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Solar thermal energy conversion to electrical power

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HIGHLIGHTS

- Solar radiation maintains a thermal tension which drives an electromotive force.
- Voltage, current and electric power are reported and discussed.
- Theoretical optimal thermoelectric conversion predictions are presented.
- Theory is validated with experimentally measured data.

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ABSTRACT

The conversion of solar energy to electricity currently relies primarily on the photovoltaic effect in which photon bombardment of photovoltaic cells drives an electromotive force within the material. Alternatively, recent studies have investigated the potential of converting solar radiation to electricity by way of the Seebeck effect in which charge carrier mobility is generated by an asymmetric thermal differential. The present study builds upon these latest advancements in the state-of-the-art of thermoelectric system management by combining solar evacuated tube technology with commercially available Bismuth Telluride semiconductor modules. The target heat source is solar radiation and the target heat sink is thermal convection into the ambient air relying on wind aided forced convection. These sources of energy are reproduced in a laboratory controlled environment in order to maintain a thermal dipole across a thermoelectric module. The apparatus is then tested in a natural environment. The novelty of the present work lies in a net thermoelectric power gain for ambient environment applications and an experimental validation of theoretical electrical characteristics relative to a varying electrical load.

1. Introduction

Innovations in the field of solar energy conversion to electricity using the thermoelectric effect have increased in recent years. The main body of these works focus on hybrid photovoltaic–thermoelectric systems [e.g., Refs. [1–7]] and on devices solely relying on the thermoelectric effect – commonly referred to as Solar Thermoelectric Generators (STEGs) [e.g., Refs. [8–13]].

The goal of the thermoelectric–photovoltaic hybrid investigations is to convert excess unwanted heat resulting from the thermophotovoltaic effect (energy not absorbed by the photovoltaic cell's band gap is converted to heat [e.g., Ref. [14]]) into electricity. This is accomplished using thermoelectric modules which have embedded doped semiconductors capable of generating an electromotive force from a thermal differential. This thermoelectric phenomenon and its application to other waste-heat recovery uses are described in detail in Refs. [15–20] among others.

The present work focuses on the thermoelectric conversion of solar energy without the use of photovoltaic materials. In this case, an asymmetric thermal field ideally creates a thermal dipole across a devices' embedded thermoelectric module in which solar radiation provides the heat source. Early investigations in the field of Solar Thermoelectric Generators (STEGs) used a radiation concentration

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Nomenclature

A	cross-sectional area, m^2
I	electrical current, A
I^*	I/I_{opt}
L	thermopellet length, m
m	mass, kg
k	thermal conductivity, W/m K
P	power, W
P^*	P/P_{opt}
q	heat transfer rate, W
$\dot{q}$	thermal energy generation per unit volume, W/m^3
R	electrical resistance, Ω
R^*	R/R_i,
T	temperature, K
TEM	thermoelectric module
V	voltage, A
V^*	V/V_{opt}

Greek letters

α	seebeck coefficient, V/K
$\alpha_{p,n}$	$\alpha_p - \alpha_n$
ΔT	$T_H - T_C$, K
ρ	electrical resistivity, Ω m

Subscripts

C	cold junction
H	hot junction
i	internal
L	load
oc	open circuit
opt	optimal
n	N-type material
p	P-type material

technique via heated aluminium blocks. For example, Goldsmid et al. [21] injected heat to the hot side of a thermoelectric module by thermal conduction through an aluminium block exposed to the sun. The thermal differential across the module was maintained by dissipating heat through natural convection into the ambient air. In their study, they found that a greater concentration of solar energy and a greater conversion efficiency was needed to improve system thermal input. To this end, Rowe [22] investigated the optical efficiency of a silicon–germanium thermoelectric module, Chen [23] developed a thermodynamic model to investigate the optimal performance of STEGs, Lenoir et al. [24] evaluated the electrical properties of STEGs based on the mineral skutterudite for possible aerospace applications, Bomberger et al. [25] investigated the effects of varying thermal input conditions on thermoelectric module performance for solar and other applications, Jang and Tsai [26] analysed the optimal module spacing for solar applications, and Weinstein et al. [27] showed that thin-film STEGs have a similar conversion efficiency to that of existing bulk material STEGs. Furthermore, design optimization of a STEG's embedded thermoelectric modules has been investigated by Wang et al. [28], Inagoya et al. [29], Bhardwaj [30], Xiao et al. [31], Al-Merbati et al. [32] and Ali et al. [33] among others.

