Applied Thermal Engineering 145 (2018) 245–250

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

On the relevance of temperature, applied magnetic field and demagnetizing factor on the performance of thermomagnetic motors

C.V.X. Bessa[a,*], L.D.R. Ferreira[a], O. Horikawa[a], S. Gama[b]

[a] *Escola Politécnica da Universidade de São Paulo – EPUSP, São Paulo 05508-030, Brazil*
[b] *Universidade Federal de São Paulo – UNIFESP, Diadema 09910-720, Brazil*

HIGHLIGHTS

- We presented the thermodynamics of thermomagnetic motors.
- We verified how temperature, applied magnetic field and demagnetizing factor change the performance of thermomagnetic motors.
- We discussed how to improve the performance of thermomagnetic motors.

ARTICLE INFO

Keywords:
Thermomagnetic motors
Thermodynamic cycle
Heat engines
Demagnetizing factor

ABSTRACT

Thermomagnetic motors are devices capable of converting heat into work with high efficiency relative to the Carnot efficiency. This work reports how the temperature, applied magnetic field, and demagnetizing factor, change the performance of thermomagnetic motors, using a thermodynamic approach. Results show that these systems present high efficiency related to the Carnot efficiency for small temperature differences and better correlation between work produced by cycle and relative efficiency when the magnetic transition occurs. The relation of work and relative efficiency can also be improved by increasing the applied magnetic field change and reducing the demagnetizing factor. For some special temperature conditions, a lower magnetic field change can result in higher work production. Also the decrease of the demagnetization factor acts as an increase of the magnetic field change applied to the motor magnetic material.

1. Introduction

Thermomagnetic motors are devices that convert heat into kinetic energy through the thermomagnetic effect [1–5], i.e., the influence of temperature on the magnetic material magnetization M [6,7], in a way that if a material that is in a ferromagnetic state is heated its M is reduced. When the material temperature T approaches the Curie temperature (T_C), a small change in T causes a broad change in M [8]. When T surpass the T_C, the material reaches the paramagnetic state [9]. If the material is cooled to a T below T_C, it then returns to the initial ferromagnetic state [7].

Thermomagnetic motors present high efficiency related to the Carnot efficiency η_{rel} for small temperature differences around the Curie temperature T_C [10–12]. Therefore thermomagnetic motors are a promising technology for the conversion of low-grade waste heat from sources close to room temperature into work [7]. These machines are suggested for conversion of solar and geothermal energies [13,14] and for energy harvesting applications [15–17], being a very good alternative to the conversion of renewable energy sources [18].

Using a thermodynamic approach, we have previously shown how the magnetic transition order and the thermal hysteresis change the performance of a thermomagnetic motor [12]. However, other parameters can change the behavior of these machines. This study investigates the influence of the operating temperatures, the applied magnetic field and the demagnetizing factor in the specific work and η_{rel} of a thermomagnetic motor by thermodynamic analysis.

2. Thermodynamics of thermomagnetic motors

One of the most relevant thermomagnetic motors was that patented by Tesla [19], and Fig. 1 shows a thermomagnetic motor design working on the same principle as Tesla's patent. The system has two parts made of the same magnetic material labeled MM1 and MM2, with the same mass, form, and dimensions. Note that when MM1 is

* Corresponding author.
E-mail address: carlosviniciusxb@usp.br (C.V.X. Bessa).

https://doi.org/10.1016/j.applthermaleng.2018.09.061
Received 23 May 2018; Received in revised form 2 August 2018; Accepted 12 September 2018
Available online 14 September 2018
1359-4311/

