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Research paper

Optimal design of a novel thermoelectric generator with linear-shaped structure under different operating temperature conditions

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HIGHLIGHTS

- TE performance of Linear-TEG is investigated under two operating temperature conditions.
- The optimal geometry dimension for the linear-TEG is discussed.
- The Linear-TEG shows better performance than the traditional π-TEG in power generation.

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ABSTRACT

A novel linear-shaped thermoelectric generator (Liner-TEG), due to its unique structure in which the p- and n-type thermoelements can be optimized independently, usually exhibits better design flexibility than a traditional π-shaped thermoelectric generator (π-TEG). In this study, the influence of the length ratio of the thermoelements $\theta = L_p/(L_p + L_n)$ on the output power and conversion efficiency of Linear-TEGs is investigated for different total lengths and heights of the thermoelements. And the predictive models on the thermoelectric performance under two operating temperature conditions are built, individually. The results show that, the maximum power and maximum efficiency are obtained at different length ratios; none of these maximums appears at the length ratio $\theta = 0.5$. This implies that in contrast to π-TEGs, the Linear-TEG has a better thermoelectric performance. Meanwhile decreasing the total length and/or increasing the height can improve the power. Interestingly, under the large temperature difference, there is a nonlinear relationship between the power and the height, and the optimal length ratio corresponding to maximum efficiency is dependent to the total length and height of the thermoelements, which are different to that under the small temperature difference. Our work will provide an alternative way for the design of high performance thermoelectric generators.

1. Introduction

Development of potential new energy source is one of important issues in the energy community due to global energy crisis and environmental pollution, and thermoelectric (TE) generators as a kind of green renewable energy sources are growing in popularity [1,2]. They can convert thermal energy directly into electric energy by electrons transport. TE generators have a broad prospect of applications in medical treatment, communication, military, and space flight and aviation, due to their excellent performances including no vibration and noise, no working medium leaking, small volume and light weight, and low maintenance cost [3–5].

As for practical application, it is endless to the demand for a high-conversion efficiency, high-output power TE generator. To improve the performance of TE generators, one may use high quality TE materials [6–10] and/or implement the optimal design of the device's structures. Based on a finite element method, Jang et al. [11] attempted to build a high-performance TE generator by determining the appropriate structure parameters. Numerical results indicated that a larger length of the thermoelements corresponds to a higher efficiency; the output power increases with a larger cross-sectional area of the thermoelements increases. Sahin and Yilbas [12] designed a TE generator with trapezoid geometry of the thermoelements. They found such a TE generator is with a higher efficiency compared to a conventional rectangular geometry

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Nomenclature

A	cross-sectional area of the thermoelement, m^2
D	height of the thermoelement, m
$\mathbf{E}$	electric field intensity vector, $V\ m^{-1}$
I	current, A
$\mathbf{J}$	electric current density vector, $A\ m^{-2}$
K_e	total thermal conductance, $W\ K^{-1}$
L	total length of p- and n-thermoelements, m
L_p	length of p-type thermoelement, m
L_n	length of n-type thermoelement, m
P	power, W
P_{max}	maximum power, W
$\mathbf{q}$	heat flux vector, $W\ m^{-2}$
$\dot{q}$	heat generation rate per unit volume, $W\ m^{-3}$
Q_h	heat inputted in the hot junction, W
R_0	external load resistance, Ω
R_e	total electrical resistance, Ω
$R_{0,opt}$	optimal external load resistance, Ω
T_1	temperature of hot junction, K
T_2	temperature of cold junction, K
θ	length ratio (L_p/L)
α_e	combined Seebeck coefficient, $V\ K^{-1}$
α_p	Seebeck coefficient of p-type thermoelement, $V\ K^{-1}$
α_n	Seebeck coefficient of n-type thermoelement, $V\ K^{-1}$
ρ_p	electrical resistivity of p-type thermoelement, Ω m
ρ_n	electrical resistivity of n-type thermoelement, Ω m
λ_p	thermal conductivity of p-type thermoelement, $W\ m^{-1}\ K^{-1}$
λ_n	thermal conductivity of n-type thermoelement, $W\ m^{-1}\ K^{-1}$
σ	electrical conductivity, $S\ m^{-1}$
η	efficiency
η_{max}	maximum efficiency
Π	Peltier coefficient, V
φ	electric potential, V

