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STUDY OF THE ENERGY CONVERSION CHAIN IN A THERMOMAGNETIC GENERATOR

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ABSTRACT

Thermomagnetic generators designed to scavenge electrical energy from a heat flow can be designed following different conversion chains. Here we numerically study a device based on a three steps conversion, from magnetic towards kinetic, and eventually electrical energy. This chain is assured by a magnetocaloric material (MCM) as active substance moving between the heat reservoirs on an elastic beam (polypropylene :60.6 x 26.6 x 1.2 mm³) designed to obtain an auto-oscillating system. The cantilever kinetic energy is recovered using piezoelectric patches (PZT 5a). After optimization of the patches size, our simulations give an output energy density of 0.03 mJcm⁻³. To achieve a further optimization we investigate the possibility to use the piezoelectric material both as a transducer and as an actuator to have a better control of the working thermodynamic cycle. In this way we show that an energy density up to 60.46 mJcm⁻³ can be achieved.

Keywords: magnetocaloric materials, thermomagnetic generator, energy harvesting.

1. INTRODUCTION

Recently the need of reliable, high power density micro-generators has increased due to the development of a huge variety of autonomous devices. Due to the ubiquity of low-level heat sources (i.e. low temperature difference), thermal energy harvesting systems seem to be a solution to autonomous devices supply. So far thermal energy harvesting has been mainly associated to developments in thermo-electric generators (TEG). However, the increasing miniaturization poses a major strain to steady-state conversion, and state of the art micro-TEGs fall short to achieve the required power densities.

In a recent paper it has been shown (Gueltig et al., 2017) that a Heusler alloy based cyclic thermo-magnetic generator (TMG), working over a 140 K temperature difference can reach a power density up to 0.1 W/cm³ at the millimeter scale. Available micro-TEG systems can hardly pass 0.03 W/cm³ in the same conditions. Ujihara and coworkers (Ujihara et al., 2007) presented a TMG whose estimated output is between 1.85 and 3.61 mW/cm³.

Indeed, the new generation of magnetocaloric materials (MCM), initially designed for room temperature refrigeration, offers a unique opportunity to develop high performance energy recovery systems using the pyromagnetic effect (i.e. the inverse of the magnetocaloric effect). Beyond material optimization, the main challenge is the detailed control of the thermodynamic transformations composing the cyclic system.

The scavenging device converts the heat flux into magnetic energy and subsequently into electricity. The optimization of the thermodynamic working cycle has been studied in (Almanza et al., 2017), where we showed that we can reach an energy density of 10 mW/cm³ for a temperature difference of 3 K.

This communication addresses the study of the second step of the energy conversion by studying, with numerical simulations, the possibility to efficiently convert magnetic into electric energy keeping the working cycle as close as possible to the ideal one. Here we shall focus on piezoelectric transducers to recover the available energy. We shall start by presenting the device, and then we will treat the energy harvesting using piezoelectric materials, discussing how to improve the recovered energy.

2. DESIGN OF THE HEAT HARVESTER

Our thermomagnetic generator is designed to work between two heat reservoirs, using the displacement of the active substance (i.e. the MCM plate) from the cold end to the hot one and vice versa, in order to switch the thermal contact and to move the material from high to weak field region in the device. To assure a good confinement of the magnetic field near the hot end we shall use an Halbach array, built using NdFeB parallelepiped magnets ($3 \times 3 \times 10 \text{ mm}^3$). The MCM (i.e. a $1 \times 6 \times 10 \text{ mm}^3 \text{ La}(\text{Fe}_2\text{Si})_{13}\text{H}$ plate) is fixed in the middle of a beam (cf. Figure 1).

