NEAR ROOM-TEMPERATURE THERMOMAGNETIC ENERGY HARVESTING

J. H. Belo[1], J. S. Amaral[2] and J. O. Ventura[1] – DOI: https://doi.org/10.1051/epn/2023302

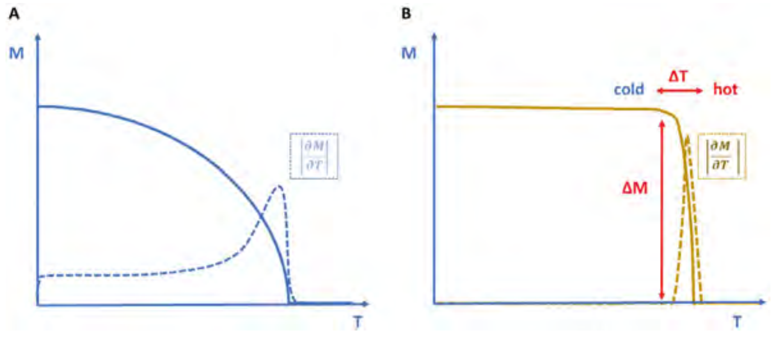
[1] IFIMUP, Departamento de Física e Astronomia da Faculdade de Ciências da Universidade do PortoRua do Campo Alegre, 687, 4169-007 Porto, Portugal

[2] University of Aveiro, Department of Physics and CICECO – Aveiro Institute of Materials

The rise of global energy demand and the effects of climate change make efficient energy generation one of the main global challenges. Thermomagnetic energy harvesting is a process that allows the genaration of electrical power in the presence of small temperature gradients near room temperature. Ongoing advances rely on improving materials and devices, in hopes of reaching widespread use of this technology, hence reducing our carbon footprint. In this work, the main concepts behind thermomagnetic energy harvesting will be described, focusing on ongoing challenges and recent reports of new approaches and device designs for this promising technology.

While crucial to the progress we have accomplished as a species, the continuous rise in global energy demand has also resulted in one of the largest threats ever faced by mankind: climate change and global warning. Although world nations have pleaded to reduce greenhouse gas emissions and limit global warming to 2 °C in the Paris Agreement of 2015, the climate actions implemented so far are still insufficient for compliance with this target. Furthermore, even if such a goal is achieved, it will not prevent a surge in heat waves, droughts or extreme weather. Therefore, new technologies able to generate electrical energy in a green and sustainable manner are needed for humanity to reach a carbon-neutral world. The conversion of thermal energy, the energy into which all others eventually transform, to useful electrical power can help counterbalance the increasing energy demand. In fact, a large portion of the produced energy is converted to thermal energy just below 120 °C [1], which is then mostly discarded as wasted heat. The most common technology able to harvest such low-grade thermal energy employs thermoelectrics, based on the Seebeck effect, which suffers from low efficiency (below 5%), limiting their widespread applicability. In contrast, the use of thermomagnetic materials, and their associated thermomagnetic effect, is a viable and promising alternative to thermoelectrics.

