) is the maximum entropy change during the magnetic transition at a field change (ΔH) of 0.3 T calculated using power law of the field [46]

Ref	Thermomagnetic Material			System Parameters			T _i variation (K)	
	Components	$\Delta S_{\max}$ ($\text{Jkg}^{-1}\text{K}^{-1}$)	ΔH (T)	Applications	Size (mm^3)	Operating Temp.(K)	From	To
$\mathcal{E}$	$(\text{MnNiSi})_{1-x}(\text{Fe}_2\text{Ge})_x$	2.58	0.3	TMO	5090	298 to 453	200	480
[47]	(Mn, Fe)₂(P, As)	3.45	0.3	Static TMG	255	290 to 306	200	350
[48]	$\text{Ni}_{45}\text{Co}_5\text{Mn}_{40}\text{Sn}_{10}$	0.38	0.3	TMG	4	298 to 375	ND	ND
[49]	$\text{Ni}_{45}\text{Co}_5\text{Mn}_{40}\text{Sn}_{10}$	0.38	0.3	Cooling	4	>408	ND	ND
[50]	$\text{Ni}_{45}\text{Co}_5\text{Mn}_{40}\text{Sn}_{10}$	0.38	0.3	TMG	ND	288 to 306	ND	ND
[38]	$\text{Ni}_{50.4}\text{Co}_{3.7}\text{Mn}_{32.8}\text{In}_{13.1}$	ND	ND	TMG	0.075	295 to 433	390	390

Table 2: Devices utilizing the thermomagnetic effect to convert waste heat to electricity. Notation: Power density (P_d), heat load temperature (T_{HL}), heat sink temperature (T_{HS}), electromagnetic induction (EMI), piezoelectric (PE), not described (ND).

First Author		Device					Current (mA)	Voltage (V)	Limitations
	design	actuation	size(mm^3)	Material	$T_{\text{HL}}(\text{K})$	$T_{\text{HS}}(\text{K})$			
Present Work	EMI	Passive	5090	$(\text{MnNiSi})_{0.7}(\text{Fe}_2\text{Ge})_{0.3}$	453	298	15	10	--
Chen [31]	PE	Passive	63	Gd	300	280	4.7×10^{-6}	0.037	Low voltage output, rare earth metal
Chen [32]	PE	Passive	35	Gd	308	279	ND	0.0304	Low voltage output, rare earth metal
Chun [24]	4×PE cantilever	Passive	32	Gd	343	263	0.013	17	Small scale device, rare earth metal
Song [23]	PE cantilever	Passive	19	$\text{La}_{0.85}\text{Sr}_{0.15}\text{MnO}_3 + (\text{Ni}_{0.6}\text{Cu}_{0.2}\text{Zn}_{0.2})\text{Fe}_2\text{O}_4$	353	273	4.1×10^{-3}	2	Complex material, rare earth metal
Chung [51]	PE	Passive	7	Gd	300	275	ND	0.0166	Low voltage output, rare earth metal
Ujihara [34]	PE+spring	Passive	4.57	Gd + Au coating	323	273	ND	ND	Small scale, rare earth metal
Guelzig [35]	EMI+cantilever	Passive	0.02	Ni-Mn-Ga	433	295	0.18	ND	Small scale device
Guelzig [38]	EMI+cantilever	Passive	7.5×10^{-3}	$\text{Ni}_{50.4}\text{Co}_{3.7}\text{Mn}_{32.8}\text{In}_{13.1}$	433	295	0.01	0.001	Low voltage output, small

									scale device
Post [50]	PE+spring	Passive	ND	Ni ₄₅ Co ₅ Mn ₄₀ Sn ₁₀	443	393	ND	ND	PE required
Elliot [52]	EMI	Active	5000	Gd	300	277	ND	ND	Rare earth metal & external pumps
Srivastava [48]	EMI	Active	3300	Ni ₄₅ Co ₅ Mn ₄₀ Sn ₁₀	375	298	ND	0.0006	Low voltage output
Solomon [33]	EMI	Active	ND	Gd	310	280	ND	ND	Rare earth metal & external pumps

Chen et al.[31] and Chung et al.[51] utilized Gd as a working material in the room temperature range to produce voltage output in the range of 16 to 30 mV using a piezoelectric (PE) material based device for energy conversion. To obtain higher voltage output, Song et al.[23] and Chun et al.[24] used a PE cantilever connected to the oscillating material.