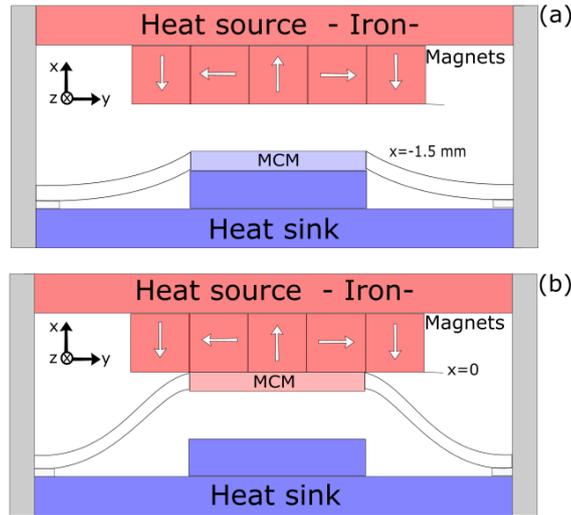


Figure 1: Thermomagnetic generator, (a) the MCM is stuck to the heat sink, (b) the MCM is stuck to the hot source.

The generator works using a Brayton cycle composed by two iso-fields, and two adiabats. The switch between the reservoirs will be driven by the magnetic force (from the cold to the hot end, step 1 in Fig.2) and by the cantilever recall force (from the hot to the cold end, step 3 in Fig.2) respectively. These displacements are expected to be quick enough to take place in adiabatic conditions. Iso-field heat exchanges will take place when the MCM is in contact with the hot and the cold reservoirs (see Fig.1 [a] and [b]). During these two transformations the MCM position will be fixed by the magnetic and the elastic force respectively and consequently the field will be constant (see Fig. 2 step 4 and 2 respectively).

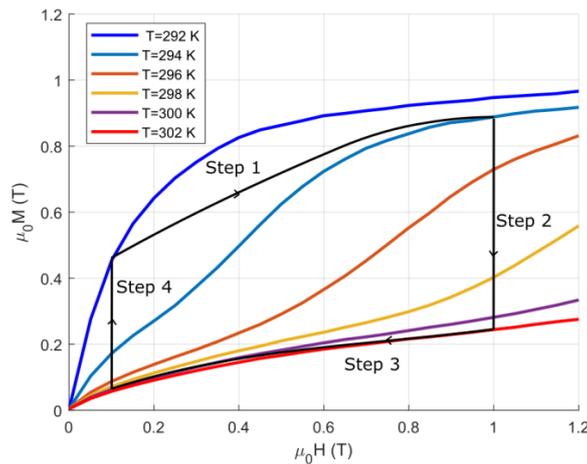


Figure 2: Thermodynamic cycle from a magnetic view. Magnetization as a function of the applied field, the temperature indicated in the legend. The two adiabatic (Step 1 and 3) and the two iso-fields (step 2 and 4) transformation are represented.

The forces acting on the MCM are:

- The magnetic one depending on the field through the position of the plate, and on the MCM temperature T (*i.e.* its magnetic state), $F_{mag} = F_{mag}(T, x)$, where x is the vertical position of the material ($x=0$, and $x=-1.5$ mm when in contact with the hot and the cold end respectively);
- The elastic return force which depends on the position, $F_r = F_r(x)$.

To achieve the self-oscillation of the device the cantilever beam must be designed in such a way that $F_{mag}(292, -1.5) > F_r(-1.5)$, and $F_{mag}(302, 0) < F_r(0)$ (cf. Figure 3). The suitable beam stiffness including the piezoelectric elements is $k = 7890$ N/m. We use the polypropylene as a material for the beam, because it is quite flexible. By calculations and validation with simulation, we need a $60.6 \times 26.6 \times 1.2$ mm³ cantilever.

