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Estimation of thermoelectric and mechanical performances of segmented thermoelectric generators under optimal operating conditions

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HIGHLIGHTS

- The temperature dependent properties of TE materials are taken into account.
- The conversion efficiency can be enhanced by employing the segmented TE materials.
- The operating conditions satisfy the mechanical strength and efficiency requirements.

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ABSTRACT

The conversion efficiency is the most important indicator describing the thermoelectric performance of thermoelectric (TE) devices. Under large operating temperature difference, the efficiency can be enhanced by the fabrication of segmented thermoelements structure. For running safety, the thermo-mechanical behavior of TE devices must be considered. In this paper, a 3D finite element model is established to estimate the TE and mechanical performance of the segmented thermoelectric generator (STEG) under optimal operating conditions. The effects of the segment lengths on the TE conversion efficiency and the maximum stress level of TE materials are examined at a given operating temperature. And for different operating temperatures, the maximum conversion efficiency and maximum stress level of TE materials are also investigated, individually. By the mechanical strength evaluation and mechanical reliability analysis, the TE behaviors of STEG are verified. The results indicate that, for a given operating temperature, some segmented cases do not satisfy the strength requirements, and the theoretical maximum efficiency does not equal to the actual optimal one; for different operating temperatures, the STEG cannot always achieve the maximum design value of conversion efficiency. These findings will have some significant positive impact on the optimal design and practical application of the STEG.

1. Introduction

Thermoelectric (TE) technique is a new type of environmentally friendly energy conversion technology, which can realize the conversion between thermal energy and electric energy in the most direct way (i.e. electron transport) by thermoelectric materials [1]. The power devices based on TE materials have many significant applications in military, medical treatment, communication, and space flight and aviation, due to their unique advantages including no working medium leaking and mechanical movement, no vibration and noise, small volume, light weight, and low maintenance cost [2–4].

For TE devices, the conversion efficiency is the key index to evaluate the TE performance. To improve the efficiency, in addition to using high-quality TE materials, the optimal design of the device's structure can be carried out. Jang et al. [5] investigated the influences of the structure parameters on the TE performance of micro-thermoelectric generators by a finite element method. Numerical results indicated that the larger length of the thermoelements corresponds to the higher TE conversion efficiency. And the efficiency increases as the cross-sectional area of the thermoelements reduces. Sahin and Yilbas [6] studied theoretically the effect of the shape parameter, associated with the TE leg geometry, on the conversion efficiency of the TE power generators. Their results

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showed that changing of the shape parameter has a very significant influence on the conversion efficiency. Chen et al. [7] analyzed the TE behavior of the two-stage TE generator, and found that for the fixed total TE elements, the ratio of number of TE elements of the top stage to the total number of TE elements have an optimal value with the highest TE efficiency. For the case of operating at a large temperature difference, the fabrication of segmented thermoelements structure for generator is one of the effective and feasible methods to achieve the higher TE efficiency. Kuznetsov et al. [8] calculated the conversion efficiency of functionally graded and segmented Bi_2Te_3-based thermocouple. It can be found that the conversion efficiency is about 10% which exceeds that of homogeneous Bi_2Te_3-based thermocouple. Vikhor and Anatychuk [9] designed the TE modules of segmented thermoelements based on the optimal control theory, and described the fact that the efficiency of the modules can be more significantly improved by using the two-segmented thermoelements compared with the traditional BiTe material generators. Reddy et al. [10] studied numerically the TE performance of a composite TE device comprised of segmented thermoelements. Their results indicated that the composite TE device shows a 24.8%, 26.2%, and 29.9% increase in conversion efficiency as compared to a conventional TE device when the hot surface temperature T_h = 550 K, 450 K and 350 K respectively.

