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Technical note

Design of a thermoelectric generator with fast transient response

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A B S T R A C T

Thermoelectric modules are currently used both in Peltier cooling and in Seebeck mode for electricity generation. The developments experienced in both cases depend essentially on two factors: the thermoelectric properties of the materials that form these elements (mainly semiconductors), and the external structure of the semiconductors. Figure of Merit Z is currently the best way of measuring the efficiency of semiconductors, as it relates to the intrinsic parameters of the semiconductor: Seebeck coefficient, thermal resistance, and thermal conductivity. When it comes to evaluating the complete structure, the Coefficient of Performance (COP) is used, relating the electrical power to the thermal power of the module. This paper develops a Thermoelectric Generator (TEG) structure which allows minimising the response time of the thermoelectric device, obtaining short working cycles and, therefore, a higher working frequency.

1. Introduction

Cooling devices are very important in everyday life. For example, a patient with diabetes should always travel with their insulin to a certain temperature level. Another example is the application of thermoelectricity in cryogenic surgery in oncology. Therefore, thermoelectric devices should be compact, easily portable and flexible. Moreover, it would be very interesting that these devices were long-lasting and maintenance free.

When the application is not related with cooling or heating new needs are created, such as modifying the geometry of the thermoelectric structure and to develop new thermoelectric materials for manufacturing these devices. The creation of these new modules is possible and depends on the design and the development process when thermoelectric modules are being performed.

These thermoelectric structures are usually classified according to its power generation and its cooling temperature range. A thermoelectric structure can perform as a refrigerator of electro−optic components [1], also can be used for turning waste heat into power [2], and it can be applied in several medical areas [3], for example. Due to current market needs, the efficiency of thermoelectric structures is a factor that should be improved. When a thermoelectric device is used as a generator (Seebeck mode), the scope of use is even more restricted [4]. It is highly important to maximize the contribution of each thermo−element; in other words, a high density of thermoelectric generation is needed.

Figure of Merit Z or the dimensionless equivalent ZT is not the only factor that determines the material choice, but it is the most important. Precisely the efficiency of thermoelectric devices is determined by the Figure of Merit, which is defined by the $Z = \alpha^2 \sigma/\kappa$ ratio. It is common to use the term *Power Factor* to designate $\alpha^2\sigma T$ or $\alpha^2\sigma$, since this term only contains the electronic properties, while κ is always a large contribution of thermal network.

One of the main problems in the conversion of solar energy into thermal or electrical power is the low efficiency of converters based on semiconductors. The reason is that a considerable part of energy flows through phonon subsystem (thermal oscillations of crystal lattice), which are not involved in the power generation.

For obtaining the *COP* (Coefficient of Performance) of a thermoelectric cell working as cooler we should know the absorbed heat by the thermoelectric structure Q_C and the electrical power output of the system P_E.

$$COP = \frac{Q_C}{P_E} \tag{1}$$

To achieve an increased efficiency, amongst other factors, the geometry of the semiconductor must be taken into account. However, the accurate characterization of a thermoelectric device, either working in Peltier or in Seebeck mode, is rather difficult [5].

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Nomenclature

Q_H	dissipated heat flow (W)
Q_C	absorbed heat flow (W)
I	electrical current (A)
Z	figure of merit (K^{-1})
R	electrical resistance (Ω)
R_s	semiconductor's electrical resistance (Ω)
R_m	electrical resistance of the junction metal in the semiconductors (Ω)
ℓ	length of a semiconductor and pellet (m)
C	equivalent electrical capacity (F)
T_c	cold side temperature (°C)
T_h	hot side temperature (°C)
T_0	room temperature that surrounds the thermal structure (°C)
$T_{1,2,3,4,5,6}$	temperatures in the different structure interfaces (°C)
n	total number of pellets in the thermoelectric structure
P_E	electrical power (W)

Greek symbols:

