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► **To cite this version:**

Morgan Almanza, Alexandre Pasko, Frédéric Mazaleyrat, Martino Lobue. Numerical study of thermomagnetic cycle. Advances in Magnetism Conference (AIM 2016), Mar 2016, Bormio, Italy. hal-01790625

HAL Id: hal-01790625

<https://hal.science/hal-01790625>

Submitted on 13 May 2018

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Numerical study of thermomagnetic cycle

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Abstract—We estimate the efficiency and power of a thermal energy harvesting thermodynamic cycle using magnetocaloric material as active substance. An accurate model of material, based on measurement, or theoretical are used to simulate a thermodynamic cycle and foresee magnetic work and then compare it to the maximum work. Afterwards power is estimated using a simple thermal exchange model. Simulations of different cycles for different working points illustrate the tradeoff between power and efficiency.

Index Terms— magnetocaloric materials, thermal energy harvesting, thermomagnetic cycle, simulation

I. INTRODUCTION

Nowadays much of the industrial energy consumption consists in thermal processes such as cement and steel production, where about one third of the used energy is discarded as low grade heat. Therefore the supply of waste heat is sufficiently abundant as to make it a key target for technology development. A thermal energy harvesting system with high power density and/or efficiency does not currently exist. Many efforts have been done on thermoelectric systems (TE). However TE efficiency and power density are still too low for application purposes. Energy harvesting systems from waste heat based on thermo magnetic generation (TMG) have been studied since the 1948 paper by Brillouin and Iskenderian [1] and the Patents by Edison and Tesla in 1890. The advent of giant magnetocaloric material (MCM) imposes a fresh assessment of the potential of TMG in term of efficiency and power and an increasing interest towards this opportunity is apparent from recent publications [2, 3]. As in the case of TE an issue too often neglected is that a tradeoff exists between efficiency and power density [4]. In this paper we focus on this aspect presenting numerical simulations, based on a simple thermal exchange model, to estimate efficiency and power density.

TMG from waste heat involve harnessing the pyromagnetic effect (PE), namely the induction of a magnetization by the action of a temperature change. Two approaches are commonly envisaged: the first consists in cycling the active material around the maximum temperature-field coupling point while temperature change between the hot and the cold reservoir produce a magnetization change in time, which drives an electric current [2]; the second uses the magnetization change in the active substance and the related force/couple exerted on a secondary material to directly produce mechanical work [3]. Efficiency and power density depend on many parameters: the heat exchanger, the material, the magnetic field available, the thermodynamic cycle used and the way we convert the magnetization change to electrical energy. Here we propose to examine in detail the tradeoff between efficiency and power on a single Ericsson cycle working between two heat sources, namely a hot one and a

heat sink. Eventually the possibility to use the same approach to regenerative multiple heat sources cycle will be discussed.

II. MATERIALS MODELING

MCM are classified following the order of the phase transition driving the effect. Second order materials present a continuous ferromagnetic to paramagnetic transition at the Curie temperature (T_C) while the first order ones have an abrupt transition with a discontinuity in the magnetization versus temperature curve. Besides a strong magneto-elastic coupling and sometimes a structural transition are often associated with the first order magnetic phase change. As in most of first order phase transitions, hysteresis and metastability can be present. The most promising MCMs are the LaFeSi or the MnFePSi based compounds [5]. These materials have a very sharp transition with critical temperature adjustable with compositions. Some of these compounds are available at industrial scale.

The estimation of TMG performance is based on the reliability of the material modeling. Historically, Brillouin have used Curie-Weiss law. Here, for second order materials, we shall use Weiss-Debye-Sommerfeld [2], to take into account the effect of field and temperature on thermal capacity, and data from real materials as $\text{Pr}_{0.65}\text{Sr}_{0.35}\text{MnO}_3$ [6]. For first order materials we shall use a Bean and Rodbell like approach [7].

III. THERMODYNAMIC CYCLE AND SIMULATIONS

Some ideal thermomagnetic cycles are shown in Fig. 1. The material is assumed to be always at thermodynamic equilibrium (i.e. the phase transition, whatever its order, is assumed to take place at equilibrium). Therefore, assuming the usual entropy balance expression, $ds = ds_e + ds_i$, $ds_e = \delta Q/T$ represents the reversibly exchanged specific entropy, and $ds_i \geq 0$ is the entropy production associated with irreversible heat exchange.

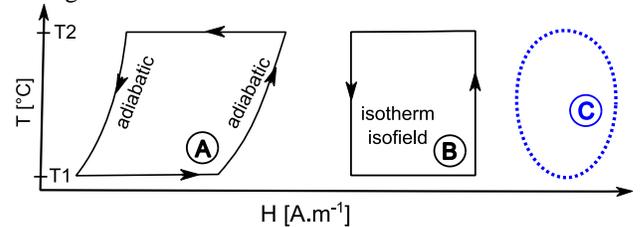


Fig. 1. Examples of two ideal cycles: (A) Carnot, (B) isofield-isothermal Ericsson cycle, and of a generic cycle (C).