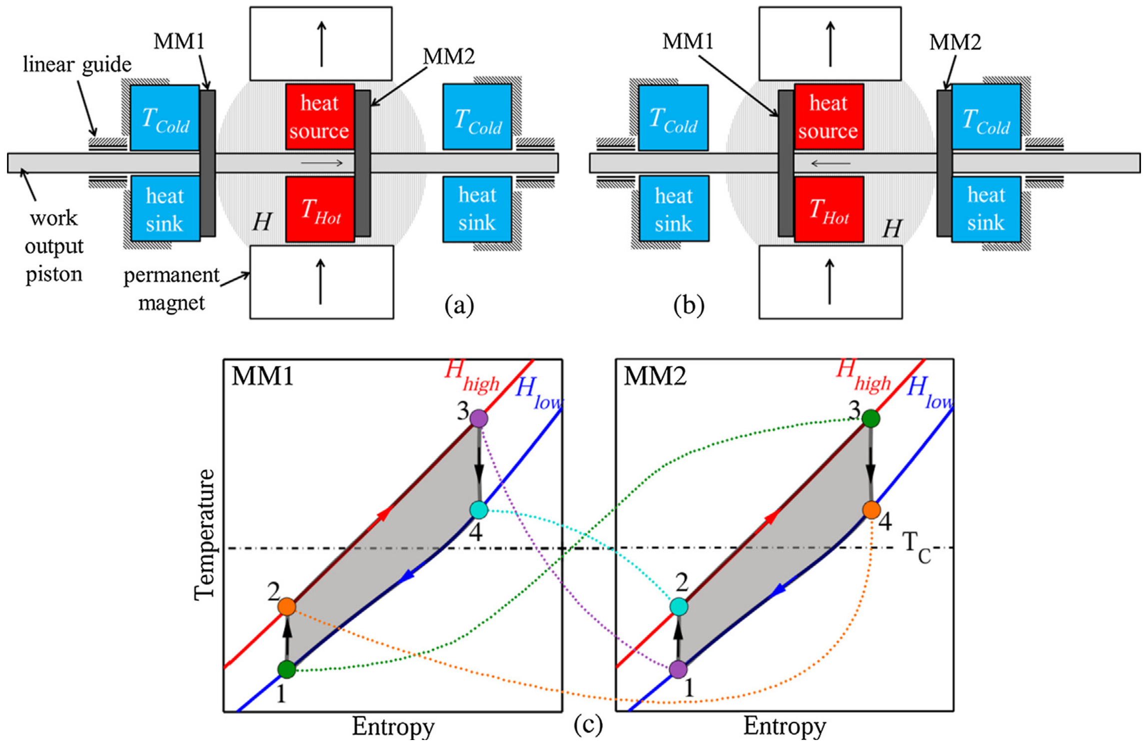

Fig. 1. Thermomagnetic motor based on the Tesla's patent [19]. (a) MM1 is exchanging heat with the heat sink, while MM2 exchanges heat with the heat source. (b) MM1 is exchanging heat with the heat source, while MM2 exchanges heat with the heat sink. (c) "Out of phase" Brayton magnetic cycles developed by MM1 and MM2. 1, 2, 3 and 4 are the thermodynamic states.

exchanging heat with the heat sink, MM2 is exchanging heat with the heat source, as shown in Fig. 1(a). While MM1 is receiving heat from the heat source, MM2 is rejecting heat for the heat sink, as shown in Fig. 1(b). When the high field region attracts MM1, MM2 is moved to the low field region and vice-versa. That happens because Tesla type thermomagnetic motors operate in a Brayton magnetic cycle [12], and MM1 and MM2 both follow Brayton cycles "out of phase", meaning that when one magnetic material part is heating, the other part is cooling. This way, describing what happens with MM1 defines what is also happening with MM2. Fig. 1(c) presents the "out of phase" Brayton magnetic cycles in the temperature-entropy diagram developed by MM1 and MM2.

At the beginning, MM1 is cold, at temperature T_1, under a low applied magnetic field H_1, having a magnetization M_1 and a specific entropy s_1, that is the thermodynamic state 1. The resultant magnetic force acting in the system moves MM1 to the region of high applied magnetic field H_2, making the system displace for the position shown in Fig. 1(b). During the displacement, MM1 does not exchange heat, undergoing a reversible adiabatic process, consequently $s_2 = s_1$. Due to the magnetocaloric effect, i.e., the magnetic material temperature change DT_{ad} due to a magnetic field change in an adiabatic process [20,21], MM1 temperature increases to T_2, resulting in a magnetization M_2, that is the thermodynamic state 2. In the new position, MM1 begin to exchange heat with the heat source, warming up under a constant applied magnetic field, $H_2 = H_3$, reaching a magnetization M_3 and a specific entropy s_3 when at the temperature T_3, and this is the thermodynamic state 3. Considering that MM2 undergoes a reverse process of MM1, if MM1 is on the state 3, MM2 is on the state 1, as shown in Fig. 1(c). This way, the high field region attracts MM2, pushing MM1 to the low field region. The system displaces again, returning to the initial position shown in Fig. 1(a). The displacement happens in a reversible adiabatic process, and due to the magnetocaloric effect the MM1 temperature decreases to T_4 when the applied magnetic field decreases to H_4, having a magnetization M_4 and a specific entropy $s_4 = s_3$, that is the thermodynamic state 4. The position of MM1 is the same for states 1 and 4, this way $H_1 = H_4$. At this position, MM1 rejects heat to the heat sink under a constant applied magnetic field H_1, and completes the Brayton magnetic cycle when MM1 reaches temperature T_1, returning to state 1.

In the Brayton magnetic cycle developed by a thermomagnetic motor, the process 1 → 2 is the reversible adiabatic process where the magnetic material (MM) produces work. The process 2 → 3 is the isofield heating process of the MM. The process 3 → 4 is the reversible adiabatic process where it is necessary to provide work to remove the MM from the high magnetic field region. Then the process 4 → 1 is the isofield process where the MM rejects heat to the heat sink. In the motor shown in Fig. 1, when MM1 goes from 1 → 2, then MM2 goes from 3 → 4; while MM1 executes 2 → 3, MM2 executes 4 → 1; if MM1 is in 3 → 4, MM2 is in 1 → 2; and when MM1 is in 4 → 1, MM2 is in 2 → 3. This way, during an entire cycle of the motor, each MM develops a Brayton cycle. The total work (W) produced in each cycle of the motor in Fig. 1 is equal to the sum of the work performed by MM1 and MM2, as shown in Eq. (1).

$$W = W_{MM1} + W_{MM2}. \tag{1}$$

W_{MM1} is the useful work produced by MM1 and W_{MM2} is the useful work produced by MM2. In which, W_{MM1} is the difference between the work produced by the magnetic force acting on MM1 during the process 1 → 2 and the work necessary to overcome the magnetic force acting on MM1 during the process 3 → 4. The magnetic force acting on an MM is equal to $V\mu_0 M\nabla H$, where V is the MM volume and μ_0 is the vacuum magnetic permeability [22]. Appling the definition of work, the integral of the force in the direction of the displacement, the work produced by a magnetic force (W_{Mag}) is defined by Eq. (2a), where H_0 is the applied magnetic field in the initial position, and H_f is the applied magnetic field in the MM final position. By definition, m is equal the product of the V and the MM density ρ, this way, the Eq. (2a) can be rewritten as Eq. (2b). By applying Eq. (2b), the difference between the work produced by MM1 during the process 1 → 2 and the required by MM1 during the process 3 → 4 can be calculated by Eq. (3).