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Thermo-element geometry optimization for high thermoelectric efficiency

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ABSTRACT

The figure of merit of thermoelectric materials is temperature dependent, and thus the local compatibility factor changes significantly along the thermo-element length. A local optimization method to maximize the efficiency of a function graded thermoelectric generator was proposed and discussed in this paper. By adjusting the cross-sectional area and segment's thickness, the reduced current equaled the compatibility factor of the material at every local thermo-element layer. This method can use the full potential of existing materials by maximizing the efficiency at every local thermo-element segment. For such a TEG working in a temperature range of 300–1100 K, the efficiencies of P-type segmented $Bi_{0.5}Sb_{1.5}Te_3$/BiSbTe/-PbTe/FeNbSb thermo-element and a N-type segmented $Bi_2Te_{2.79}Se_{0.21}$/$Bi_2Te_{2.9}Se_{1.1}$/SnSe/SiGe thermo-element were 25.70% and 21.73%, respectively, much higher than the conventional segmented thermo-elements. The overall efficiency of the device was more than 23.72%, making it a promising technology to harvest energy from medium and high-temperature industrial components. The optimized TEG can be fabricated by SLS/SLM technology.

1. Introduction

1.1. Segmented TEG for high energy conversion efficiency

Waste heat recovery from industrial process presents tremendous opportunities for energy savings across the industrial sectors, such as vehicle exhaust, power station, iron and steel manufacturing [1]. Thermoelectric energy conversion is a solid-state energy conversion technology using electrons and phonons as the virtual “working fluids”. The efficiency of an ideal TEG is governed by its figure of merit ($ZT = \alpha^2 T/\kappa\rho$), where α is the Seebeck coefficient, ρ is the electrical resistivity, and κ is the thermal conductivity [2–6]. Generally, the efficiency of a TEG made by homogeneous materials is less than 10%, since no single material can achieve a high efficiency in a wide temperature range. It is believed that one of the most promising ways to increase the efficiency of the TEG is to fabricate inhomogeneous materials and structures, such as segmented/cascaded TEGs [7–9] and FGTM [6,10–12]. Currently, the best single-material-based TEG has an energy conversion efficiency of 16.4%, using skutterudites at a temperature difference of 500 K [13]. And the use of three-stage cascade-type TE modules could yield an overall energy conversion efficiency of 19.6% with the hot end temperature of 1200 K [9].

A typical segmented TEG (Fig. 1) consisting of low-, medium-, and high-temperature thermoelectric materials can take full advantage of the characteristics of different thermoelectric materials, thus achieving a high overall efficiency in a broad temperature range [7,8]. The concept to use the segmented design or FGTM to increase the overall efficiency of the device was first proposed by Ioffe et al. in the 1940s [14]. Since the 1970s, segmented RTGs, based on PbTe and SiGe, with efficiencies ranging from 3.0% to 7.0%, have been successfully applied in spacecraft as energy sources, providing heat and 2.7–290 W of electricity for the spacecraft during 5–10 year space missions [7]. The success of segmented TEGs in deep space application proved the potential they had in medium and high-temperature energy harvesting. The very essence of a segmented TEG design was to maximize local segment operating efficiency according to the local temperature [15,16]. In a broad sense, a FGTM can be regarded as a segmented TEG with infinite segments. In a FGTM, by changing the composite ingredients or the doping concentration along the thermo-element

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Nomenclature

Symbols

T	Temperature (K)
Q	Heat flow (W/m^2)
P	Power output (W)
ZT	The figure of merit
J	Current density (A/m^2)
I	Current (A)
A	Area (m^2)
E	Electric field intensity (V/m)
L	Leg length (m)
κ	Thermal conductivity (W/(m K))
u	Reduced current (1/V)
s	Compatibility factor (1/V)
α	Seebeck coefficient (V/K)
ρ	Electrical resistivity (Ω m)
η	Efficiency

Subscript

P	P-type thermo-element
N	N-type thermo-element
H	Hot side
C	Cold side
r	Reduced efficiency
MAX	Maximum value

