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# Optimal electrical load for peak power of a thermoelectric module with a solar electric application

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ABSTRACT

This paper builds upon the recent progress made in the field of thermoelectric energy conversion when using Bismuth Telluride $Bi_2Te_3$ semiconductor modules. These commercially available modules have been the subject of many recent studies in which the common goal is to better understand their thermoelectric behavior when converting a low cost heat source to electricity. The present experimental work investigates the thermopower properties of a single module relative to the electrical load resistance with the use of two experimental apparatuses. The first test stand is built with a precision control of the injection and rejection of heat to and from the module; the second test stand is a novel demonstration of the module's application to thermoelectric solar energy conversion. The thermopower characteristics of the module are measured over a wide range of thermal input conditions. The results highlight the importance in calibrating to an optimal electrical load for peak power output. A normalized thermopower theoretical evolution curve relative to load resistance is presented. Furthermore, a method of thermoelectric recovery of solar radiation is demonstrated using laboratory controlled working conditions.



## 1. Introduction

In order to investigate new methods of harnessing solar energy, thermoelectric modules are now being considered for its ability to convert solar radiation to electricity amongst other low cost heat sources [1–3]. Indeed, Refs. [4–7] outline the thermoelectric potential of vehicle exhaust, Ref. [8] describes a liquid-to-liquid thermoelectric generator for waste-heat recovery applications, Ref. [9] demonstrates a successful biomass cook stove application and Ref. [10] details the potential of a thermoelectric conversion of solar radiation. The thermoelectric recovery of solar energy has been tested by Ref. [11] in which heat resulting from solar radiation is conducted to a thermoelectric module through an aluminum bloc. In their study, it was shown that it is necessary to improve the concentration of solar radiation when applying it to the thermoelectric effect. To this end, Refs. [12,13] used Fresnel lens' to focalise an ensemble of solar rays onto the surface of a module. The shortcoming of their system was that the concentration of solar radiation was not evenly distributed over the surface of the module. In an effort to use the excess heat from photovoltaic solar panels, Refs. [14,15] placed thermoelectric modules adjacent to the panels. The coupling of these technologies is currently limited by the temperature gradient necessary for effective thermoelectric conversion. More recently, Ref. [16] combined thermoelectric technology with that of solar vacuumed tubes. In their study, the energy captured is driven to a single module via a heat pipe. Despite improving the available temperature gradient across the module, the relative geometries of the heat pipe and the thermoelectric module limit the available contact surface.

For these applications and many others, the semi-conductors Bismuth Telluride ($Bi_2Te_3$) were shown by Refs. [17–19] to be the most efficient materials for exploiting the thermoelectric phenomenon within the temperature range of 273–473 K. For this reason, many works focus on better understanding the thermoelectric characteristics of $Bi_2Te_3$ Refs. [20–23]. More recently, optimization methods for systems using thermoelectric modules inserted into a liquid-to-liquid generator were presented by Ref. [24] who showed that power output can be almost doubled with favorable inner turbulence and by Ref. [25] who showed that the thermoelectric peak power is very sensitive to the electrical load resistance and that the optimal load resistance is less than the internal resistance of the system. The importance in properly identifying the electrical load is detailed in discussions on Maximum Power Point Tracking (MPPT) in the thermoelectric works of Refs. [26–28].

The current experimental study builds upon the results of Ref. [25] by investigating the optimal electrical load resistance and its

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**Nomenclature**

| | | | |
|---|---|---|---|
| $A$ | contact area of a thermocouple pellet ($m^2$) | $P$ | power (W) |
| $H$ | hot side | $P^*$ | $P/P_{max}$ |
| $C$ | cold Side | $\dot{q}$ | thermal energy generation per unit volume ($W/m^3$) |
| $i$ | internal | $R$ | electrical resistance (Ω) |
| $I$ | electrical current (A) | $R^*$ | $R/R_i$ (Ω) |
| $L$ | load | $T$ | temperature (K) |
| $k$ | thermal conductivity W/m K | $V$ | voltage (A) |
| max | maximum | $V^+$ | $V/V_{oc}$, |
| $oc$ | open circuit | $\alpha_{p,n}$ | Seebeck coefficient (V/K) |
| $opt$ | optimal | $\rho$ | electrical resistivity (Ω m) |

related characteristics for a single thermoelectric module. In particular, the thermopower characteristics for varying temperature fields relative to an increasing electrical load are reported and discussed. To this end, a noncomplicated test apparatus is built in which a controlled heat input is applied to one side of a $Bi_2Te_3$ thermoelectric module and a controlled heat diffusion is maintained on its opposite side resulting is a stable thermal field across the module. Furthermore, a novel thermoelectric application to solar radiation is built and tested. Both test apparatuses are equipped with a rheostat which increases the electrical load yielding precision measurements of the optimal load relative to the internal electrical resistance. It is shown that: a varying temperature field has negligible effects on the ratio of the electrical load to internal resistance of the module; at peak power, the electrical load is strictly less than the internal resistance; identifying the optimal electrical load is necessary for peak thermopower.