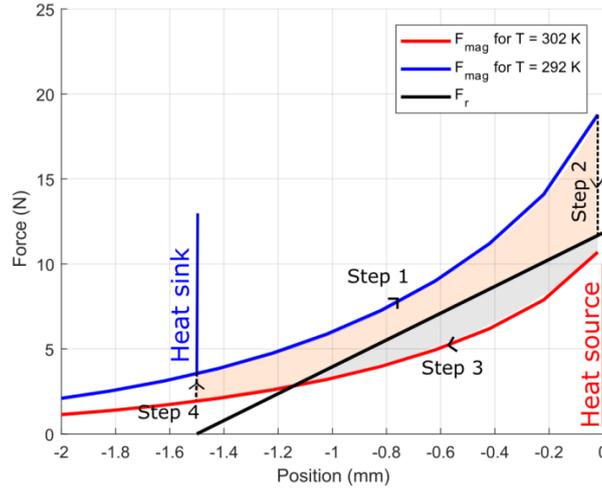


Figure 3: Thermodynamic cycle on force-displacement diagram. Magnetic force (F_{mag}) at $T= 292$ K, $T= 302$ K and return force of the beam (with open circuit piezoelectric elements) (F_r) as a function of position (x). The two adiabatic (Step 1 and 3) and the two iso-field (step 2 and 4) are represented. The light red and grey filled area represent the energy available during the step 1 and 3.

Representing the thermodynamic cycle in the force vs position diagram of Fig.3, the energy available in step 1 is the light-red filled area between the blue and the black lines, the energy available in step 3 is the light-grey filled area between the black and the red lines. These energies must be converted by the piezoelectric transducer to avoid their conversion to a kinetic energy and finally to their dissipation into the shock between the MCM and the reservoirs. As shown Eq.(1), the kinetic energy accumulated is the difference between the work of the spring and the work of the magnetic force. To recover this energy, an ideal transducer must compensate the difference between the recall force and the magnetic forces.

$$d\left(\frac{1}{2}mv^2\right) = F_r dx - F_{mag} dx - dW_{rec} \quad \text{Eq.(1)}$$

where m is the mass of the MCM, v its speed, dW_{rec} corresponds to the work done by the piezoelectric patches. In the following section we shall study the final kinetic to electric energy conversion using a piezoelectric transducer.

3. ENERGY HARVESTING USING PIEZOELECTRIC MATERIALS

We propose to study different mode to use the piezoelectric material, the first consist to deform the piezoelectric patches in open circuit and then harvest the energy stored in the capacitor, the second mode, consist to apply a voltage during the displacement in order to have an increased control on the thermodynamic cycle and a consequent improvement of the recovered energy.

Using 3-D finite element model created under ANSYS, we study the energy harvesting using four commercially available piezoelectric patches ($0.3 \times 20 \times 10$ mm³), PZT 5a.

In the first mode, the simulation gives the open circuit voltage at maximum strain around 5.6 V and the energy produced is estimated through the following expression (Rendon et al., 2016):

$$E = \frac{1}{2} C_p V^2 = \frac{1}{2} \frac{\epsilon_0 \epsilon_r L_p b_p}{h_p} V^2 \quad \text{Eq. (2)}$$

Where V is the voltage, ϵ_r the relative permittivity, L_p the patch length, b_p its width and h_p its thickness. Since there are 4 patches the total energy is 0.01 mJ per cm^3 of MCM. A rough optimization considering $h_p = 0.9 \text{ mm}$, $b_p = 26.6 \text{ mm}$, $L_p = 15 \text{ mm}$ improves the energy density to 0.03 mJ/cm^3 .

In the second mode, we consider to be able to control the voltage of the piezoelectric transducers. This can be done using a set of batteries or using a suitable power electronics device. A system where an electric tension can be applied on the piezoelectric patches, will recover more energy as we increase the work done by the beam on the piezoelectric patches. The main aim by doing this, is to decelerate the MCM in a such a way to have vanishing speed when the it reaches the heat end. This will allow to avoid the energy loss associated to the shock, and to limit the consequent mechanical deterioration of the MCM. Now different piezoelectric driving might be considered. A controlled, gradual, deceleration would imply a dynamic tuning of the applied tension. For the sake of simplicity here we consider a device where we can just switch between two fixed electric tensions.

