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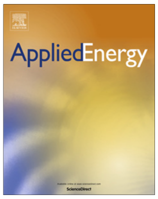

Power and mass optimization of the hybrid solar panel and thermoelectric generators

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HIGHLIGHTS

- The dynamics of the hybrid PV/TEG system operating in outer space is studied.
- A generalized thermodynamic model of the hybrid PV/TEG system is given.
- This model is then simplified to consider the outer space scenario.
- The design of the hybrid PV/TEG system is optimized using the NSGA-II algorithm.
- The optimized hybrid system is more efficient than its monolithic counterparts.

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ABSTRACT

The thermoelectric generator (TEG) has been widely considered as an electrical power source in many ground applications because of its clean and noiseless characteristics. Moreover, the hybrid photovoltaic cell and TEG (PV/TEG) system has also received wide attention due to its improved power conversion efficiency over its monolithic counterparts. This paper presents a study of the dynamics and the operation of the hybrid PV/TEG system in an outer space environment where a unified thermodynamic model of this system is presented. Moreover, the multi-objective NSGA-II genetic algorithm is utilized to optimize the design of the TEG both in terms of optimal output power and in terms of mass. Specifically, the design of the single stage and the two stage variant of the aforementioned TEG are considered. Simulation results indicate that the optimized PV/TEG system does indeed achieve better efficiencies than that of the monolithic counterparts. Furthermore, it is shown that the single stage TEG is more beneficial than the two stage TEG in terms of achieving optimal performance.

1. Introduction

Thermoelectric generators (TEG) have widely been studied in literature as an effective robust, clean and noiseless electric power generator [1–6]. A popular example of the use of the TEG for power generation is in the automotive industry where the TEG can extract electrical power from the vehicle exhaust [7–9]. In addition, the same TEG is popularly used for cooling or heating purposes by the principle of Peltier cooling [10–14].

Unfortunately, the practicality of TEGs is currently limited mainly because of its relatively low conversion efficiency from heat to electricity. The performance of the TEG is often characterized by the figure of merit $ZT = \frac{\alpha\sigma}{\lambda}T$ where a higher Z means a higher TEG performance. α, σ and λ are respectively the Seebeck Coefficient, electrical conductivity and thermal conductivity of the material used in the thermocouples that generate electricity from heat. Because these parameters are all material dependent parameters, this has motivated ongoing research to find new materials that maximize α and σ while minimizing λ and hence maximizing Z [15–21]. State of the art materials used for the TEG thermocouples include bismuth telluride [15,19], a material with optimized performance at room temperature, lead telluride [16] and skutterudites [18]. Recently, researchers have even found a new class of materials known as nanostructured materials which is found to achieve an even better ZT performance [20,21].

In the meantime, other researchers have also focused on the geometric aspects of the TEG design [22–29]. In [29], a two stage thermoelectric generator was proposed and an optimization process of the geometric characteristics of such a TEG was provided. From many of these analyses, it is shown that the efficiency of the TEG is influenced by the area, length and the number of