Ujihara et al.[34] in their passive system used a thermomagnetic material connected to a piezoelectric spring to convert mechanical motion to electrical energy. Ni-based alloys were used as the working material by Gueltig et al.[38] and Post et al.[50] to develop a small-scale device, which used a cantilever connected to the oscillating material for power generation. However, piezoelectric (PZ) materials are brittle, require contacts, and exhibit limited amplitude of thermomagnetic oscillations [53]. PZ devices generate electric current in the range of nA to μ A per cycle [38], resulting in low power output and limiting energy storage [54].

In an active system, a permanent magnet is cycled between the hot and the cold reservoirs by an external force. Elliot et al.[52] and Solomon et al.[33, 55] demonstrated an active system using Gd as the working material, additional pumps were used to circulate the fluids between the hot and cold reservoirs. A Ni-based alloy was used by Srivastava et al.[48] in an active system to obtain an output voltage of 6 mV per cycle. Active systems can have their own limitations e.g., use of an external pump to regulate the flow of hot and cold fluids on the working material, this pump requires input power. These studies do not specify how the energy is stored or utilized for practical purposes.

Active actuation generally shows higher efficiency in terms of thermal-to-mechanical energy conversion compared to passive actuation. However, due to the use of input external energy in active actuation, net energy generation is low. Hence, passive devices are preferred, such devices can work tirelessly without external energy input due to thermomagnetic effects.

Thus, various devices have been developed to convert waste heat to electricity. However, most of these devices are limited by low current (nA to μ A per cycle), small device size and short service life. Hence, we developed a hybrid device (**Fig. 3**) utilizing passive magnetic actuation which can efficiently convert waste heat to electricity while simultaneously cooling a heat load. The system operates on the principle of the thermomagnetic cycle. The system performance was investigated experimentally, analytically, and by numerical simulations. The numerical model was utilized to determine the role of sample mass, device height, thermal conductivity, and heat load temperature on the voltage generated.

2. EXPERIMENTAL SETUP

A thermomagnetic alloy (TMA) exhibiting a first order transition (**Table 1**) was utilized in our thermomagnetic oscillator, which we developed in two configurations: (i) single thermomagnetic oscillator (STMO) (**Fig. 1**) and (ii) hybrid thermomagnetic oscillator (HTMO) (**Fig. 3**).

The HTMO was constructed by connecting an NdFeB magnet PM2 (type: N52, diameter: 1.3 cm and height: 2 cm) to the TMA by a spacer. The spacer length was adjusted to position the magnet PM2 below coil 2. In the STMO configuration, the output voltage obtained from coil 1 was generated only by the TMA, whereas in the HTMO configuration, coils 1 and 2 were placed in series for the HTMO configuration to obtain the sum of the voltages from the TMA and PM2. **Table A.1** (in supporting information) summarizes the range of parameters utilized for the two configurations.

Fig. 3: (a) Schematic of the hybrid thermomagnetic oscillator (HTMO). A spacer and a permanent magnet (PM2) are added to the STMO to construct the HTMO. (b) Experimental device and schematic of (c) up and (d) down position of the TMA. Both the STMO and the HTMO consist of four regions, viz., **region 1**: Three permanent magnets (PM1) (type: N52, dimensions: 10cm×5cm×2.5cm), **region 2**: heat load (HL), **region 3**: coils for electromagnetic induction (EMI), and **region 4**: heat sink (HS). The TMA oscillates due to the thermomagnetic effect. In the HTMO device, both a TMA and a NdFeB magnet PM2 (type: N52, 2 cm diameter×1.3cm height) are connected to the TMA by a spacer generate voltage. Two copper coils, coil 1 (1000 turns) and coil 2 (6000 turns) were used for voltage generation by electromagnetic induction. The generated emf was stored in a storage circuit and could be used to light a LED by turning on a switch.

The STMO device was investigated for 15 g and 20 g TMA. The mass of the TMA was selected as 20 g for the HTMO based on the STMO results, this mass facilitates lifting of the coupled permanent magnet along with the TMA. Experimental investigations were performed by analyzing time-dependent voltage profiles and the TMA velocity. Numerical investigations were performed for voltage and velocity profile.

2.1. Operating Principle: Thermomagnetic Cycle

The STMO and HTMO utilize the thermomagnetic cycle to induce mechanical oscillation of the TMA and the PM2 (**Fig. 1** and **Fig. 3**). The thermomagnetic cycle is elaborated below.

The thermomagnetic cycle starts when the TMA is at the heat sink (HS). The HS and TMA are at room temperature. The TMA temperature is below its T_{CH} and the TMA exhibits ferromagnetic response and rises due to the effect of the magnetic field of PM1 on the TMA. The TMA reaches the heat load (HL) and heat is transferred from the HL to the TMA. This heat transfer results in cooling of the HL.