Now let us focus just on step 1 (step 3 will behave in a similar way). Fig. 4 shows how different applied voltage will modify the motion of the MCM. The optimal trajectory would be the one represented in black dotted point with vanishing speed at the hot end. Unfortunately the system is highly sensitive to the applied tension and the ideal trajectory cannot be easily achieved with a constant voltage. So we choose the 30 V trajectory, the one showing the smallest final speed without breaking the self-oscillation. A similar analysis gives a -1 V tension for step 3. In this way, neglecting the transducer losses, the electrical energy recovered W_{rec} during a complete cycle is given by the following equation:

$$W_{recovery} = \oint F_r dx = \int_{-1.5}^0 F_r \text{ for } 30 \text{ V} dx - \int_0^{-1.5} F_r \text{ for } -1 \text{ V} dx = 3.63 \text{ mJ} = 60.46 \text{ mJ/cm}^3 \quad \text{Eq.(3)}$$

The fig. 5 shows an approximation of the energy recovered during the step 1 and 3, represented respectively by the red and grey filled area. We assume that the recall force under an imposed voltage does not change the cycle shape.

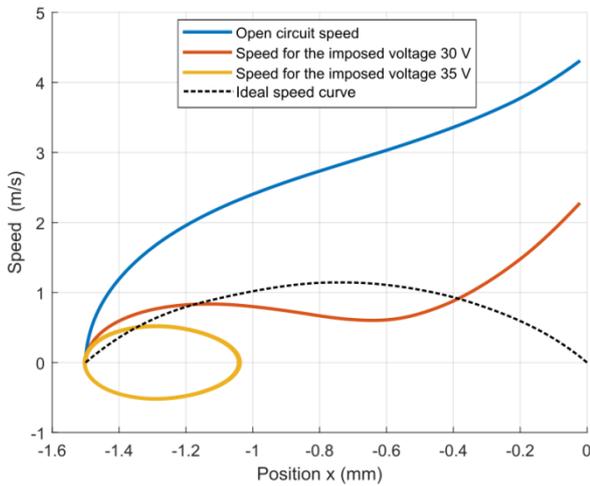


Figure 4 : Speed of the MCM as a function of its position in the first step, for the imposed voltages of 0 V, 35 V and 40 V.

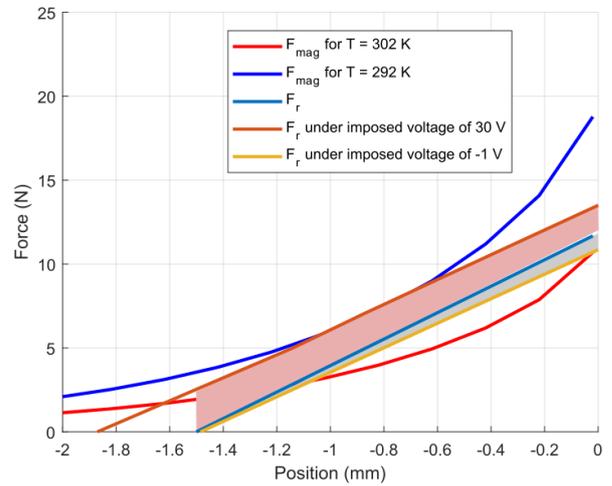


Figure 5 : Magnetic strength (F_{mag}) at $T= 292 \text{ K}$, $T= 302 \text{ K}$, recall force) (F_r) and the recall force under the imposed voltage of 30 V and -1 V, as a function of position (x).

4. CONCLUSIONS

In this paper, we designed a self-oscillating thermomagnetic harvester and we describe the interaction between piezoelectric material, the spring effect of the beam and the magnetic force of the magnetocaloric material induced by the temperature change. We show that it is possible to recover energy from the thermal energy to an electrical energy using different transducer, the magnetocaloric material converts the thermal energy to mechanical energy and then the piezoelectric and the elastic beam converts the mechanical energy into an electrical energy. Our study, decoupling the magnetic/thermal and the mechanical/electrical interaction, proposes a simple approach to study the energy conversion chain of a thermomagnetic generator. It finally let us foresee the possibility of such device in term of energy density.

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