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Accurate simulation of thermoelectric power generating systems

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HIGHLIGHTS

- We model the thermal and electrical dynamics of thermoelectric power generating systems.
- Both transient and steady-state conditions are considered.
- We develop a computer program for transient simulations of thermoelectric systems.
- The program simulates the electro-thermal coupled effects that occur during changes in the operating conditions.
- Comparison of experimental and simulation results shows great accuracy.

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ABSTRACT

Recent interest in the use of thermoelectric generators (TEGs) to recover waste heat in large-scale applications calls for precise simulation to appropriately design complicated and dynamic systems. The aim of this work is to develop a computer tool to accurately simulate the thermal and electrical dynamics of a real thermoelectric (TE) power generating system.

The computer-aided model presented here is able to accurately simulate the non-linear electro-thermal coupled effects which occur during changes in the operating conditions, e.g. temperature or load changes.

Simulation results are compared to experimental data obtained from a real TE system. The comparison shows great accuracy both during transients and in the steady-state, thus validating the model as a reliable tool to simulate TE generating systems.

1. Introduction

Thermoelectric (TE) devices can directly convert thermal energy into electrical energy and vice versa. Thermoelectricity, based on the fact that charge carriers can be set in motion by a difference of temperature, generally refers to two main physical phenomena: the Seebeck effect and the Peltier effect. The former states that a certain open-circuit voltage is created in a material kept between two different temperatures. The Seebeck coefficient α (V/K) is a material property that relates the open-circuit thermoelectric potential V_{OC} (V) with the temperature difference ΔT (K), or

$$V_{OC} = \alpha \Delta T \tag{1}$$

The Peltier effect states that a direct current I(A) passing through a circuit of dissimilar materials pumps thermal power from one material to the other:

$$P_P = \pi I = \alpha I T_j \tag{2}$$

where π (V) is the Peltier coefficient and the last equivalence comes from the Kelvin relationship; T_j is the junction temperature.

Other important phenomena occurring in thermoelectric devices are the well-known Joule heating and the Thomson effect. The latter states that there is reversible absorption or liberation of heat (in excess of the joule dissipation I^2R) in a homogeneous material simultaneously exposed to temperature gradient and electric current:

$$P_T = \tau I \Delta T \tag{3}$$

where τ (V/K) is the Thomson coefficient, defined as

$$\tau = T_{AVG} \frac{d\alpha}{dT} \tag{4}$$

The Thomson effect is usually much smaller than the Joule heating [1,2] and ts contribute can be significant under large temperature differences [3,4]; also, the Thomson coefficient is difficult to obtain experimentally, therefore it is often neglected in literature. Its effect is not included in this article.

Doped semiconductors prove to be the materials with the best thermoelectric properties. Multiple pellets of *p*- and

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n-semiconductor are connected electrically in series and thermally in parallel to achieve and/or sustain higher voltages, thus forming a TE module. This paper will focus on TE generators (TEGs); Fig. 1 shows a 3D model of a TEG module where thermal energy is applied on the bottom ("hot" side). The pellets are electrically series-connected by solder and an Aluminium-based ceramic layer serves as electrical isolation and mechanical substrate. The resulting module is quite robust and reliable, and operates without any vibration or noise. It is commercially produced in a wide range of sizes from a few millimetres to several centimetres on a side. Multiple modules can be electrically connected in series or parallel in order to achieve higher output voltages and currents. Heat is conducted through the module while additional heat is generated (Joule) inside the module and pumped (Peltier) through the hot and cold sides as described by the coloured arrows. In TE power generation the Peltier effect is parasitic because it reduces the temperature difference across the device, thus increasing the module's effective thermal conductivity. Thermoelectric heat pumps (coolers or heaters) have been used for many years in applications ranging from IC microcoolers, to refrigerators [5], to power stations [6], and they are often referred to as Peltier devices. Due to their low efficiency, often less than 5%, thermoelectric generators have on the contrary been used predominantly in military and aerospace projects or for applications in which cost is not as important as the ability to reliably generate power in hostile or maintenance-free environments. However, interest in TEGs has recently increased because of concerns about climate change, coupled with increasing performance and lower module cost. TEGs can effectively lend themselves to sustainable applications of waste heat recovery in which thermal energy is rejected to ambient and is effectively free, e.g. in vehicles [7–10] and stoves [11,12]. TEGs can also be used to harvest geothermal energy [13] or combined to PV, solar thermal or thermophotovoltaic systems [14–16]. Moreover, recent advances in TE materials and 'mass-production' volumes [17,18] will continue to lead to a further improvement of TEGs' efficiency and reduction of their cost, respectively.