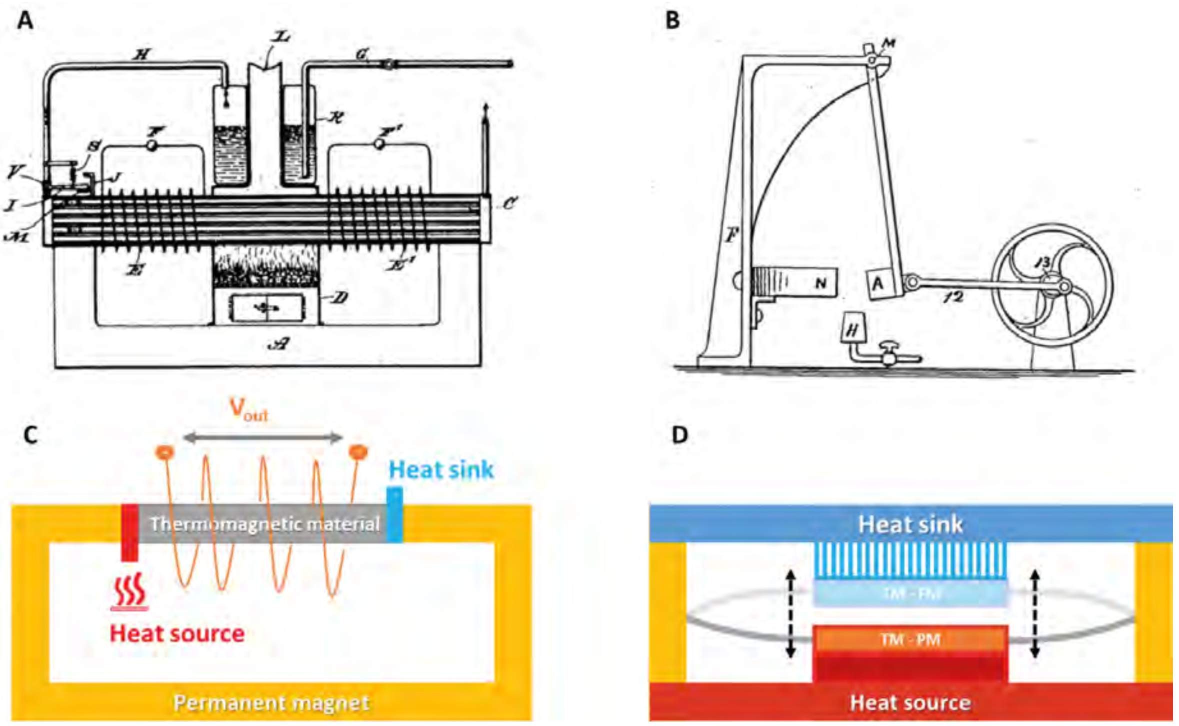
▼ **FIG. 1:** Dependence of magnetization, M, (solid) and of magnetization temperature derivative, |dM/dT|, (dashed lines) on temperature for (A) a second-order phase transition ferromagnet and (B) a first-order phase transition ferromagnet, showing operating temperature range and correspondent magnetization change from a cold or hot thermal contact.



The thermomagnetic effect

A magnetic material that at a certain temperature (T) shows spontaneous magnetization (M), such as a ferromagnet or ferrimagnet, can undergo, when surpassing a critical temperature (T_C), a transition to a magnetically disordered state with no spontaneous magnetization (paramagnetic state). This transition, depending on its nature, can be broad or sharp, either of second- or first-order, as schematically shown in Figure 1.

This thermomagnetic effect can be employed for energy conversion and harvesting in two distinct ways. In so-called active devices, there is a direct energy conversion in which the variation of the magnetization with temperature, and therefore of the associated magnetic flux, induces a voltage in a coil according to Faraday's law. These devices then rely on cyclic temperature variations and complex pump and valve systems. On the other hand, in passive thermomagnetic devices, the magnetization change is transduced into an intermediate mechanical motion (either linear or rotary) that can then



▲FIG. 2: 19th century thermomagnetic device designs of Nikola Tesla: (A) Electrical generator based on the magnetic flux change of a ferromagnet in alternating contact with cold and hot sources, with surrounding pick-up coils [3] and (B) thermomagnetic engine, where the circular movement of a piston is produced from the cyclic magnetization/demagnetization of a thermomagnetic material subjected to a magnetic field and to a heat source [4]. Diagrams of a (C) active thermomagnetic device, or thermomagnetic generator, in which electrical energy is generated directly from the magnetization variation and (D) passive thermomagnetic device, or thermomagnetic motor, in which thermal energy is converted into a linear or rotary mechanical motion.

be converted into electrical energy using an appropriate mechanism (such as electromagnetic induction, the piezoelectric or triboelectric effects [2]). Devices based on these effects are not new; Nikola Tesla patented designs for thermo-magnetic generators and motors in 1889 and 1890, as shown in Figure 2.