The TMA heats up resulting in decreasing magnetic attraction. The TMA becomes paramagnetic when the TMA temperature is equal to T_{CH} . This paramagnetic TMA is not attracted by the magnet PM1, resulting in its fall due to gravity. The hot TMA falls in the HS and is submerged in water. Thus, the TMA transfers heat from the HL to the HS. When the temperature of the TMA is sufficiently below T_{CC} , it possesses sufficient ferromagnetic character to be pulled up by the magnet PM1 and the cycle repeats.

During each oscillation of the TMA, it passes through coil 1, generating emf by electromagnetic induction. For the HTMO, during each thermomagnetic cycle, the TMA as well as the attached magnet PM2 oscillate, resulting in emf generation in coil 1 as well as coil 2, respectively. The generated emf charges a capacitor, which stores the resulting energy. Hence, the waste energy of a heat load can be converted into useful electrical energy using these devices.

2.2. Simulation Model

The experimental parameters used as input in the simulations are the temperature dependent susceptibility (χ_T), density (ρ), and mass (m) of the TMA. The number of turns of coil 1 was used to determine voltage. Our numerical model was first compared with experimental results for a given Curie temperature (T_C) of the TMA, heat load temperature and heat sink temperature. The STMO performance was predicted for a range of magnetic fields, sample mass, and device heights. We defined a reference point (0, 0, 0) at the centre of the coil 1. The axis of the coil 1 was defined along the $\pm y$ direction. The permanent magnet PM1 and the heat load are located in the $+y$ region (**Fig. 4a**). The heat sink (located in the negative y region) was assumed to be at room temperature.

The magnetic field distribution was simulated and compared to the experimental results and found to be in good agreement (**Fig. 4b**). The effect of several parameters on the device performance was then studied, as described in the following sections and supporting information.

Fig. 4: Numerical modeling of the single thermomagnetic oscillator (STMO). (a) Up and down position of the TMAC (in black). A reference point $(x, y, z) \equiv (0, 0, 0)$ was defined at the centre of the coil 1 (in cyan). The up position is obtained when the TMA is ferromagnetic (temperatures $< T_c$) under the magnetic force of PM1. The down position is obtained after the fall due to gravity, of the paramagnetic TMAC (temperatures $\geq T_c$). T_c denotes the Curie temperature. (b) Experimental and simulated magnetic field distribution of the magnet PM1.

3. RESULTS

3.1. Single Thermomagnetic Oscillator (STMO)

Fig. 5 shows the voltage output for both the 15 g and the 20 g TMA at a heat load temperature of 180°C. For the 15 g TMA (**Fig. 5 (a-c)**), a maximum voltage of 0.35 V was obtained, for an oscillation time period of ~2 min. The voltage and velocity profile after 124 s were analyzed by experiments and numerical simulations (**Fig. 5b,c**). During the movement of the sample towards the HL, the voltage profile exhibited a peak of 0.1 V for the TMA moving up, into coil 1, followed by a larger peak of -0.3 V due to the TMA moving upwards, out of coil 1. The maximum velocity was 2.6 m/s. The simulation results for voltage and the velocity profiles match closely with the experimental results.

Fig. 5: Performance of the single thermomagnetic oscillator (STMO) device for (a-c) 15 g and (d-f) 20 g thermomagnetic alloy cylinder (TMA) oscillating in coil 1. (a, d) Experimental voltage profiles. Experimental results compared with simulations for (b, e) voltage and (c, f) TMA velocity.

For the 20 g TMA (**Fig. 5 (d-f)**) a maximum voltage of 0.75 V was obtained, with an oscillation time period of ~ 160 s. A single profile after 29 s was analyzed by experiments and simulations (**Fig. 5e,f**). During the rise of the sample towards the HL, the voltage profile exhibited a peak value of 0.38 V due to the TMA moving into coil 1, followed by a larger peak of -0.75 V due to the TMA moving out of the coil 1. A lower velocity of 1.6 m/s was observed for the case of the 20 g TMA compared to the case of the 15 g TMA. The lower velocity is due to the higher mass of the TMA. The simulation results show a good match with the experimental voltage profile. The experimental velocity exhibits a quasi-linear profile compared to the simulated nonlinear profile, hence a slight deviation was observed. The mismatch may also be partly due to the nonlinear response of the TMA at lower magnetic fields, this non-linearity becomes significant at lower magnetic volume force. The higher magnitude of the second peak is due to the higher sample

velocity when it leaves the coil compared to the velocity when it enters into the coil. However, no significant peaks were obtained during the fall of the TMA because of the negligible magnetic flux of the paramagnetic TMA.