From standard thermodynamic relations applied on an elementary volume (i.e. volume specific quantities), we can write,

$$du = \delta Q - \vec{M}d\vec{B} \quad (1)$$

$$Tds = c_H dT + T \frac{\partial s}{\partial H} dH = \delta Q \quad (2)$$

In (1) u is the internal energy, $-MdB$ the magnetic work, Q the heat exchange, s the entropy and c_H the heat capacity at constant field, all these quantities being defined per unit of volume. The efficiency of the cycles, defined by how much work is produced compared to the heat absorbed, only depends of H, T path.

$$\eta = -\frac{W_{mag}}{Q_{hot}} = 1 + \frac{Q_{cold}}{Q_{hot}} \quad (3)$$

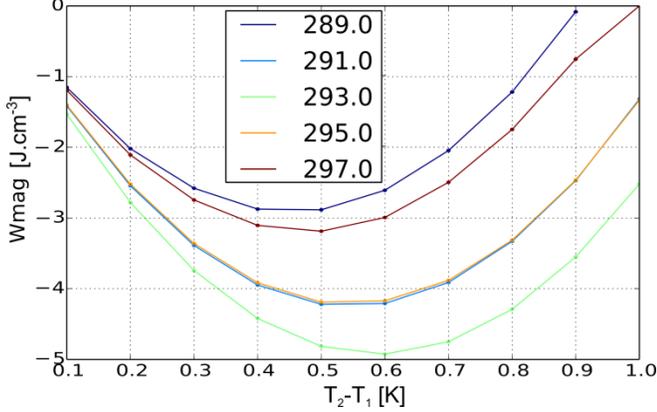


Fig. 2 Magnetic work for the cycle \textcircled{A} for different T_1 temperature with an applied field of 1T with $\text{Pr}_{0.65}\text{Sr}_{0.35}\text{MnO}_3$

To estimate power of a cycle, the following simple heat exchange model describes the thermal exchange with the two reservoir where are $k_{hot}(T, H)$ and $k_{cold}(T, H)$ in $[\text{W} \cdot \text{K}^{-1} \cdot \text{m}^{-3}]$.

$$\delta Q = [-k_{hot}(T - T_{hot}) - k_{cold}(T - T_{cold})]dt, \quad (4)$$

When the MCM is said to be in thermal contact with the hot reservoir then k_{hot} is more or less a big number depending on the exchange efficiency and k_{cold} is null and vice versa. Using the material model and (2) in (4) integrated, the period of the cycle is computed as represented in the Fig. 3.

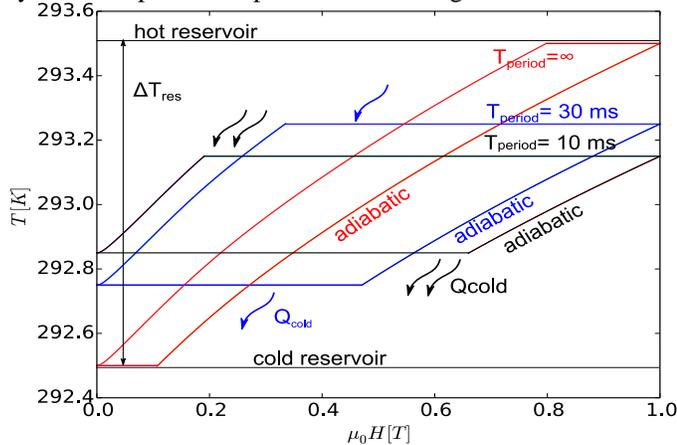


Fig. 3. Example of \textcircled{A} cycle with its period T_{period} where different temperature difference is used for the heat exchange

To evaluate how far the cycle is from the maximum work cycle for given reservoirs, the entropy production dues to heat exchange has to be considered,

$$\delta s_i(T, H) = \left(\frac{1}{T} - \frac{1}{T_s(T, H)} \right) \delta Q(T, H) \quad (5)$$

The system studied is now the MCM and the sources. The temperature of the source T_s which the MCM exchanges, is alternatively T_{hot} and T_{cold} . For example, in \textcircled{A} cycle entropy production is due to irreversible heat exchange along the transformation at constant temperature. If, and only if, there is only two reservoirs, the cold and the hot, entropy production is linked to the efficiency of the Carnot cycle, the cycle which in this case extracts the maximum work or which doesn't produce entropy due to the heat exchange:

$$\eta = 1 - \frac{T_{cold}}{T_{hot}} - \frac{s_i T_{cold}}{Q_{hot}} = \eta_{Carnot} - \frac{s_i T_{cold}}{Q_{hot}} \quad (6)$$

Relative efficiency η_{rel} is the ratio of the cycle efficiency to the efficiency of the Carnot cycle:

$$\eta_{rel} = \frac{\eta}{\eta_{Carnot}} = 1 - \frac{s_i T_{cold}}{\eta_{Carnot} Q_{hot}} \quad (7)$$

Faster is the cycle, with $T_{period} = \infty, 30, 10 \text{ ms}$ i.e exchange heat, faster the relative efficiency decreases with respectively $\eta_{rel} = 1, 0.5, 0.3$, from the red to the black cycle in the Fig. 3. This glance reveals the trade-off between power and efficiency, with some assumptions and with cycle \textcircled{A} the following expression exhibits this trade-off:

$$P = \frac{\Delta T_{res}^2 k_{on}}{4T_{hot}} \eta_{rel} (1 - \eta_{rel}) \text{ with } \eta_{rel} = \frac{\Delta T_{res}}{T_2 - T_1} \quad (8)$$

In the final paper, comparison between cycles with estimation of power and efficiency based on simple heat exchange model, will be done for the experimental and the theoretical material model for second order material and with theoretical material model only for the first order. And different optimum working point for magnetic power production and tradeoff will be proposed.

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