Optimized Thermomagnetic Materials

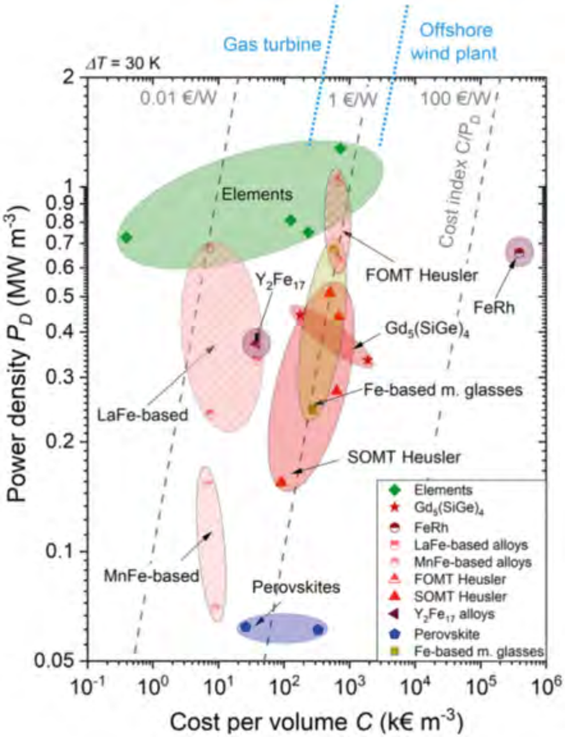
The performance of a thermomagnetic device is directly linked to the magnetic and thermal properties of the active (thermomagnetic) material. As the thermomagnetic effect is stronger for larger dM/dT values, then first-order phase transition ferromagnets with tuned T_C values, such as $Gd_5(Si,Ge)_4$, $La(Fe,Si)_{13}$, Mn-Fe-P-Si and Heusler alloys have greater potential to lead to better performance devices, when compared to the use of second-order phase transition ferromagnets, such as Gd and other elemental alloys, as shown in Figure 3.

Besides the all-important matter of cost, other material properties such as specific heat and thermal conductivity must be considered in device design. These play a crucial role on heat exchange kinetics, with impact on device working frequency, and, consequently, energy generation. Also, despite their larger dM/dT, first-order phase transition materials typically exhibit magnetic and thermal irreversibility (hysteresis) which lead to losses that can be detrimental to the final device efficiency. The chemical and structural stability of these materials can also be a concern for device longevity.

Devices

State-of-the-art thermomagnetic devices are being developed using both passive and active concepts and second- and first-order phase transition thermomagnetic materials. In Figure 4, some selected devices are shown. At the industrial scale, a thermomagnetic generator operating 24/7 using low temperature waste heat from a biomass power plant has been reported [6], reaching a 1 kW maximum mechanical power output (Figure 4A). At the tabletop scale, a room temperature thermomagnetic regenerator is shown in Figure 4B where performance was enhanced by exploring multiple magnetic circuit topologies. This device presents several permanent magnet (PM) placements, La-Fe-Co-Si thermomagnetic materials and pickup coils, and has shown an electrical output power of 1.24 mW [7]. At the millimeter scale, Figure 4C shows a thermomagnetic generator designed and built based on a ferromagnetic Ni-Mn-Ga Heusler alloy film mounted on a flexible cantilever, also holding a pickup coil [8]. The assembly is placed under a heatable PM, at a temperature higher than the T_C of the alloy. Cyclic movement is achieved due to temperature-driven magnetization/demagnetization and corresponding changes to the magnetic force between the magnet and alloy, opposing the cantilever weight, resulting in a power density of 0.1 $W.cm^{-3}$. Figure 4D shows a hybrid passive device relying on heat and cold sources at constant temperatures. In this example, a PM is placed near the heat source at the top while the ● ● ●

▸ **FIG. 3:** Analysis of Power density versus cost for several families of thermomagnetic materials, for a temperature difference of 30 K [5]. Reprinted (adapted or reprinted in part) with permission from Reference [4]. Copyright 2021, AIP Publishing.