3.2. Hybrid Thermomagnetic Oscillator (HTMO)

The HTMO generates voltage due to the TMA as well as due to the magnet PM2 oscillating in coils 1 and 2, respectively. The magnetic flux change due to PM2 is higher compared to the flux change due to the TMA, this significantly enhances total voltage. This subsection describes the performance of the HTMO device (**Fig. 6** and **Fig. 7**).

Fig. 6: Performance of the hybrid thermomagnetic oscillator (HTMO) device, demonstrating electricity harvesting and cooling of the heat load (HL). (a) Voltage profile for a time duration of 50 min. (b) Current profile for a single cycle plotted against time (s).

Fig. 6a shows the voltage profile for a time period of 50 min. The upward motion of the HTMO results in a peak voltage of -10 V. The voltages generated during the downward motion are in the range of 3 V to 5 V. In **Fig. 7a**, the smaller positive peaks (≤ 0.5 V) are due to the TMA moving up through the coil 1 towards the heat load.

Fig. 6b shows the current profile in the HTMO device. The current profile exhibited a 15mA peak current per cycle. This magnitude of the generated current from our energy harvesting device is significant compared to other energy harvesting approaches. Specifically, for piezoelectric devices, though voltages are on the higher side, the current values are in the range of pA to μ A, [38] which are at least 10000 times less than the current generated by our HTMO device.

Fig. 7: The heat load (HL) temperature for (a) first 25 cooling cycles. (b) Transient cooling cycles showing variation in the peak temperatures. (c) The stabilized cooling cycles having constant peak temperatures. (inset) A cooling cycle, showing peaks corresponding to the temperature when the TMA rises to the HL (A), maximum cooling of the HL (B), TMA reaches T_{CH} and falls due to gravity (C), cooling of the HL due to air (D).

The cooling performance of the HTMO device was investigated. The temperature profile of the heat load was collected for 25 oscillations of the TMA (Fig. 7a). Small variations are observed in the peak temperatures of the initial cycles (Fig. 7b) which stabilizes after the 13th cycle. The temperature profile after stabilization of the HL temperature (Fig. 7c) reveals constant peak temperature of the HL during the heating and cooling cycles.

The cooling profiles of the heat load is followed along path AB, this cooling occurs due to absorption of heat by the TMA which rose from the HS to the HL. The temperature of the TMA at point A is T_{CC} . The TMA gets heated (path BC). At point C, the temperature of the TMA reaches T_{CH} and the material becomes paramagnetic losing magnetic attraction to the magnet PM1. The paramagnetic TMA falls towards the HS under the influence of gravity and transfers the heat absorbed from the HL to the HS until the TMA reaches the temperature T_{CC} . A small cooling of HL was observed after the TMA falls towards the HS, this cooling effect is due to air replacing the volume occupied by the TMA at the heat load. The HL is cooled by air during the path CD in Fig. 7c. Subsequently, the temperature of the HL increases to a steady state value. The TMA at HS becomes ferromagnetic due to its cooling at HS and is again lifted to the HL. Path AB (Fig. 7c) exhibited a cooling of 70°C, this cooling is attained when the TMA, initially at room temperature, comes in contact with the heat load (point A) under the action of the magnetic volume force F_m .

3.3. Electricity Storage and dissipation

The HTMO converts the waste heat of a heat load (HL) to electricity. We stored the output voltage in a capacitor via a full wave rectifier (**Fig. A.1** in supporting information). The capacitor stores the energy during each thermomagnetic cycle. The capacitor charges to 2 V after operating the HTMO for 65 min (**Fig. 8a**). The energy stored in the capacitor, calculated from Eq. (13), is shown in **Fig. 8b**.

Fig. 8: (a) Voltage across the capacitor connected to the storage circuit during heating and cooling cycles and (b) energy stored in the capacitor for 65 min. (c) The capacitor voltage discharge across the LED. (inset) LED off and on states.

The stored energy can be used for different applications. As an example, we used the stored energy to light up a LED which is connected to the capacitor by a switch. The stored energy continuously discharges across the LED, lighting it for 90s (**Fig. 8c**). Power density is a parameter for an energy harvesting system. Considering the energy stored in the first storage cycle of the capacitor (0.4 mJ in 180 s), a power density of $0.6 \mu\text{W}/\text{cm}^3$ was obtained. The significance of the present energy-harvesting prototype is the self-actuation system without the need of a fluid pump or piezoelectric materials utilized in previous work (**Table 2**).