In an effort to enhance the thermal input due to the harnessed solar radiation, Vatcharasathien et al. [34] used compound parabolic collectors to increase the heat source to a series of sixteen thermoelectric modules and a refrigeration unit as a heat sink. The energy consumption however of the refrigeration unit offset any thermoelectric power gain. Similarly, Mgbemene et al. [35] used compound parabolic concentrators to enhance the solar radiation heat source to the thermoelectric module but used a simple fan and ambient air for cooling purposes. The thermoelectric conversion efficiency of their device was reported to attain a maximum of 0.24%. Solar concentrators can also be used to supply heat to a thermoelectric cogeneration system (TCS) [e.g., Refs. [36,37]].

Yazawa et al. [38,39] used Fresnel lenses to further concentrate the solar radiation heat applied to the module and pumped cold water to the cold side of the module in order to enhance thermal transport of the heat sink. In doing so they effectively increased the thermal dipole yet the cold water flow refrigeration cost offset the thermoelectric power gain. Furthermore, the disadvantage to concentrator lenses is that they increase the total area of operation of the device thereby compromising the system's output per unit area.

Since thermoelectric power output increases exponentially with respect to the thermal dipole of the asymmetric thermal field in which it is subjected to [e.g., Ref. [40]], He et al. [41,42] stocked solar radiation in evacuated solar tubes in order to further increase the thermoelectric module's heat source side temperature. Solar tubes effectively capture solar radiation by heating a gas embedded in the tube which is insulated by a vacuum double walled outer encasing. A performance evaluation of these tubes is provided in Refs. [43–45] showing that they are capable of capturing solar radiation up to an 80% efficiency. With these tubes, He et al. [41,42] channelled solar thermal energy from the natural Sun to the hot side of a single thermoelectric module. The thermal differential across the modules was maintained by pumping cold water to the heat sink side of the module. In their study, a solar energy to electrical energy conversion efficiency ranging from 0.6% to 1.5% was reported without accounting for the pumping penalty associated with the work done to channel cold water to the heat sink. Similarly, Zhang et al. [46] used solar tubes to apply heat to a set of thermoelectric modules refrigerated with cold water forced convection providing a hot water by-product. In their configuration, the device's thermoelectric production partially offsets the pumping cost.

The difficulties in the current state-of-the-art in solar thermoelectric generators lie in the power cost of the heat sink. The most promising heat source for STEG power generation reported in the afore mentioned literature is that which captures solar radiation with evacuated solar tubes. However, currently tested devices use water cooling systems at the heat sink which require costly hydraulic power.

In an effort to alleviate this adverse pumping penalty, the present work presents an apparatus that effectively converts solar radiation to electricity without relying on an external water pump for cooling. In this investigation, solar energy is captured and stocked in a double walled vacuum insulated solar tube. This harnessed thermal energy is driven towards one side of a thermoelectric module by way of an embedded copper cylindrical tube. The cold side of the module is cooled by dissipating heat into the ambient air with the use of a CPU heat exchanger and a ventilation simulating wind assisted forced convection. The resultant thermal dipole generates an electromotive force in the embedded Bismuth Telluride Bi_2Te_3 semiconductors. This material is used in the present study since it has been shown to be the most effective thermal to electric conversion material for the present work's target temperature range of 40–120 °C [e.g., Ref. [47]]. The apparatus is then used in a field test study in which the heat source and the heat sink are naturally occurring solar radiation and wind aided air convection respectively.