It is of fundamental importance to carefully design large-scale systems in which materials cost is of great relevance. However TE systems are usually composed of heat masses, TEGs and power and control electronics and they are influenced by several thermal and electronic phenomena whose interaction is complex. Moreover TEGs are often employed in dynamic environments which frequently undergo thermal transients. Actual CAD tools do not yet include the ability to model thermoelectric effects therefore they cannot be successfully used to accurately simulate the electro-thermal coupled effects which take place during changes in the system operating conditions, e.g., temperature, power or load changes. In literature some research has focused on this issue; Lineykin and Ben-Yaakov [19] have divided the TE module into a grid of spatially discretized thermal circuits then transformed into their electrical analogies. The transient term is included in the model as a parallel electrical capacitor to take into account an additional time-related term due to the change in stored heat energy. A similar approach has been followed by Chen et al. [20]. The accuracy of the simulation is related to the number of cells used and the parameters are difficult to obtain from manufacturers' data sheets, but most importantly they do not offer a theoretical solution to the problem because their governing equations are based on steady-state solutions. A more appropriate approach would be to study the transient physical equations which describe TE devices behaviour; among these the most important is the heat equation. Al-Nimr et al. [21] have already explored this possibility but they used fixed temperatures as boundary conditions at the two sides of the TE module, assuming that those temperatures are not varying, i.e., supposing thermal isolation (or steady-state). However, during thermal transients there is exchange of heat through the sides.

Very recently two very interesting works by Cheng and Huang [22] and Meng et al. [23] proposed two models for thermoelectric coolers. The former slightly overestimates the temperature difference in steady-state, while the second has a maximum error of 4.5 K over a temperature difference of around 37 K (with a current input of 1 A).

We have already provided a mathematical solution of the one-dimensional heat conduction equation for TE devices that includes internal Joule heat generation and dynamic exchanges of heat through the hot and cold sides in [24].

The aim of this work is to couple the aforementioned solution with the other thermal and electrical phenomena occurring in real TE systems. The resulting physical model, described in Section 2, takes into account the dynamic relations between the several thermal masses and the most important thermoelectric phenomena occurring in a generalised TE system.

The physical model is then used as the basic structure to develop a computer tool, described in Section 3, capable of accurate simulations of the thermal and electrical dynamics of a physical TE power generating system. The model is created in Simulink and Matlab and a comparison between experimental and simulated

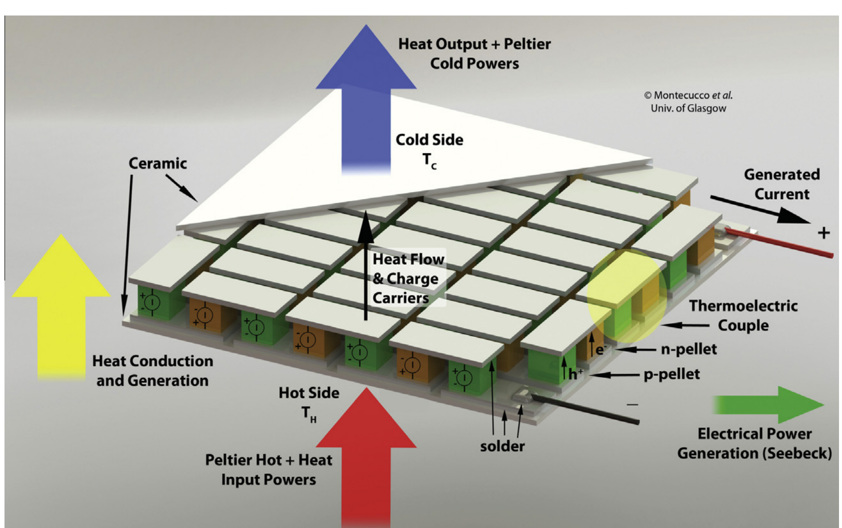

Fig. 1. 3D model of a thermoelectric generator showing the main physical effects.