4. NOVELTY AND APPLICATION

We have shown for the first time that a system which can be used for simultaneous cooling and energy harvesting by thermomagnetic alloy and a permanent magnet. Electricity generation by electromagnetic induction resulting from the self-oscillations of a thermomagnetic alloy has been performed for the first time. The existing thermomagnetic energy harvesters rely on piezoelectric connectors, triboelectric materials or external pumps (**Table 2**). On the other hand, the hybrid thermomagnetic oscillator produces electricity directly from the mechanical motion of the TMA using electromagnetic induction, thus eliminating the requirement of piezoelectric, triboelectric or external pumps. The electricity storage in the HTMO device is more effective due to higher output current compared to piezoelectric devices [38].

Current applications of thermomagnetic energy harvesters are limited to small scale devices (**Table 2**). Thermomagnetic response in a ferrofluid has been previously used for cooling applications in a self-pumping prototype [56]. On the other hand, the present device has a wide range of practical applications because of its temperature tunability, no mechanical actuation, high current output, and utilization of low-grade waste heat for simultaneous cooling and energy harvesting. Due to the substantially greater device

size, waste heat from larger equipments such as industrial heat outlets, processing equipments etc. can be effectively handled. The temperature of the heat load can be regulated using the cooling cycles of HTMO by restricting the heat load from crossing a critical temperature, simultaneously generating electricity. A schematic of a potential application for HTMO integrated with hot end of the heat exchanger of processing equipment is shown in **Fig. 9**. Further real applications can be explored by integrating the HTMO with piezoelectric, triboelectric and solar cells for hybrid generators [57]. Therefore, the HTMO proves to be a promising device for cooling and energy harvesting.

Fig. 9: Potential application of the HTMO for generation of electricity by an array of oscillators using heat from hot end of the heat exchanger as the heat source.

5. CONCLUSION

Thermomagnetic oscillator device utilizing a thermomagnetic cycle have been developed for the conversion of waste heat to electricity and for cooling of a heat load simultaneously. A novel approach for generation of electricity using electromagnetic induction coupled with oscillation of the thermomagnetic alloy (TMA) was utilized. Single (STMO) and hybrid (HTMO) thermomagnetic oscillators were developed using the oscillation of the TMA between the heat load and the heat sink. The TMA having a highly tunable Curie temperature provides a wide range of operating temperatures for the device. The Curie temperature of the alloy was tuned slightly below the heat load temperature to facilitate the heat

transfer.

The HTMO configuration was achieved by coupling this thermomagnetic alloy with a permanent magnet, resulting in higher voltage output of 10 V per cycle, current of 15 mA and heat load cooling by 70°C. The voltage generated was stored in a capacitor and utilized to light up a LED. Our numerical investigations demonstrated superior device performance at higher magnetic field strength, optimized device height, larger mass of the thermomagnetic alloy, higher thermomagnetic alloy conductivity and lower heat load temperatures. The device can be optimized for various practical applications for cooling and electricity generation.

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Appendix A. Methodology

A.1. Velocity Measurement

High-speed imaging of the TMA oscillations was performed at 720p resolution and frame rate of 240 frames/s. For stable imaging, the camera was mounted by Manfrotto accessories, consisting a tripod (P/N: MT055XPRO3), a universal smartphone clamp (P/N: SKU MCLAMP), and a 3 axis gear head (P/N: 410). To determine TMA velocity, the recorded videos were analyzed in Fiji (ImageJ) software [58].

A.2. Electricity storage circuit

A capacitor-based storage circuit was used for energy harvesting. The circuit consists of a full wave rectifier D1 with 4 Schottky diodes (1N58191A) and a 3.3 mF capacitor (C1) to store energy (**Fig. A.1**). A Tektronix oscilloscope (model: DPO 5054B) recorded the instantaneous signal profiles of the output voltage.

Fig. A.1: Circuit diagram of the rectifier (D1), capacitor C1 (3.3mF) for storage, and a LED. The stored energy from this device was used to light up a LED by means of switch S1.

A.3. Materials

A TMA, exhibiting a steep ferromagnetic to paramagnetic transition at a temperature near the heat load temperature, was used as the working material (**Fig. 2**). The working material chosen was $(\text{MnNiSi})_{1-x}(\text{Fe}_2\text{Ge})_x$, which exhibits a steep magnetic transition within a narrow temperature range. The alloy was synthesized by arc melting of Mn (99.9%; Sigma Aldrich), Fe (99.9%; Alfa Aesar), Ni (99.95%; Alfa Aesar), Si (99.95%; Sigma Aldrich) and Ge (99.999%; Alfa Aesar). The mass of the elements was selected on the basis of the nominal composition.