∇	three–dimensional partial derivative
α	Seebeck coefficient ($\mu V \cdot K^{-1}$)
β	thermal diffusivity ($m^2 \cdot s^{-1}$)
σ	electrical conductivity ($\Omega \cdot m^{-1}$)
ρ	electrical resistivity ($\Omega \cdot m$)
κ	thermal conductivity ($mW \cdot cm^{-1} \cdot K^{-1}$)
κ_0	thermal conductivity of material in contact with air ($mW \cdot cm^{-1} \cdot K^{-1}$)
κ_{cc}	thermal conductivity of the ceramic cold plate ($mW \cdot cm^{-1} \cdot K^{-1}$)
κ_{ch}	thermal conductivity of the ceramic hot plate ($mW \cdot cm^{-1} \cdot K^{-1}$)
κ_m	thermal conductivity of the metal contacts between semiconductors ($mW \cdot cm^{-1} \cdot K^{-1}$)
κ_s	thermal conductivity of the semiconductor used ($mW \cdot cm^{-1} \cdot K^{-1}$)

When it comes to modelling a semiconductor, the figure of merit is required. There are several methods to obtain this measurement but these should be applied with a degree of caution [6]. Generally speaking, modelling is considered from a point of view in which the properties of materials used in the thermoelectric structure have an average value according to the working conditions –normally the temperature difference between faces–, or also Finite Element Models that lead to the division of the analyzed structure in a number of finite parts, bearing in mind separately that each part has certain specific properties.

At present, frequency behavior is rarely studied in the modelling of thermoelectric structures. However, the importance of the temporal response in the performance of the thermoelectric structures is shown in Refs. [7,8], for example. There are applications that are related with cell miniaturization and the inertia in the transient response that require a frequency study.

For all these reasons, in this paper a discrete model based on electric analogy is used to develop and manufacture a thermoelectric generator with a configurable time response that is hardly expect reached by any commercial thermoelectric module.

Developed thermoelectric device can be used in an industrial scenario for converting the wasting heat in electrical power, but with the advantage that the transient response can be configured according to the final application. Regarding electric analogy used in this paper, this model has been already tested in conventional structures [9] and its use allows taking into account the time constant of the thermoelectric system.

2. Model used in the design

2.1. Basic relations

In general, the heat flow in a semiconductor could be expressed according to the laws of heat for the three dimensions:

$$\nabla(\kappa \nabla T) - T(I \nabla \alpha) + I^2 \rho = 0 \tag{2}$$

In one dimension, this is expressed as:

$$\frac{\partial}{\partial x}\left(\kappa A \frac{\partial T}{\partial x}\right) - IT\frac{\partial \alpha}{\partial x} + I^2 \rho = 0 \tag{3}$$

When considering a steady state system in which the change of internal energy is zero, the model can be determined as a function of the heat absorbed or dissipated in the external faces of the semiconductor [10]:

$$\begin{bmatrix} \alpha I - \kappa & \kappa \\ -\kappa & \alpha I + \kappa \end{bmatrix} \cdot \begin{bmatrix} T_h \\ T_c \end{bmatrix} = \begin{bmatrix} Q_h - \frac{1}{2} I^2 R \\ Q_c + \frac{1}{2} I^2 R \end{bmatrix} \tag{4}$$

Although the simple model above does not define other phenomena which take place in the thermoelectric structure – such as the Thomson effect, or the Nerst effect inside a magnetic field –, nor the different phenomena related to the structure set up and used for supporting the semiconductors, it does reveal the high significance of geometry in the evaluation of the model's coefficients [11].

When trying to obtain a change of state where there is a high temperature difference, as ΔT, into another state where there is no temperature variation $\Delta T = 0$, a dynamical study of the thermoelectric device must be carried out.

2.2. Electrical analogy model

The model is considered in one dimension that provides essential information from the thermal structure. The following model is based on temperature increases between interfaces of the different materials that constitute the thermal structure [12]. The thermal parameters are assumed as constant (they actually depend on temperature, geometry, and other factors). Only the thermal conduction phenomenon will be considered, assuming that the structure is immersed in an isotropic medium [13].

In the simple structure it is assumed that there are n semiconductors and, therefore, the same number of metallic contacts between the semiconductors [14]. Both ceramic surfaces will support all the structure as shown in Fig. 1.

The linear equations that define the thermal structure are:

$$\kappa_0(T_0 - T_1) - \kappa_{cc}(T_1 - T_2) + Q_c = 0 \tag{5}$$

$$\kappa_{cc}(T_1 - T_2) - \frac{n}{2}\kappa_m(T_2 - T_3) = 0 \tag{6}$$