generator. However, it is not for the output power. Haider et al. [13] studied theoretically the effect of the shape parameter, associated with the exponential-type area of the thermoelements, on thermal performance of the TE power generators. Their results showed that the variation of the shape parameter has a very significant influence on the thermal efficiency and output power. Rezania et al. [14] mainly investigated the output power of a TE generator, and found that for the fixed total footprint area of the thermoelements, the footprint ratio of n- and p-type thermoelements has an optimal value with the highest power generation. When operating over a large temperature range, the majority of TE material consequently operates below its expected maximum performance. The fabrication of segmented TE material structure or multi-stage TE structure are the effective methods to improve the TE performance [15–20]. Besides the device design, the optimal design of the related heat sink is recently proposed as an alternative to improve the TE performance of TE generators [21–23]. One may notice that these works mainly focus on a TE generator with π-shaped structure (π-TEG). The traditional generators require the same lengths of p- and n-type thermoelements when assembled into a TE module. Undoubtedly, this encounters inevitable difficulty in the fabrication due to the mismatch thermal expansion of the thermoelements, and also somewhat lowers the performance of TE materials. A novel TE device with linear-shaped structure is first designed for cooling based on the Peltier effect; electrical current flows only along a single direction in the device under operation [1]. Kim et al. [24] fabricated a linear-shaped segmented TE generator with a dovetail-shaped electrode, which is superior over the π-TEG with the same segmented thermoelements in the output power, the specific power density and the shear stress characteristics. Such a linear-shape TE generator (Linear-TEG), due to its unique structure where the p- and n-type thermoelements can be optimized independently, usually shows a better design flexibility than traditional π-TEGs. Just like the π-TEG, the TE performance of the Linear-TEG is also largely related to geometry dimension. However, little attention has been paid to the geometry design of the Linear-TEG.

In this study, we explore the optimal length ratios of thermoelements (i.e. the ratio of the length of p-type thermoelement to the total length of p- and n-type thermoelements) corresponding to maximum output power and maximum TE conversion efficiency for a Linear-TEG. The impacts of total length and height of the thermoelements on the TE performance are also investigated, respectively. When performing the design of the structure, two operating temperature cases, the small temperature difference and/or the large temperature difference cases, are considered. For the small temperature difference case, the properties of TE materials can be seen as constants; a simple 1D analytical model is developed to predict the TE performance of the Linear-TEG. For the large temperature difference case, the TE properties are temperature dependent and the governing equations of the thermoelectricity are nonlinear and coupling, thus a 2D finite element model is established to predict the TE performance and optimize the geometry dimension of the device. Moreover, the TE performance of the π-TEG will be presented for comparison in this paper.

2. Calculation model

The geometric configuration of a Linear-TEG composed of a pair of TE materials is shown in Fig. 1. The p- and n-type thermoelements are connected through the electrodes. Under the action of a temperature difference, holes in p-type thermoelement and electrons in n-type thermoelement are transported from the hot end to the cold end, which results in a TE potential difference generating at cold sides of thermoelements in terms of the Seebeck effect. There is a direct current flowing through the device, once the circuit is closed by an external load resistance R_0. This is the process that the TE generator convert thermal energy into electrical energy directly through the temperature difference at the ends of the

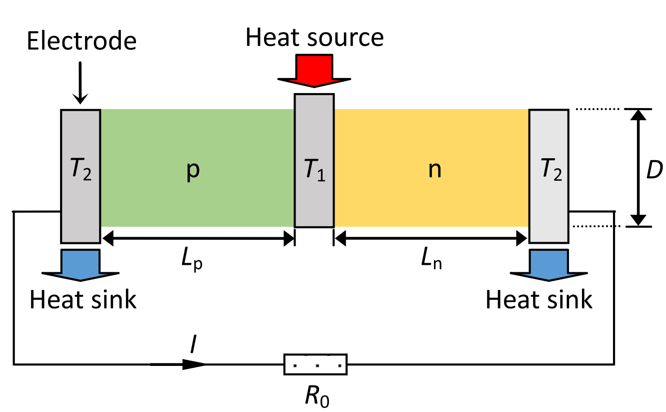

Fig. 1. Structure of the linear-TEG.