## 2. Thermopower and electric load matching

The underlying physics of the present study pertain to the power output of a thermoelectric element relative to its electrical load resistance $R_L$. In particular, a better understanding of the relation between $R_L$ and the internal electrical resistance (noted $R_i$) is sought. For the purpose of the discussions that follow, a detailed account of the electromotive force generated by a semiconductor subject to a thermal field e.g. Refs. [29,30] is provided with a particular attention to the commonly used load matching result.

In order to generate the thermopower production known as the Seebeck effect, crystalline structured semiconductors are doped such that n type semiconductors favor negative charge carrier mobility and p type semiconductors favor positive charge carrier mobility. This is best accomplished by combining two chemical elements for which the difference in the number of their respective valence electrons is one. In this way, through a natural mutual attraction, the resultant crystalline lattice either has a single "free" valence electron in the outer shells of its atoms or a "hole" in the outer shells of its atoms depending on how they are doped. The "free" single valence electrons easily migrate to neighboring atoms and are referred to as negative charge carriers. Conversely, the "holes" attract electrons from neighboring atoms thereby transferring the location of the "hole" and are referred to as positive charge carriers. For example, in this study, the chemical elements Bismuth and Tellurium, having five and six valence electrons respectively, are combined into the crystalline structure $Bi_2Te_3$. The resultant material, when subject to a difference in temperature at its extremities, produces an electromotive force which mobilizes charge carriers from a hot pole to a cold pole. As illustrated in Fig. 1, by coupling a negatively doped material with a positively doped material, an electric circuit can be created in which the charge carrier flow direction is unilateral.

The conservation of energy of the closed system and Fourier's law of conduction requires that the one dimensional form of the heat equation for the thermalcouple illustrated in Fig. 1, be of the form

$$\frac{d}{dx}\left(k\frac{dT}{dx}\right) - \dot{q} = 0 \tag{1}$$

in which $\dot{q}$ is the thermal energy generation per unit volume.

In assuming isotropic properties and equalized contact surfaces on the cold and hot side, Ohm's Law reduces the one dimensional heat equation to,

$$\frac{d^2T}{dx^2} + \frac{I^2\rho}{kA^2} = 0 \tag{2}$$

in which $\rho$ and $k$ are the electrical resistivity and the thermal conductivity respectively of the material, $I$ is the electrical current and $A$ is the contact surface. It is important to note that the sign change in the second term of Eq. (2) is due to the fact that the system's conversion of thermal to electrical reduces its total thermal energy. Furthermore, the calculation of the thermoelectric power of this study, the Thomson effect (which relates the passage of current in an electrical conductor subject to a thermal dipole to the reversible heat) is considered to be negligible. This effect is commonly neglected in low temperature thermoelectric applications Ref. [30]. Indeed, the Kelvin relationship states that the Thomson coefficient is proportional to the rate of change of the material's Seebeck coefficient with respect to temperature. As previously stated, the material properties in the present work are considered isotropic. Furthermore, the linear profile of the forthcoming electric tension

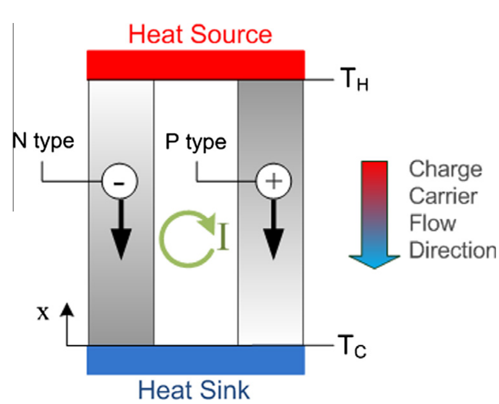


**Fig. 1.** Charge carrier flow direction for a thermocouple with n type and p type pellets in parallel.