The magnetostructural transition temperature (T_t) of $(\text{MnNiSi})_{0.7}(\text{Fe}_2\text{Ge})_{0.3}$ alloy was 129°C during cooling cycle and 144°C during heating cycle as shown in **Fig. 2**. The alloy spontaneously cracked into coarse powder during cooling after arc melting, these powders were crushed, using a mortar and pestle, to obtain a fine powder (average size of 0.5 mm). TMA pellets weighing either 15 g (19 mm diameter, 15 mm height) or 20g (19 mm diameter, 20 mm height) were prepared using these fine powders. These TMA pellets were wrapped in an aluminium foil and subsequently in multiple layers of Teflon tape to form a cylinder. The device parameters are mentioned in (**Table A.1**).

Table A.1: Experimental sets performed for the STMO and the HTMO configurations.

Sets	Set 1	Set 2	Set 3
Configuration	STMO	STMO	HTMO
TMA composition		$(\text{MnNiSi})_{0.7}(\text{Fe}_2\text{Ge})_{0.3}$	
Mass (g)	15	20	20
TMA cylinder dimensions diameter $\times$ height (mm $\times$ mm)	18 $\times$ 15	18 $\times$ 20	18 $\times$ 20
Heat load temperature(°C)	180	180	180
Heat sink temperature(°C)	25	25	25

Appendix B. Theoretical and Simulation Modeling

The modeling of the STMO and HTMO are provided below.

B.1. Equation of Motion

During each cycle, the TMA moves upward (positive y-direction) when the magnetic force $\mathbf{F}_m$, is greater than the gravitational force $\mathbf{F}_g$ (negative y-direction). Hence, the equation of motion of the TMA under the influence of the vector forces $\mathbf{F}_m$ and $\mathbf{F}_g$ is given by,

$$m(\partial \mathbf{v} / \partial t) = \mathbf{F}_m - \mathbf{F}_g \quad (1)$$

m is the mass of the TMA. $\mathbf{v}$ is the velocity vector due to the TMA of the net force. The motion

of the TMA and the emf are determined by this competition between $\mathbf{F}_m$ and $\mathbf{F}_g$, as elaborated below.

B.2. Magnetic (F_m) and gravitational (F_g) force

Maxwell's equations for magnetostatics were used to describe the magnetic field,

$$\nabla \cdot \mathbf{B} = 0 \quad (2)$$

$$\mathbf{B} = \mu \mathbf{H} = \mu_0 \mu_r \mathbf{H} = \mu_0 (1 + \chi) \mathbf{H} = \mu_0 (\mathbf{H} + \mathbf{M}) \quad (3)$$

$\mathbf{B}$ and $\mathbf{H}$ are the vectors of induced magnetic flux density and applied magnetic field strength, respectively. The magnetization vector and the magnetic susceptibility of the sample are denoted by $\mathbf{M}$ and χ , respectively. The permeability (μ) and relative permeability (μ_r) are defined by $\mu = \mu_0 \mu_r$ and $\mu_r = (1 + \chi_{ff})$, respectively. μ_0 is the permeability of the free space.

The magnetization of the TMA at large magnetic fields follows a nonlinear behavior, described by the Langevin function $L(\gamma H)$. Hence, the magnetization $\mathbf{M}(H)$ and the magnetic susceptibility χ_H at an applied magnetic field H are defined by [59, 60],

$$\mathbf{M}(H) = M_s L(\gamma H) = M_s \coth(\gamma H - [1/\gamma H]) \quad (4)$$

$$\chi_H = (M_s/H) L(\gamma H) = (M_s/H) \coth(\gamma H - [1/\gamma H]) \quad (5)$$

where $\gamma = (3\chi_0/M_s)$. The initial magnetic susceptibility and saturation magnetization are denoted by χ_0 and M_s , respectively.

The thermomagnetic behavior is determined by the temperature dependent susceptibility (χ_T) of the TMA. The Curie-Weiss relationship between susceptibility χ_T and temperature T is,

$$\chi_T = C/(T - T_C) \quad (6)$$

C and T_C are the Curie constant and Curie temperature, respectively.

The magnetic force $\mathbf{F}_m$ defines the motion of the TMA in the presence of a magnetic field H ^[61-63]. The magnitude of this force is determined by the total volume of the TMA and its magnetization at a specific temperature. The magnetic volume force $\mathbf{F}_m$ acting on the TMA of volume $\mathcal{C}$ and susceptibility χ_H is given by,

$$\mathbf{F}_m = \mathcal{C} \chi_H (\mathbf{B} \cdot \nabla \mathbf{B}) / \mu_0 \quad (7)$$

The gravitational force ($\mathbf{F}_g$) on the TMA acts downward (in the negative y -direction) on the

TMA and is given by,

$$\mathbf{F}_g = -mg \quad (8)$$

where g is the acceleration due to gravity, the negative sign indicating that the gravitational force is acting in the downward direction.

