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A new design of solar thermoelectric generator with combination of segmented materials and asymmetrical legs

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ABSTRACT

In this work, a novel solar thermoelectric generator (TEG) design is proposed to enhance its output power and conversion efficiency. It combines segmented thermoelectric materials and asymmetrical legs with variable cross-sectional area along the leg length. A three-dimensional multiphysics thermoelectric model is employed to examine the performance of the new design. The optimal leg length ratio of two segmented materials (P1 and P2 materials) and the optimal cross-sectional area ratio of cold end to hot end are determined. In comparison with using P1 and P2 materials, the results show that the segmented design increases the output power by 14.9% and 16.6%, respectively, when the leg length ratio is optimized. When the asymmetrical legs are introduced to the segmented design, the output power can be additionally increased by 4.21%, as compared with the optimal segmented design. Moreover, a simple analytical model is proposed to predict the optimal leg length ratio of two thermoelectric materials for the present new design. The proposed model can be reduced to the existing models when the leg cross-sectional area ratio of cold end to hot end is equal to 1. Thus, the model can be considered as a generalized model, which can evaluate the optimal leg length ratio for the segmented design with any leg shape. Based on the model, the optimal leg length ratio should make the interface temperature between the two materials equal to the temperature of intersection point of their *ZT* (figure of merit) curves. Theoretically, this conclusion can be extended to any leg shape with a constant or variable cross-sectional area. The present simulations verify the theoretical prediction of the optimal leg length ratio.

1. Introduction

With the increasingly serious energy crisis and the increasing importance of environmental protection, the research and development of clean and green energy technologies have become a hot worldwide topic. Among these technologies, semiconductor thermoelectric technology can convert heat into electricity directly, noise is of far less importance since it can be mastered for whatever alternative technique. At the same time, it also has many advantages such as small volume and light weight, low-cost operation and strong reliability, environmental friendliness and so forth. As a result, the technology has attracted a great deal of attention.

The thermoelectric performance of thermoelectric materials is evaluated by the figure-of-merit, $ZT = \alpha^2\sigma T/\lambda$, where α is the Seebeck coefficient, σ is the electric conductivity, λ is the thermal conductivity, and T is the absolute temperature at which the properties are measured. Thermoelectric materials with larger *ZT* can significantly enhance the output power and conversion efficiency of thermoelectric generators (TEGs). It is generally believed that the materials with a *ZT* exceeding 1 have commercial applicability. Therefore, improving *ZT* is always the goal for researchers and manufactures. At present, a variety of methods have been proposed to improve *ZT*, such as doping various elements into thermoelectric materials, possessing multi-scale microstructures, and modifying the atomic and molecular structure in thermoelectric materials [1]. Song et al. [2] reported that Zn_4Sb_3 material doped with Ag exhibited a promising *ZT* value of 1.2 at 575 K. Biswas et al. [3] demonstrated a *ZT* value of 2.2 at 915 K in P-type PbTe endotaxially nanostructured with SrTe. Zhang et al. [4] presented that a *ZT* value of ~1.83 was measured at 773 K for N-type PbTe-4%InSb composites. The significant enhancement in *ZT* value was attributed to the incorporation of InSb into the PbTe matrix which led to multiphase nanostructures and hence simultaneously modulated the electrical and thermal

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transport.

In the last two decades, thermoelectric materials have been subject to a remarkable progress, the *ZT* values of some reported thermoelectric materials have exceeded 2 [3,5] and even reached 3 [6]. It should be noted that *ZT* is a strong function of temperature but does not monotonically increases with increasing temperature. As a result, all thermoelectric materials have their own favorable temperature range to achieve higher *ZT* values. According to their favorable temperature ranges, the thermoelectric materials can be divided into high-temperature materials ($>$ 900 K), medium-temperature materials (500–900 K) and low-temperature materials (300–500 K) [7]. Beyond the favorable temperature range, *ZT* is reduced significantly. When a TEG is operated in high temperature environment like concentrated solar energy and waste heat recovery, the temperature across the TEG may cover the three temperature ranges, such that no single material can work properly in such large temperature range. For example, in the waste heat recovery of automobile exhaust, the exhaust temperature can reach more than 1000 K when the car runs at high speed [8]. On basis of this fact, a concept of segmented thermoelectric generators (STEGs) was originally proposed by Ioffe et al. in 1949 and published in 1960 [9]. Subsequently, employing a thermal resistance model and numerical iteration, Swanson et al. [10] proposed a method to optimize the leg length of each material to obtain the maximum efficiency of the STEG design in 1961. Fredrick et al. [11] applied for a patent for the STEG design in 1962. Based on these pioneering works, many efforts have been devoted to studying and optimizing the performance of STEGs. Caillat et al. [12,13] of JPL (Jet Propulsion Laboratory) in America built a STEG with P-type $Bi_{0.4}Sb_{1.6}Te_3$, Zn_4Sb_3 and $CeFe_4Sb_{12}$ as well as N-type $Bi_2Te_{2.95}Se_{0.05}$ and $CoSb_3$. The conversion efficiency could reach 15.5% when the temperatures of the hot and cold ends were 975 K and around room temperature, respectively. This result proved the feasibility and effectiveness of the STEG design. The existing studies of STEGs can be summarized in the following aspects. First, the performance of STEGs with various combinations of thermoelectric materials was investigated experimentally and numerically. Commonly employed combination includes Bi_2Te_3-based materials segmented with PbTe-based materials [14,15], $CoSb_3$-based materials [16,17], and skutterudites [18,19]. Second, with specific material combinations, the performance of STEG was investigated for various operating conditions and leg geometries, such as the temperature difference through STEGs [20,21], total leg length and leg length ratio [22,23], and leg cross-sectional area [24,25]. Third, the optimal leg length ratio for segmented materials was determined by experiments [26], numerical simulations [27,28], optimization algorithms [29], and theoretical analysis [30,31]. Fourth, some specific heat sources were focused on, such as solar energy [32,33], automobile exhaust [34,35], and industrial waste heat [36,37]. To enhance the utilization of heat sources and improve the output power and conversion efficiency of TEGs, the segmented design was employed instead of the single material design.