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Nomenclature

α	Seebeck Coefficient (V/K)
σ	electrical conductivity (S/m)
λ	thermal conductivity (W/(mK))
ε	surface emissivity
I	operating current (A)
I_{sc}	short circuit current of the solar panel (A)
I_{PV}	photovoltaic current of solar panel
I_0	dark current of solar panel
I_{TEG}	current generated by the TEG (A)
V	operating voltage (V)
V_t	thermal voltage (V)
a	ideal diode constant of the solar cell
T	temperature (K)
T_{Solar}	temperature of core of solar cell (K)
V_{ocN}	open circuit voltage of the solar cell (V)
I_{scN}	short circuit current of the solar cell (A)
K_i	temperature coefficient of the current of the solar cell (A/K)
K_v	temperature coefficient of the voltage of the solar cell (V/K)
$V_{oc(TEG)}$	open circuit voltage of the TEG (V)
$I_{sc(TEG)}$	short circuit current of the TEG (A)
I^*_{TEG}	the quantity of current flowing through the TEG which obtains the optimal TEG power output (A)
R	electrical resistance (Ω)
R_{TEG}	total internal electrical resistance of the TEG (Ω)
R_{Ck}	electrical contact resistance of the TEG thermocouples to its electrical interface
G	input sunlight irradiance (W/m^2)
G_N	input sunlight irradiance to solar cell at nominal conditions (W/m^2)
n_p	number of solar cells in parallel
n_s	number of solar cells in series
n_k	number of thermocouples present in the kth TEG stage
η_{In}	optical efficiency of input surface of TEG
A	surface area (m^2)
T_H	temperature of the reservoir at the input side of the hybrid PV/TEG system
T_L	temperature of the reservoir at the output side of the hybrid PV/TEG system
Q_{irr}	input sunlight power to the surface of the solar cell (W)
Q_e	radiated heat at the input portion of the hybrid assembly (W)
Q_r	radiated heat at the output portion of the hybrid assembly (W)
Q_{FromS}	the heat that is transferred to the TEG via the solar cell
Q_{ToTEG}	the heat that enters the TEG thermocouples
$Q_{TCIn}(k)$	a function describing the heat flow into the kth common interface of the TEG (W)
$Q_{TCOut}(k)$	a function describing the heat flow out of the kth common interface of the TEG (W)
$Q_i(k)$	heat conduction through the supportive material of the TEG
Q_{SP}	solar cell electrical power output (W)
Q_{TEG_P}	TEG electrical power output (W)
κ	convection coefficient (W/(m^2 K))
F	specific power (W/kg)
r	TEG outlet to inlet ratio
P	the population vector for the NSGA-II algorithm
R	the offspring population vector for the NSGA-II algorithm

Subscripts and superscripts

k	an index variable indicating the kth term of either the temperature of a surface in the TEG or the kth TEG stage
s	refers to the properties of the solar cell
t	refers to the properties of the TEG
In	refers to properties at the inlet of the TEG
Out	refers to properties at the outlet of the TEG
p	p-type type thermopile
n	n-type type thermopile

Abbreviations

TEG	thermoelectric generator
RTG	radioisotope thermoelectric generator
NSGA-II	non-dominated sorting genetic algorithm II
PV	photovoltaic
Mat	an identifier integer for identifying the type of material for the thermocouples.

Numerical constants

$\gamma = 5.670373 \times 10^{-8}$ W m^{-2} K^{-4} the Stefan–Boltzmann constant
$k_B = 1.3806503 \times 10^{-23}$ J/K Boltzmann constant
$q = 1.602 \times 10^{-19}$ C one electron charge

thermocouples. Furthermore, the efficiency is also influenced by increasing the convective heat transfer at the outlet of the TEG. In a more recent study, [3] presented an analytical solution to the temperatures at each surface of the TEG although the solution involves very complex expressions and is also applicable to a single stage TEG with only the heat reservoirs as the source and sink. In [26,27], analytical models that describe series and parallel connected TEG modules were proposed. This is essentially the equivalent of analyzing an equivalently large sized single TEG. These models also required many assumptions such as constant thermoelectric properties and constant internal resistance amongst the TEG modules.

By realizing the waste heat generated by photovoltaic (PV) cells during operation, some researchers have also considered using TEGs to further extract electrical energy from such waste heat. Such a configuration is known as the hybrid PV/TEG system and has been a major subject of research in recent years [25,30–35]. In [33], a novel spectral beam splitter was utilized to split the sunlight into two spectrums – One within the high spectral response of the solar cell of interest which of course, is given directly to the solar cell itself and the remaining portion is redirected to a TEG device. In [36], a genetic algorithm was used to optimize the performance of the hybrid PV/TEG system although it is in terms of active Peltier cooling rather than TEG power generation. TEGs are also found to have improved performance when combined with a concentrated PV cell (CPV) because of the typical large heat generated by such systems [32,34,35]. A mathematical model of the hybrid PV/TEG system was also presented in [25] although it is based on a single stage TEG and it also relies on analytical solutions which require assumptions on certain parameters.

Despite the rich literature on the utilization of TEGs for ground applications, the analysis and usage of TEGs in an outer space environment has not been as widely considered. As of the state of the art, TEGs in outer space are popularly in the form of radioisotope thermoelectric generators (RTG) [37–39]. Such a technology utilizes a nuclear source to provide the heat required for electric power generation. An obvious disadvantage of the RTG is the limitations of the finite energy source.