In practice, TE devices are applied in certain temperature environments. The thermal stress, caused by temperature gradient and thermal expansion mismatch among various components of TE devices, will affect the security service of TE devices. It is therefore essential to consider the influence of mechanical performance when evaluating the TE devices. During the last few years, there are some research works having focused on the mechanical behaviors of TE devices. Clin et al. [11] simulated numerically the thermomechanical behavior of Bismuth-Telluride TE module. Their results indicated that the stress level increases with the length of the TE leg decreasing. Besides, the boundary condition of TE devices and mechanical strength of soldering alloy have some significant effects on the stress distribution in TE elements. Turenne et al. [12] further investigated the thermomechanical characteristics of Bismuth-Telluride TE generators. Numerical results demonstrated that the plastic deformation of soldering materials can effectively reduce the stress value of TE legs. The shorter distance from the TE leg to the edge of the module renders, the higher the maximum stress level in the leg. Al-Merbati et al. [13] discussed the influence of device pin geometry on the thermal stress of TE power generator. They showed that changing the pin geometry can improve the temperature variation in TE device and reduce the maximum stress levels in the TE legs, and thus improve the service reliability. Li et al. [14] investigated the effect of the copper pad thickness on thermomechanical performance of TE modules. Numerical results indicated that for the whole device, the maximum stress level is located on the contact surface between the AlN substrate and the top copper pad because there corresponds to a larger mismatch in thermal expansion coefficients. Under the same temperature difference the thicker the pad thickness is, the higher the maximum Von Mises stress is. The researches on TE and mechanical performance have also been reported. Chen et al. [15] carried out a numerical simulation on the thermal-mechanical-electrical behavior of TE devices based on the actual working environments. Gao et al. [16] investigated the relationship between the thermal stress and the structure parameters of TE leg for a Bi_2Te_3-based TE module, and proposed the optimal lengths of leg and side to improve the conversion efficiency and the stability of the TE module. It can be seen that the research work focuses on homogeneous TE materials devices. To the authors' knowledge, up to now there have been few studies conducted to investigate the mechanical behaviors of segmented thermoelectric generator (STEG) and to guide the structure design by analyzing the mechanical reliability.

In this paper, a 3D finite element model of STEG is established to analyze the TE and thermomechanical behaviors of device under optimal operating conditions. First, based on thermal-electric coupling calculation, the TE conversion efficiency under a given operating temperature is optimized by selecting the appropriate segmented material length. And for different operating temperatures, the theoretical maximum conversion efficiency is also discussed. Then, the thermal-structure coupling calculation is performed and the maximum stress levels of TE materials are obtained under different operating conditions. By the mechanical strength evaluation and mechanical reliability analysis, we investigate the rationality of various segmentation case for a given temperature condition and point out the actual optimal efficiency as well as the corresponding segmentation scheme. For the given operating temperature range, the effective temperature point is also determined, in which not only can the strength requirements be satisfied but also a good efficiency can be produced.

2. Calculation model

2.1. Constitutive equations of thermal-electric and thermal-structural couplings

The geometry model of segmented thermoelectric generator established in this paper is shown in Fig. 1. The STEG is comprised of segmented TE materials, welding strips, conductors and substrates. And the dimensions of the STEG components are listed in Table 1. When a temperature difference is imposed between the up and down substrates, holes in p-type TE material and electrons in n-type TE material are transported from the hot end to cold end, a TE potential difference will be generated at cold sides of thermoelements due to the Seebeck effect. Once the circuit across the thermoelements is closed by a load resistance, there is a direct current flowing through the device. This is the process that TE materials convert thermal energy into electrical energy directly through the temperature difference at the ends of TE device. The process is also accompanied by the Peltier effect, Thomson effect and irreversible Joule and Fourier effects at the same time. Thus, the power generation capacity should be determined by the combination of these effects. The governing equation of heat flow can be expressed as [17].

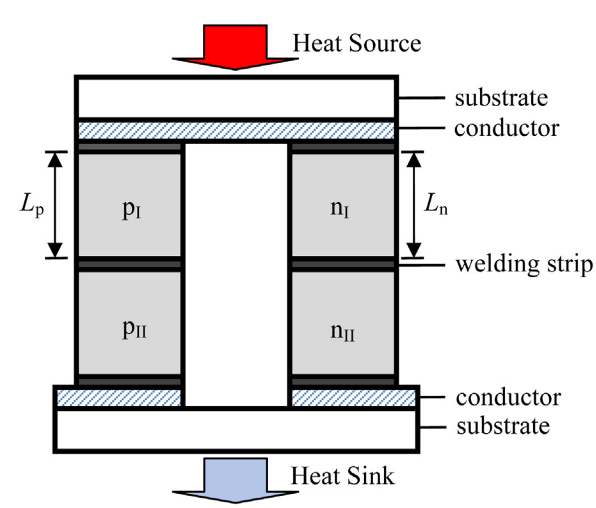

Fig. 1. Structure of the STEG.