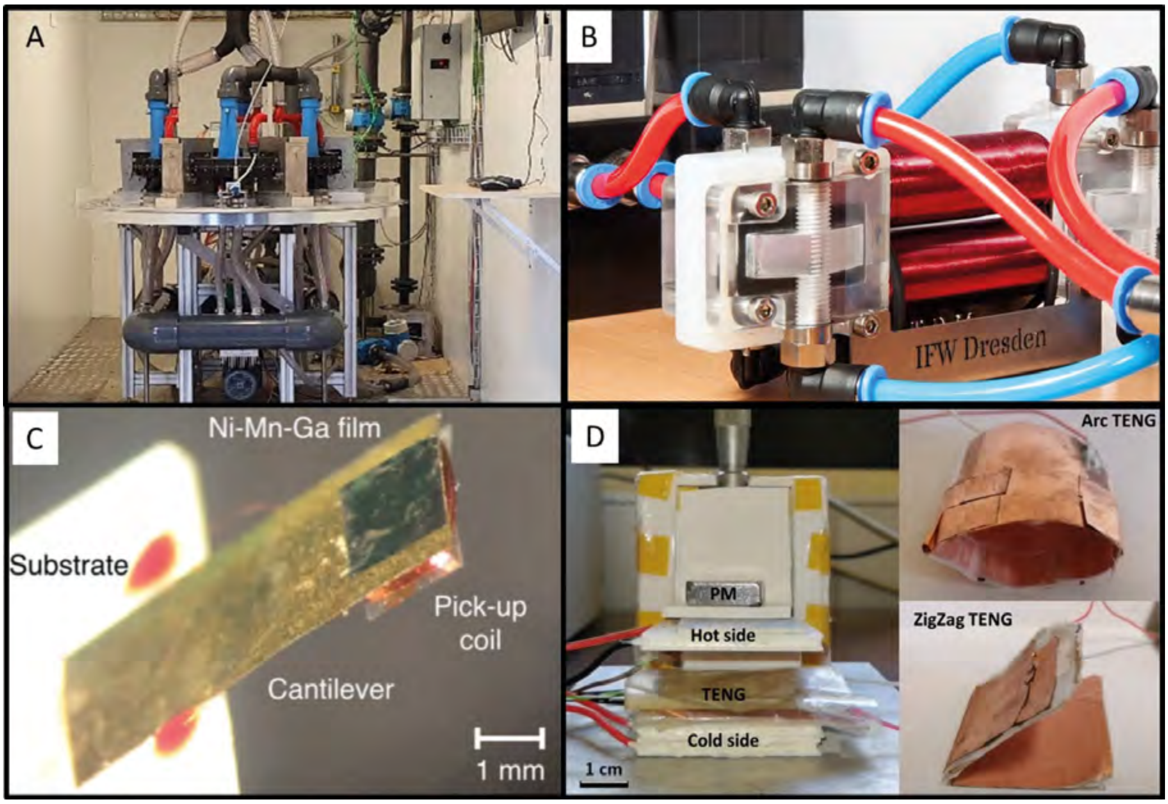
heat sink is placed at the bottom part. When the thermomagnetic material (Gd) is in the ferromagnetic state, it is attracted by the magnet to the heat source, where its temperature increases. The resulting transition to the paramagnetic state breaks the magnetic force, making the plate fall into the heat sink, where it cools down again. This cycle is repeated in a sustainable manner as long as the temperature gradient is maintained. To generate electrical power, a mechanical-to-electrical transduction mechanism was added. In this case, a triboelectric nanogenerator (TENG), relying on the conjugation of electrostatic induction and the triboelectric effect, was placed in the bottom part to efficiently convert the low-frequency movement of the thermomagnetic material [2]. A maximum power density of 54.7 μW.m^{-2} was achieved, a value 35 times higher than that obtained using a conventional coil. Other assembling and conversion mechanisms, *e.g.* based on piezoelectric membranes, have also been reported [9].

