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A comprehensive design method for segmented thermoelectric generator

Guobin Zhang, Linhao Fan, Zhiqiang Niu, Kui Jiao *, Hai Diao, Qing Du, Gequn Shu

State Key Laboratory of Engines, Tianjin University, 92 Weijin Rd, Tianjin 300072, China

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ABSTRACT

A comprehensive method for indicating the length ratio of segmented thermoelectric generator (TEG) is proposed to increase the output power and thermoelectric conversion efficiency. It is found that for a segmented TEG, there is an optimal length ratio corresponding to the highest maximum output power or thermoelectric conversion efficiency, which is not only dependent on the material properties but also the heat transfer conditions and geometry structure. The optimal length ratios corresponding to the output power and thermoelectric conversion efficiency are different. This method is also validated, and the error is within a reasonable range, indicating that this method can be used accurately and time-efficiently for the design of segmented TEGs.

1. Introduction

Thermoelectric generator (TEG) is an environmentally friendly energy conversion device that converts thermal energy into electrical energy directly. It has many merits such as compact design, high reliability and zero emission. Due to the increasing demand on energy saving, TEG received considerable attention for waste heat recovery in many major energy conversion devices. For example, Karri et al. [1] applied quantum-well (QW) based TEGs for the waste heat recovery of a sports utility vehicle (SUV) and a generator set, and by using the TEGs, the fuel consumption rates were reduced by about 2% and 3%, respectively; and Yilbas and Sahin [2] combined a TEG with a refrigerator, by investigating the effect of TEG location on the performance of the combined system, they showed that it is promising to place the TEG with the condenser.

The main problem of TEG is the low thermoelectric conversion efficiency, which limits its application. The thermoelectric conversion efficiency of a thermoelectric material depends on the value of figure of merit (Z), and generally, the thermoelectric conversion efficiency increases with the increment of Z [3]. In addition, the geometry of the TEG units and modules, and the heat transfer conditions on the hot and cold sides, all have significant effects on the performance.

One direction is to optimize the design of TEG units and modules, together with heat transfer enhancement on the hot and cold sides. Lavric [4] found that there exists an optimal length of a TEG to maximize the power density. Meng et al. [5] found that the output power and the thermoelectric conversion efficiency might be improved significantly if the semiconductor number, leg length and other geometrical parameters could be optimized. Geometry optimization of TEG was also carried out by Ali et al. [6]. To investigate the heat transfer effects, Liang et al. [7] found that for the waste heat recovery of internal combustion engine exhaust, the effect of heat source temperature is greater than that of the cold source. By using fins for heat transfer enhancement, Jang et al. [8] concluded that both the output power of TEG and the extra pumping power of flow increase with the increment of the height and number of fins, and there is an optimal combination of height and number of fins to obtain the highest net power output. Gou et al. [9] developed a mathematical model to study the dynamic characteristics of TEGs and found that the fluctuation of heat source could result in rapid change of the output power, which is unfavorable for powering electronic devices.

Rather than design optimization and heat transfer enhancement, development of thermoelectric materials to improve the thermoelectric properties is another research direction for TEG. Matsubara [10] found that the thermoelectric conversion efficiency could reach about 6–8% by using Co-doped Bi_2Te_3 thermoelectric units. Brown et al. [11] developed a complex Zintl compound $Yb_{14}MnSb_{11}$, which represents the first complex Zintl phase with high ZT (~1.0 at 1223 K). By adding CeO_2 and Dy_2O_3 to ZnO, Park et al. [12] found that the power factor ($\alpha^2\sigma$ ($W\,m^{-1}\,K^{-2}$), where α ($V\,K^{-1}$) is the Seebeck coefficient, and σ ($S\,m^{-1}$) is the electrical conductivity) of $Zn_{0.995}Dy_{0.005}O$ is much higher than that of ZnO.

* Corresponding author. Tel.: +86 22 27404460; fax: +86 22 27383362.
E-mail address: kjiao@tju.edu.cn (K. Jiao).

