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Transient response of a thermoelectric generator subjected to spatially non-uniform heating: Implications for heat and IR sensing applications

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ABSTRACT

We present a combined experimental and computational investigation of the transient behavior of a thermoelectric generator (TEG) subjected to temperature gradients of less than 0.5 K across its thickness. Such conditions can exist when TEGs are used as heat sensors or IR detectors. Spatially non-uniform heating was initiated by allowing light to strike the central portion of one side of the TEG or by placing a small heated probe in contact with that surface. The time-dependent, open circuit voltage output of the TEG was predicted using temperature results from a three dimensional transient heat conduction finite element model. It is shown that the transient voltage output is influenced by the configuration of the mounting hardware, by the thermal properties of the TEG's materials of construction, and by convection. Three-dimensional heat conduction in the TEG determines the nature of the transient voltage output, which, in some cases, exhibits an overshoot.

1. Introduction

Thermoelectric generators (TEGs) are solid state devices that use the Seebeck effect to convert heat (driven by a temperature difference) directly into electrical energy [1–5]. These devices can use any heat source and have a variety of applications. For example, combustion of fossil fuels in conjunction with TEGs can be used in remote locations to power such equipment as navigational aids, data acquisition and telemetry systems, and cathodic corrosion protection systems, e.g., for natural gas pipelines. TEGs have been used to power wireless sensors that can operate without batteries or wires for power or communications [6–8]. Radioisotope thermoelectric generators produce electricity from the heat released by the decay of a radioactive material (typically plutonium-238) [1–3,9]. They have been used to power numerous space missions, including space probes to the outer planets. Researchers are investigating the use of TEGs to harvest waste heat from industrial processes and internal combustion engines in motor vehicles [1–3,9]. Thermopiles, including micromachined devices, are used as thermal and infrared (IR) detectors for a variety of applications [10–13]. Conventional and miniaturized TEGs have been used as sensors, micropower generators, and in heat recovery experiments [1–3,6–8,10–19]. When TEGs are used as detectors it is essential to understand the time dependence of their response.

In energy harvesting applications the cold side of a TEG is typically attached to a good heat sink. While this is also desirable in sensing applications, it is not always done. Predicting the behavior of sensors based on TEGs poses unique challenges as the TEG surface may be subjected to non-uniform heating; and mounting hardware may

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degrade sensor performance by acting as a non-optimal heat sink and adversely affecting the temperature gradient across the TEG. For applications such as IR detectors the thermal gradients across the TEG will be small, often less than 1 °C. Non-uniform heating, complex conduction pathways, and small thermal gradients across the TEG require that a computational, three-dimensional thermal analysis be used to accurately predict its performance. Several recent modeling studies deal with optimization of the performance of TEGs, however these models assumed one dimensional heat conduction and transient effects were not considered [20–23]. Antonova and Looman [24] developed methodology for a coupled thermal–electrical analysis of a TEG using finite elements. Heat transfer was effectively one dimensional, as temperatures were prescribed on either side of the TEG. The modeling approach was developed using a block consisting of two pellets electrically connected at the top but not at the bottom. The authors demonstrated how several blocks could be electrically connected to model an entire TEG. Because the model does not accommodate thermal, only electrical exchange between adjacent blocks, the modeling approach is not suited to modeling non-uniform heating. Cochran and Babin [25] used a similar finite element approach. Rather than focusing solely on the thermal behavior of the device, they attempted, with limited success, to predict the coupled thermal-electric behavior of the TEG based on material properties. Although their geometry is similar to that used in the investigation presented in this paper, the applied temperature difference across the device was 50 K, much larger than in our work, and was achieved by applying a uniform 300 K temperature on the top surface of the TEG and a uniform 350 K temperature on the bottom surface. The investigations described in [24,25] attempt to model transient electrical behavior, while imposing fixed temperature boundary conditions on opposite sides of the TEG. Nguyen and Pochiraju [26] used a finite difference approach to predict the coupled thermal–electrical response of a TEG subjected to a transient heat source on one side of the device and natural convection on the other. Although the heating varied with time, it was applied uniformly over the surface of the TEG. The numerical predictions showed good correlation with test results, however, uniform heating was assumed and only one-dimensional heat conduction was considered. The temperature across the TEG was between 9 and 15 K, more than an order of magnitude larger than the temperature gradients expected when TEGs are used as detectors. For a TEG subjected to non-uniform heating there are lateral as well as transverse temperature gradients, so one dimensional models will not represent the temperature distribution over the entire TEG accurately. Other studies have used finite volume and computational models based on electrical analogies to model TEG transient behavior [27,28]. These models assume one dimensional heat transfer, which limits their usefulness for non-uniform heating cases. The models available in the open literature provide useful modeling strategies when the TEG is subjected to a uniform heat flux or uniform boundary temperature. Uniform heat flux cannot be assumed for many sensor applications. Additionally, for most sensor applications the TEG open circuit output voltage is of primary interest and Joule, Peltier and Thomson effects can be neglected. A coupled thermal–electrical modeling approach is not required. Instead the open circuit output voltage can be determined from the thermal gradient across each of the semiconductor elements that make up the TEG and the Seebeck coefficients of those elements. For sensor applications, especially those with the TEG supported by mounting hardware, a high fidelity three dimensional, transient heat transfer model can predict the temperature field over the entire TEG, allowing the open circuit output voltage to be determined from the model results and the Seebeck effect.

We investigated the consequences of non-optimal TEG mounting on sensor performance. We present a combined experimental and computational investigation of the transient behavior of a TEG subjected to spatially non-uniform heating, producing small temperature gradients of less than 0.5 K across its thickness. Such conditions can exist in some micropower energy harvesting situations and when TEGs are used as IR detectors. A finite element model of the time-dependent, three-dimensional heat flow in the TEG was developed. As an example of the significance of this study, we note that recent publications presented unusual and unexplained TEG output transients under some conditions when these devices were exposed to continuous broadband (CB) IR radiation [17–19]. For a particular TEG mounting geometry, after the device was exposed to CB-IR radiation the open circuit output voltage reached a peak after 15–36 s, which was followed by a decay [17–19]. The investigators claimed that IR power generation in a TEG is not equivalent to power generation by conductive and convective heat transfer [19]. Here we show that three-dimensional heat transfer by conduction does indeed produce TEG output transients similar to those produced by radiative heat transfer when a similar experimental geometry is used. Our model predicts that under some TEG mounting and heating conditions, the temperature gradient that develops across some of the semiconductor pellets of the device is negative. The thermal model in conjunction with the Seebeck effect is shown to explain the dependence of the transient TEG output on the mounting geometry.

Our findings have significant implications for researchers using TEGs as detectors in IR and heat sensing experiments. It is essential to consider the TEG mounting configuration and the TEG size relative to the size of the IR beam or other heat source. Furthermore, our findings also provide insight into possible consequences of non-optimal TEG mounting in energy harvesting applications.

2. Materials and methods

2.1. Experimental setup and procedures

The TEGs used for our experiments are Custom Thermoelectric model 07111-9L31-04B devices, the same type as used by the authors of [17–19]. They are 30 mm × 30 mm, 4.7 mm thick, and are constructed from 142 semiconductor pellets composed of doped Bi_2Te_3-based alloys, henceforth simply referred to as Bi_2Te_3. These pellets are