Abbreviation

TEG	Thermoelectric generator
FGTM	Functional graded thermoelectric material
RTG	Radioisotope thermoelectric generator
SPS	Spark plasma sintering
AM	Additive manufacture; SLS/SLM Selective laser sintering/melting

length gradually, the thermoelectric properties of the materials vary continuously [17–20]. The local carrier concentration of the thermoelectric material can be adjusted to obtain the desired transport properties, thus achieving high efficiency in a wide temperature range. In recent years, the academic field witnessed inspiring progress in FGTM for power generation applications [12,21]. However, the implementation of FGTM is still impeded by some practical difficulties associated with material fabrication, characterization, and modeling.

In homogenous thermoelectric materials, the properties of the materials do not change much in a relatively narrow temperature range, and thus the Thompson Effect can be neglected [22]. However, the properties of segmented TEGs vary significantly with temperature and the Thompson Effect has a significant influence on the system. In addition, the fabrication of segmented TEG requires more than simply piling up thermoelectric segments for different temperature intervals. The performance of segmented TEGs and FGTMs is closely related to the compatibility factor $(s = (\sqrt{1+ZT} - 1)/(\alpha T))$, which varies with temperature appreciably. When the compatibility factors differ by a factor of 2 or more, the maximum efficiency can in fact decrease by segmentation [23]. Only when the reduced current $(u = J\nabla T)$ is equal to s, will the local thermoelectric material achieve the maximum efficiency [16]. However, since the electric current on the thermo-element is constrained by the cross-sectional area of the TEG, the change in u is limited. The difference between u and s for the local thermoelectric segment makes the actual efficiency of a TEG less than the theoretical peak value.

1.2. Literature review

Conventionally, attempts to improve the economic viability of TEGs concentrated primarily on increasing their figure of merit (ZT). Though considerable effort has been put into this area since the 1990s when Hicks and Dresselhaus proposed that low dimensional thermoelectric materials might enhance the ZT value by several times [24,25], materials with good and stable performance are still in exploration. The very essence of thermoelectric material research is to reduce the thermal conductivity while preserving the electrical conductivity. Many new concepts were examined in the past decade, like matrix and precipitates band alignment, all-length-scale hierarchical architectures, modulation doping, etc. A lot of progress was made in both improving the performance of existing materials and exploring new materials. The ZT of some materials, like SnSe (n-type), and PbTe-SrTe (p-type), were reported to be higher than 2.0 in a wide temperature range. Comprehensive reviews summarizing the most recent state-of-the-art approaches to designing high-performance thermoelectric materials can be seen in Refs. [26–29].

Another attempt to improve their economic competitiveness is

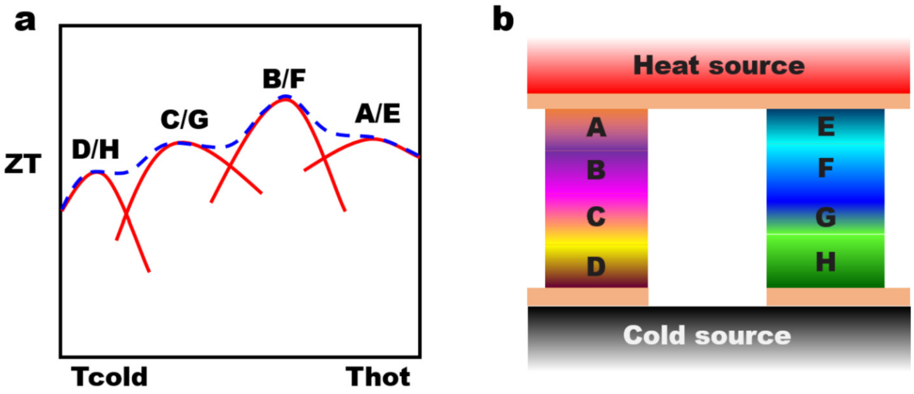

Fig. 1. **(a)** Segmented TEG using different TE materials to achieve highest averaged ZT value in a broad temperature range; **(b)** A segmented TEG design using these materials for high device efficiency.