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Nomenclature

A_1	contact area of heat source and the top side of the segmented TEG unit (m^2)
A_{2p}	cross-sectional area of the p-type leg (m^2)
A_{2n}	cross-sectional area of the n-type leg (m^2)
A_{3p}	contact area of heat sink and the copper connecting to the p-type leg on bottom side of the segmented TEG unit (m^2)
A_{3n}	contact area of heat sink and the copper connecting to the n-type leg on bottom side of the segmented TEG unit (m^2)
E	total electrical potential (V)
h_1	constant heat transfer coefficient between the segmented TEG unit and heat source ($W\,m^{-2}\,K^{-1}$)
h_2	constant heat transfer coefficient between the segmented TEG unit and heat sink ($W\,m^{-2}\,K^{-1}$)
I	electric current (A)
l	total length of the p-type (n-type) leg (m)
m	a variable reflecting the geometry structure and heat transfer condition of the segmented TEG unit ($m\,K\,W^{-1}$)
P	output power (W)
Q_{total}	heat transfer rate in the segmented TEG unit (W)
Q_p	heat transfer rate in the p-type leg (W)
Q_n	heat transfer rate in the n-type leg (W)
Q_J	heat generation rate by Joule effect (W)
Q_T	heat generation rate by Thomson effect (W)
Q_{hot}	heat transfer rate absorbed from the heat source (W)
Q_{cold}	heat transfer rate released to the heat sink (W)
R	thermal resistance ($K\,W^{-1}$)
R_1	thermal resistance between the segmented TEG unit and heat source ($K\,W^{-1}$)
R_8	thermal resistance between the segmented TEG unit and heat sink ($K\,W^{-1}$)
R_p	total thermal resistance of the p-type leg ($K\,W^{-1}$)
R_n	total thermal resistance of the n-type leg ($K\,W^{-1}$)
R_{total}	total thermal resistance of the segmented TEG unit ($K\,W^{-1}$)
r	internal resistance (Ω)
S_T	source term of the steady-state conservation of energy ($W\,m^{-3}$)
S_s	source term of the conservation of the Seebeck potential ($V\,m^{-2}$)
T_h	temperature of heat source (K)
T_c	temperature of heat sink (K)
T_1	temperature of the top surface of the segmented TEG unit (K)
T_{2p}	temperature of the interface of $p1$-type and copper on top side of the segmented TEG unit (K)
T_i	temperature of the interface of two semiconductor materials (K)
T_{ip}	temperature of the interface of $p1$-type and $p2$-type (K)
T_{in}	temperature of the interface of $n1$-type and $n2$-type (K)
T_{3p}	temperature of the interface of $p2$-type and copper on bottom side of the segmented TEG unit (K)
T_{2n}	temperature of the interface of $n1$-type and copper on top side of the segmented TEG unit (K)
T_{3n}	temperature of the interface of $n2$-type and copper on bottom side of the segmented TEG unit (K)
T_4	temperature of the bottom surface of the segmented TEG unit (K)
V_{ohm}	Ohmic potential (V)
V_s	Seebeck potential (V)
Z	figure of merit (K^{-1})
$(ZJ)_p$	new power factor ($W\,m^{-1}\,K^{-2}$)
$(ZJ)_e$	new efficiency factor (K^{-1})

Greek letters

α	Seebeck coefficient ($V\,K^{-1}$)
δ	thickness (m)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
ρ	electrical resistivity ($m\,\Omega$)
σ	electrical conductivity ($S\,m^{-1}$)

Subscripts and superscripts

c	cold side of segmented TEG
cal	calculated value
cu	Copper
h	hot side of segmented TEG
highest	the highest value
J	Joule hot
n	n-type
$n1$	$n1$-type
$n2$	$n2$-type
ohm	Ohmic potential
p	p-type
$p1$	$p1$-type
$p2$	$p2$-type
x	the amended values

Butt et al. [13] found that Pb-doping of $(Ca_2CoO_3)_{0.62}(CoO_2)$ could further increase the value of figure of merit.

Although great efforts have been made by researchers on the development of new materials, immediate breakthrough is still difficult. On the other hand, the design optimization mentioned previously based on presently available materials becomes significantly important. It is well known that the presently available semiconductor materials all have their own favorable temperature range to achieve the best performance, however, in real applications, for example, the waste heat recovery of internal combustion engines, significantly large temperature difference exists between hot and cold sides, and almost no single material could work properly in such large temperature ranges. Segmented TEG design is one of effective ways to deal with this problem, by having different materials along the heat transfer direction to fit optimal temperature range of each material [14]. It was already reported that proper segmented design of TEG could significantly improve the power density comparing with the corresponding single-material TEGs [15].

Appropriate material selection is needed for segmented TEGs. Snyder [16] found that segmentation of $(AgSbTe_2)_{0.15}(GeTe)_{0.85}$ (TAGS) with SnTe or PbTe could only produce little extra power, while filled skutterudite could increase the efficiency from 10.5% to 13.6%. Ngan et al. [17] showed that segmentation might even decrease the total efficiency without taking into account the compatibility of thermoelectric materials.

Therefore, to understand the heat and mass transfer characteristics, and for proper design optimization of TEGs, many numerical and analytical models have been developed. Crane and Jackson [18] developed a numerical model for an integrated thermoelectric heat exchanger in a cross flow configuration. Based on the results of the numerical model, for a modestly sized heat exchanger, the net power density based on heat exchanger volume could reach about 45 $kW\,m^{-3}$. In the model of Chen et al. [19], the external