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Solar thermoelectric generator performance relative to air speed

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ABSTRACT

The electrical characteristics of a solar thermoelectric generator (STEG) are measured. The STEG device is novel in that it requires no external pumps such as a water refrigeration unit to maintain a thermal differential. The heat source is simulated solar radiation heating a double walled evacuated tube. The heat sink is a CPU cooler subjected to simulated wind energy. The peak power performance of the STEG for a fixed heat input and a varying forced convection brought upon by the artificial wind is reported. The STEG's thermoelectric power output under naturally occurring solar and wind energy is also reported. A discussion on the thermoelectric effect presents experimental results showing the effect of varying the circuit's load resistance on a Bi_2Te_3 module's electromotive force, electrical resistance, and thermal resistivity.

1. Introduction

The increasing demand for electricity across the world – which is a consequence of the development of nations, population growth and industrialization – has been driving efforts towards electrical energy availability and supply. The International Energy Agency [1] reports that there are, approximately, 1.4 billion people in the world without access to electricity. For these people, as well as for people that live in areas where the power grid is not reliable [e.g., 2], off-grid Solar thermoelectric generators (STEGs) are an alternative method of converting solar energy to electrical energy [e.g., 3–8]. Indeed, Xi et al. [9] reports that thermoelectric devices can convert solar thermal energy from a temperature difference into electric energy in an effort to meet the demand for energy conservation.

To this end, Omer and Infield [10,11] argue that the design goal for thermoelectric generators is to improve the power output per unit material. This is accomplished through thermal system management of the heat source and heat sink with the aim of maintaining the thermal differential driving the thermoelectric effect. As demonstrated by Kraemer et al. [12], for solar energy applications this can be achieved by concentrating the solar radiation so as to create a high temperature gradient across the thermoelectric device. Baranowski et al. [13] demonstrated that STEGs can be designed by embedding commercially available semiconductor materials. These semiconductor materials are packaged into an alternating array of positively and negatively doped elements – referred to as a thermoelectric module (TEM). The application of these modules to excess heat sources to generate an electric potential is fully described in the works of [14–19] – among others.

In an early investigation into STEG technology, Telkes [20] evaluated the optimum characteristics of flat-plate solar collectors for thermoelectric energy conversion. Similarly, Goldsmid et al. [21] went on to combine the glass plate design with aluminum blocks which acted as thermal vehicles to and from a TEM. The thermal diffusion into the ambient air was shown to limit the STEG to negligible power output results. This lead to solar concentrator STEG systems requiring liquid refrigeration units [e.g., 22] to maintain the thermal difference across the system's embedded TEM. Commercially available TEMs used in most solar thermoelectric devices in the open literature use Bismuth Telluride semiconductor

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Nomenclature

Symbol	Description (Unit)
I	electrical current (A)
P	power (W)
$\dot{q}$	thermal energy generation per unit volume (W/m^3)
R	electrical resistance (Ω)
R_s	source electrical resistance (Ω)
R_s^*	R_s/R_L (–)
R_T	thermal resistivity (m K/W)
R_L	circuitry electrical load resistance (Ω)
STEG	solar thermoelectric generator (–)
TEM	thermoelectric module (–)
V	voltage (A)
v	air speed (m/s)

Greek letters

ε	electromotive force (V)
μ	R_T/R_s (m K/W Ω)

Subscripts

F	fixed (–)
L	load (–)
max	peak power (–)
s	source (–)
V	variable (–)

materials since they have been shown by [23] and others to have the highest conversion efficiency for the operating temperatures of STEGs. The cost effectiveness of including these materials into solar thermoelectric generators is discussed in [5,12].

Durst et al. [24] developed a solar thermoelectric apparatus which is able to generate thermal and electric power. The system consists of a parabolic trough concentrator acting as a heat source for a thermoelectric module and a heat sink consisting of circulating water. In this way, the STEG's embedded TEM mobilizes charge carriers due to the thermal dipole generated by the heat sink and the heat source and acts as a heat pump yielding hot water as a desired by-product. Similar solar concentrator set-ups using a water driven refrigeration system or other external pumps have also been investigated by Hasan et al. [25].