B.3. Thermal Transport equations

The heat equation in terms of temperature T takes the following form,

$$\rho C_p (\partial T / \partial t) + \rho C_p (\mathbf{u} \cdot \nabla T) + \nabla \cdot \mathbf{q} = Q \quad (9)$$

$$\mathbf{q} = -\lambda_{TMA} \nabla T. \quad (10)$$

λ_{TMA} is the thermal conductivity (SI unit: $\text{Wm}^{-1}\text{K}^{-1}$) of the thermomagnetic alloy. ρ and C_p denote the density and the specific heat capacity at constant pressure, respectively. $\mathbf{q}$ and $\mathbf{u}$ denote the heat flux by conduction and the velocity vector, respectively. Q denotes the heating power per unit volume.

B.4. Electromagnetic induction

Emf is generated according to Faraday's law of induction when the TMA and PM2 pass through the coils. This emf is due to the rate of change of the magnetic flux Φ . Hence, for a coil of N turns, the emf is given by,

$$\text{emf} = -N (d\Phi/dt) \quad (11)$$

The magnetic flux Φ for the induced magnetic field $\mathbf{B}$ and area $\mathbf{A}$, is defined by,

$$\Phi = \iint \mathbf{B} \cdot d\mathbf{A} \quad (12)$$

The emf is stored in the capacitor (capacitance C). When the switch of the storage circuit is switched on to light a LED, the energy in the capacitor is discharged across the LED. The stored energy (E) of the capacitor at any instant is given by,

$$E = (1/2) CV^2 \quad (13)$$

B.5. Simulation Model

Multiphysics numerical simulations were performed in COMSOL software using the experimental configuration of the single thermomagnetic oscillator (STMO). Our simulation methodology predicts upward motion and the voltage generated in the STMO. A moving mesh axis symmetric method was selected with AC/DC and heat transfer modules. “No currents method” in AC/DC module was employed to simulate the applied magnetic field H of the permanent magnet PM1. The moving mesh method was applied to the TMA, with the mesh displacement determined by the velocity v . Extra-fine meshing was used for the whole geometry with a minimum element size of $3.5\ \mu\text{m}$.

Appendix C. Parameters Governing Device Performance

The performance of the STMO and the HTMO is determined by the generated voltage and the resulting cooling of the HL. Both the generated voltage and the heat load cooling depend on the thermomagnetic response of the TMA. The role of various parameters on the STMO performance was analytically modeled. Numerical simulations were also performed.

C.1. Analytical Results: Competing Forces

Eq. (1) was used to determine the profile of the magnetic and the gravitational force acting on the TMA during the thermomagnetic cycle (**Fig. C.1**).

Fig. C.1: Analytical investigation of the competing forces acting on the TMA. The TMA rises towards the heat load (HL) when the magnetic force at the heat sink F_{m1} exceeds the gravitational force F_g (at $m1$). The TMA drops to the heat sink (HS) when F_g exceeds the magnetic force at the heat load F_{m2} (at $m2$).

The magnetic force $\mathbf{F}_m$ (in positive y -direction) and the gravitational force $\mathbf{F}_g$ (in negative y -direction)

oppose each other. For the ferromagnetic state of the TMA (below T_c), the force $\mathbf{F}_m$ exceeds force $\mathbf{F}_g$, resulting in upward motion of the TMA. The force $\mathbf{F}_g$ exceeds $\mathbf{F}_m$ when the TMA is paramagnetic (temperature $\geq T_c$), resulting in downward motion of the TMA. A force greater than 196 mN is required for the upward movement of the 20 g TMA towards the heat load (point m1 in **Fig. C.1**). The TMA, initially located at the heat load, falls when $\mathbf{F}_g$ exceeds the $\mathbf{F}_m$ at the HL (point m2).

C.2. Numerical simulations: effect of magnetic field, mass, and height

We employed numerical simulations to investigate STMO behavior (**Fig. C.2**). The simulation model has been described earlier. A reference point $(x, y, z) \equiv (0, 0, 0)$ was defined at the center of the coil. The y-direction indicates the vertical axis of symmetry, +y corresponds to the up direction and the negative y-direction points down.

We first investigated the effect of magnetic field strength of the permanent magnet PM1 on the device performance (**Fig. C.2a**). The magnetic volume force $\mathbf{F}_m$ acting on the TMA is determined by the field strength of PM1. At higher field strength of PM1, the velocity of TMA will be larger. Also, for greater magnetic field strength of PM1, the magnetic flux in the coil is higher because of larger magnetization of the TMA passing through this coil. Hence, oscillations of the TMA for the higher field strength of PM1 will result in greater voltage. A slow increase in voltage was observed for magnetic fields ≤ 0.4 T. For magnetic fields higher than 0.4 T, a sharp increase in generated voltage was observed. At 1.2 T, voltage attains the maximum value of 7 V for the STMO configuration. Hence, voltage increases nonlinearly with increasing magnetic field.