Future prospects

Besides price and performance metrics, a novel thermomagnetic device concept and design, together with the material employed, should have sustainability in mind. While rare-earth based magnets are now ubiquitous and applied thoroughly in prototype design and dimensioning, the use of rare-earth free magnets, particularly based on abundant Fe-based oxides, would be advantageous in terms of critical materials and device cost. This is an ongoing challenge for thermomagnetic device design, particularly for the development of new thermomagnetic materials, but also for the development of new permanent magnets.

The development of tricritical thermomagnetic materials is also an interesting prospect. These materials exist at the border between second- and first-order phase transitions, and can show a sharp magnetic transition with

▸ **FIG. 4:** Thermomagnetic generator devices, ranging from (A) large/industrial scale [6], (B) tabletop [7] down to (C) millimetric size [8], and (D) a tabletop hybrid thermomagnetic triboelectric device [2]. Reprinted (adapted or reprinted in part) with permission from reference [8]. Copyright 2021, AIP Publishing.



high dM/dT, while simultaneously avoiding magnetic/thermal hysteresis. Optimized thermal properties, such as specific heat and thermal conductivity, as well as smart material microstructuring or higher surface to volume ratio, to improve thermal exchange, are also poised to lead to significant advances towards high-performance devices.

Compared to thermoelectrics, thermomagnetic devices can be particularly competitive in terms of both cost per Watt and efficiency [5]. This is particularly accurate in the ultra-low temperature gradient region (below 10 °C), with power densities of 50 $\mu W/cm^2$ for temperature variations as small as 3 °C having already been achieved [10]. Therefore, thermomagnetic devices are, at this stage, especially suitable for the emerging Internet of Things (IoT), where miniaturized, low-power consumption sensors can be energized in a self-powered manner by energy harvesting technologies. ■

About the Authors

Joao H. Belo is a Junior researcher at the University of Porto, at the Institute of Physics for Advanced Materials, Nanotechnology and Photonics (IFIMUP), and his research focuses on magnetic materials for energy, thermomechanical and biomedical applications. jbelo@fc.up.pt

João Amaral is an assistant researcher at the University of Aveiro, at the Department of Physics and CICECO – Aveiro Institute of Materials. His research focuses on magnetic materials for energy applications. jamaral@ua.pt

Joao Ventura is a principal researcher at the University of Porto, at the Institute of Physics for Advanced Materials, Nanotechnology and Photonics (IFIMUP). His research focuses on advanced materials for neuromorphic and energy harvesting applications. joventur@fc.up.pt

References

[1] G. Schierning, *Nat. Energy* **3**, 92 (2018)

[2] C. Rodrigues *et al.*, *Advanced Functional Materials* **32** **(21)**, 2110288 (2022)

[3] N. Tesla, US Patent 396121 (1889)

[4] N. Tesla, US Patent 428057 (1890)

[5] D. Dzekan *et al.*, *APL Mater.* **9**, 011105 (2021)

[6] Swiss Blue Energy, http://www.swiss-blue-energy.ch

[7] A. Waske *et al.*, *Nature Energy* **4**, 68 (2019)

[8] M. Gueltig *et al.*, *Advanced Energy Materials* **7** **(5)**, 1601879 (2016)

[9] J. Chun *et al.*, *Scientific Reports* **7**, 41383 (2017)

[10] J. Joseph *et al.*, *Joule* **4**, 2718 (2020)