With regards to the optimizing of the thermal system strategy of the STEG, Li et al. [26] numerically investigated the heat loss rates of a STEG apparatus under varying operating conditions. In Li et al.'s work, natural convection was identified as a critical heat sink mechanism for maintaining the thermal dipole of a thermoelectric device. Chen [27] analytically investigated the performance characteristics of a class of STEGs in order to develop performance bounds on working parameters such as the electrical load. Target STEG applications have been modeled in works such as those of [28–30].

The difficulties in STEG operation lie in the heat sink often yielding an adverse pumping penalty. Indeed, STEG devices such as those of He et al. [31,32] operate with a water circulation system requiring an external pump for which the required pumping power is not offset by the generated thermoelectric power output. What is needed is an autonomous STEG apparatus which operates solely on solar and wind energy. To this end, Trinh et al. [33] investigated the thermoelectric characteristics of a STEG apparatus in which the heat source was a solar evacuated tube exposed to 804.1 W/m^2 and the heat sink was a CPU cooler exposed to a wind speed of 1.72 m/s. The present work evaluates the thermoelectric characteristics of the evacuated tube STEG under varying wind speeds. Furthermore, the thermoelectric characteristics due to load circuitry of an individual Bismuth Telluride thermoelectric module are reported and discussed.

2. The thermoelectric effect

The Seebeck effect is a phenomenon in which electrical charges are mobilized by the flow of heat in an asymmetric thermal field. The resulting flow of positive and negative charges is in the same direction as the heat flow. For this reason, in practice, positively doped and negatively doped semiconductor materials are combined in an alternating array in order to generate an electrical current in a circuit. This is illustrated in Fig. 1 which presents the electrical circuit used in the present work's experimental set-ups.

Applications of the thermoelectric phenomenon require thermal system management in which the maximum power output is obtained. This is of particular importance when operating a thermoelectric module under varying operating conditions requiring a power point tracking system [e.g., [36–38]]. The maximum thermoelectric power output operating conditions for a thermoelectric module are deduced from the one-dimensional heat equation which is fully described in [39]. Considering an idealized one dimensional thermal differential acting on a thermocouple of negatively and positively doped materials – as illustrated in Fig. 1 – the thermoelectric effect mobilizes the charge carriers thereby driving an internal electromotive force. This electromotive force, noted ε, generates en electric current I. Considering the source resistance (R_s) of the thermocouple's materials, the thermal energy generation transfer rate is simply

$$\dot{q} = -I^2 R_s. \tag{1}$$

By considering the hot and cold side temperatures of the thermocouple as boundary conditions and applying Ohm's law in the absence of the Thomson effect, the one-dimensional heat equation generates a temperature profile the length of the thermocouple. As detailed in [33] the heat balance at the hot and cold junctions generates a system of equations which reduces to a thermoelectric power generation of

$$P = \varepsilon^2 \frac{R_L}{(R_L + R_s)^2} \tag{2}$$

in which R_L is the load resistance of the electric circuit.

In order to solve for the peak power output conditions, Eq. (2) is differentiated and set to zero while considering the electrical load as the independent variable. All other terms are considered dependant of R_L yielding,

$$\varepsilon\left(R_s - R_L\left(2\frac{dR_s}{dR_L} + 1\right)\right) + 2R_L(R_s + R_L)\frac{d\varepsilon}{dR_L} = 0. \tag{3}$$

Defining the normalized source resistance as $R_s^* = R_s/R_L$, Eq. (3) reduces to,

$$2\frac{1}{\varepsilon}\frac{d\varepsilon}{dR_L} = \frac{1}{R_L} + \frac{2}{1 + R_s^*}\frac{dR_s^*}{dR_L}. \tag{4}$$

Solving the ordinary differential equation yields an electromotive force related to the load resistance and the internal source resistance,