Fig. C.2: STMO device performance showing voltage over a range of (a) magnetic fields, (b) sample mass, and (c) device height. The experimental device dimensions were used for (a, b). The experimental magnetic field of PM1 was used for (b,c). TMA mass of 20 g was used for (a, c).

The effect of TMA mass was studied (**Fig. C.2b**). A large increase in voltage was obtained with increasing mass from 10 g to 250 g. After 150 g, voltage saturates at ~4.5 V.

The effect of device height was investigated (**Fig. C.2b**) for all simulated sets. The device height was changed while keeping the coil at the centre and heat load at the top. We found that an optimized device height of 50 mm is required to generate a maximum voltage of 2.5 V, for a fixed sample mass of 20g and magnetic field strength of 0.4 T. The voltage exhibits a sharp increase until an optimum device height is reached, followed by a slow decrease after this optimum height.

Hence, the generated voltage of the STMO increases significantly with increasing magnetic field, mass and exhibits a sharp increase with increasing device height until an optimum height.

C.3. Numerical simulations: the role of thermal conductivity and temperature

Our simulation model was used to determine the role of factors affecting the heating rate of the TMA. The heating rate ((b) and (d) in **Fig. 7**) determines the oscillation frequency of the TMA. Hence, the time for heating of the TMA has been determined (**Fig. C.3**). We compared our experimental results with the simulation model results (**Fig. C.3a**), Time-dependent simulations were performed, the simulated temperature profile (**Fig. C.3a**) is in good agreement with the experimental profile (**Fig. 7c**). Both the experimental results and the simulation profiles follow a similar temperature profile and similar time constant.

We then used this model to investigate the role of thermal conductivity ratio (λ) of the TMA (**Fig. C.3b**) and the heat load temperature (THL) value (**Fig. C.3c**). The thermal conductivity ratio λ is the ratio $\lambda_{\text{sim}}/\lambda_{\text{exp}}$, where λ_{sim} and λ_{exp} are the simulation and experimental thermal conductivities (in $\text{Wm}^{-1}\text{K}^{-1}$). The experimental thermal conductivity was $\lambda_{\text{exp}} = 20 \text{ Wm}^{-1}\text{K}^{-1}$. **Fig. C.3b** shows the effect of λ on the temperature profiles. Numerical investigations were performed for λ values in the range of 0.5 to 10. We found that, with increasing λ value, the heating rate of the TMA increases, increasing cycle frequency. The rate of TMA heating increases significantly for λ values from 0.5 to 2.5, reducing heating time of the TMA from ~360 s (at $\lambda = 0.5$) to ~60 s (at $\lambda = 2.5$). For $\lambda > 2.5$, the temperature profiles start to saturate. Hence, heating duration decreases with increasing λ .

Fig. C.3: Numerical simulation of the effect of thermal conductivity and heat load (HL) temperature on heating of TMA.

Temperature profiles of the path BC: **(a)** Experimental and simulation **(b)** Effect of thermal conductivity ratio (λ). $\lambda = \lambda_{sim}/\lambda_{exp}$ is the ratio of the simulation (λ_{sim}) and experimental ($\lambda_{exp}=20 \text{ Wm}^{-1}\text{k}^{-1}$) thermal conductivities. λ was varied in the range from 0.5 to 10. **(c)** Effect of HL temperature, in the range from 200°C to 600°C for $\lambda = 1$ (solid lines) and $\lambda = 5$ (dashed lines).

The effect of HL temperature on the temperature profiles, for λ values of 1 and 5 is depicted in **Fig. C.3c**. The HL temperature was varied in the range from 200°C to 600°C. **Fig. C.3c** shows decreasing initial slopes with increasing HL temperatures, indicating reduction in heating rate of the TMA, for λ values of 1 and 2. The decrease is more significant at $\lambda=1$ compared to $\lambda=5$. At 200°C, saturation is reached in ~ 15 s for both λ values, whereas at 300°C it is reached at 30 s for $\lambda=5$ and at 120 s for $\lambda=1$. For an increase in HL temperature from 300°C to 600°C, heating time of the TMA increases from ~ 120 s to ~ 240 s for a λ value of 1. The duration of heating of the TMA increases with increasing HL temperatures, especially at $\lambda=1$.

Hence, superior performance of the STMO can be obtained at higher magnetic field strength, larger TMA mass, optimized device height, higher thermal conductivity of the thermomagnetic alloy, and lower heat load temperatures.