In addition to thermoelectric materials, the performance of TEGs is also closely related to their structures. Previous studies have shown that the leg length and cross-sectional area significantly affect the TEG performance. For the TEG with single material legs, Lavric [38] and Meng et al. [39] analyzed the effects of the leg length and cross-sectional area on the TEG performance through one- and three- dimensional model, respectively. Chen et al. [40] reported the influence of the leg geometry and the number of TEG in each stage on the performance of a two-stage TEG. For the STEGs, the structure design includes not only the leg length and cross-sectional area, but also the length of each material in the segmented legs. In order to make full use of the advantages of the segmented design, theoretical analyses and numerical simulations were implemented to optimize the segmented structure. El-Genk and Saber employed a one-dimensional model [41] and a three-dimensional model [42] to optimize the leg length and interface temperature of a STEG. Tian et al. [43] compared the performance of the segmented and conventional TEGs under different operating conditions, and analyzed the effect of the total leg length and the length ratio of two materials on the STEGs performance. Ouyang et al. [44] simulated the performance of STEGs with various state-of-the-art thermoelectric materials spanning a wide temperature range, from 300 K up to 1000 K. They demonstrated that successful segmentation required a smooth change of compatibility factor from one end of the STEG leg to the other, even if values of two ends differed by more than a factor of 2. Moreover, on basis of the fact that the N-type materials were universally weaker than their P-type counterparts, an asymmetrical geometry with $A_N < A_P$ was employed in their study to yield the optimized STEG performance. They also proposed a relationship of A_N/A_P to accurately speculate the optimal geometrical ratio for the maximum efficiency of STEG modules.

At present, commercial TEGs commonly use rectangular legs with a constant cross-sectional area along the leg length. Recently, some new leg designs were proposed in which asymmetric legs with variable cross-sectional area along the leg length were employed. The variable cross-sectional legs were firstly proposed by Hoyos et al. in 1977 [45]. They employed conical semiconductor legs to enhance the transient supercoiling performance of thermoelectric coolers. Sahin et al. [46] proposed a trapezoid leg structure with linear variation in the cross-sectional area, and their analysis showed that when the temperature at both ends of leg was fixed, the variable cross-section could decrease the total resistance and output power but increase the thermal efficiency. Later, Ali et al. [47] and Shi et al. [48] respectively investigated the TEGs with exponential and quadratic variations of the cross-sectional area of the legs. Niu et al. [49] simulated seven TEGs with different leg shapes, together with convective heat transfer boundary conditions. Their results showed that the variable cross-section structure could enhance the temperature gradient inside legs, significantly increase the electric potential and output power. Fabián et al. [50] compared the performance of thermoelectric modules with constant and variable cross-section structures by simulation and experiment under the boundary conditions that the heat flux at the top end and the temperature at the bottom end of the module were constant. Their results showed that the variable cross-section design could enhance the temperature difference and increase the output power. These studies demonstrated that variable cross-section designs also had a great effect on TEG performance.

Based on the above analysis, the output power can be enhanced by segmented designs and asymmetric leg designs. Therefore, it can be expected that TEGs which combine segmented thermoelectric materials and asymmetric legs should yield a better performance than conventional TEGs. However, no such study exists so far. Therefore, the objective of this work is to verify whether the new TEG design with combination of segmented thermoelectric materials and asymmetric legs can enhance the output power and conversion efficiency of generators via a three-dimensional multiphysics thermoelectric model developed in our previous work [51]. It should be noted that the TEG with segmented materials and asymmetric legs has been numerically investigated in Ref. [44]. The asymmetric legs in Ref. [44] mean different cross-sectional areas employed in N-type and P-type legs, while the legs are still rectangular with a constant cross-sectional area. In the present study, the asymmetrical legs mean variable cross-sectional areas along the leg length direction in both N-type and P-type legs. Therefore, although employing the same words “asymmetric legs”, the design idea in the present study significantly differs from that in Ref. [44]. Furthermore, the optimal leg length is the most important design parameter once the thermoelectric materials of a STEG are chosen. The previous models used to determine this parameter were proposed based on the segmented legs with constant cross-sectional area. Apparently, these models fail for the segmented legs with variable cross-sectional area. Therefore, another objective of this work is to develop a generalized model to evaluate the optimal leg length ratio. We expect that the new model can evaluate the optimal leg length ratio for the segmented design with constant or variable cross-sectional area.