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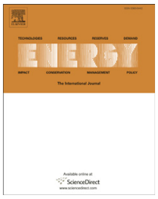

Multi-objective and multi-parameter optimization of a thermoelectric generator module

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ABSTRACT

A multi-objective and multi-parameter optimization is implemented to design the optimal structure of bismuth-telluride-based TEG (thermoelectric generator) module. A multi-physics TEG model combining the SCG (simplified conjugate-gradient) algorithm is used as the optimization tool. The semiconductor pair number, leg length, and base area ratio of semiconductor columns to TEG module significantly affect the TEG performance, and hence are all incorporated into the present optimization study. A single-objective optimization is first implemented to provide input parameters for the multi-objective optimization. The results show that when taking the output power as the single-objective function, the output power can be elevated significantly by optimization of the three geometric parameters but which also accompanies the significant reduction in the conversion efficiency. The same result also occurs when taking the conversion efficiency as the single-objective function. By combining the output power and conversion efficiency with a weight factor as the multi-objective function, the optimization is again implemented. The optimal design obtained by multi-objective optimization makes a proper balance between the output power and conversion efficiency, so that the both are improved simultaneously.

1. Introduction

TEGs (thermoelectric generators) are based on the Seebeck effect of semiconductor materials to convert thermal energy to electricity directly [1,2]. In recent years, thermoelectric technology is attracting more and more attention, mainly because of the following two aspects: on the one hand, there are not working fluids or other moving parts, so TEs (thermoelectric devices) have many good features, such as reliable operation, layout flexibility, adaptability and other characteristics [3,4]; on the other hand, TEs do not produce secondary pollution gases such as carbon dioxide or other unfriend polluting gases in the progress of using the life or industrial waste heat for electricity generation [5,6].

Previous studies show that the TEG performance, including the output power (P) and conversion efficiency (η), is strongly dependent on semiconductor material properties. In general, the dimensionless figure of merit is adopted to represent the influence of material properties on the TE (thermoelectric device) performance, which is defined as $ZT = \alpha^2\sigma T/\lambda$, 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 [7]. A larger ZT represents better performance of TEs, therefore, researchers who are engaged in thermoelectric materials are committed to enhancing ZT, which means increasing the Seebeck coefficient and electric conductivity, and at the same time keeping thermal conductivity values as low as possible [8,9]. Minnich et al.'s research [8] showed that bulk nanostructured thermoelectric materials have the most promise for commercial use due to their plasticity and compatibility. Tang and Zhang [9] found that the ZT of thermoelectric material $Fe_xCo_{4-x}Sb_{12}$ ($x = 0$–3) can be improved significantly by filling Ce, Ba, and Y.

Except for thermoelectric materials, the impact of the geometry on the TEs performance cannot also be ignored. TEs geometry optimization can be divided into two categories: one is the single-parameter optimization [10–15], and the other is multi-parameter optimization using various inverse problem approaches [16–19]. Up to now, the single-parameter optimization is the most widely used method. For example, Jang et al. [10] adopted the single-parameter method to study how the thickness of ceramic plate,

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Nomenclature

P	output power (W)
η	conversion efficiency
COP	coefficient of performance
ZT	figure of merit
T	temperature (K)
f	weight factor
C	search variable
A_{total}	area of TEG module base
J	objective function
N	semiconductor pair number
A_{pair}	base area of TEG unit
A_{pn}	cross-sectional area of p- or n-type semiconductor
H	height (mm)
W	width (mm)

Abbreviation

TEG	thermoelectric generator
TEC	thermoelectric cooler

Greek letters

α	Seebeck coefficient (V K^{-1})
σ	electric conductivity (S m^{-1})
λ	thermal conductivity (W m^{-1} K^{-1})
ρ	electric resistivity (Ω m^{-1})
Δ	difference
β	search step size
π	search direction
γ	base area ratio of semiconductor columns to TEG module

Subscripts

opt	optimal
pn	p- or n-type semiconductor
Cu	copper
k	number of variables

Superscript

n	number of iterations

foot length and cross-sectional area of the p- or n-type semiconductor affect the performance of a micro TEG (thermoelectric generator) unit. They found that for each of the three geometry parameters, there is always a specific size corresponding to the optimal P or η, however, the optimal P and η cannot be reached simultaneously. Yu et al. [11] lay emphasis on the influences of the junction temperature difference (ΔT_2) in the second stage, the length of thermocouples (L_1) and the NUM (number of thermocouples) in the first stage on the cooling performance of a two-stage TEC module. They included that: 1) For a fixed ΔT_2, the decreases of L_1 and NUM can improve the coefficient of performance ; 2) When keeping a constant coefficient of performance, the decreases of L_1 and NUM can also decrease ΔT_2, and thus increase the cooling capacity. Chen et al. [12] proposed a new cycle model consisting of a multi-couple thermoelectric device and involving several key irreversibilities of real TEGs to optimize the value of $(S_p/l_p)n$, where S_p and l_p are the cross-sectional area and leg length of p-type semiconductor, n is the number of couples. For the fixed total number of thermoelectric elements of two-stage thermoelectric refrigerator driven by two-stage thermoelectric generator, Meng et al. [13] optimized the allocations of the thermoelectric element pairs for the maximum cooling load and coefficient of performance. Yilbas and Sahin [14] examined the influence of the slenderness ratio and the external load parameter on the maximum efficiency of a TEG, and found that the efficiency attains high values for the slenderness ratio less than 1 for almost all the external load parameters considered, which is more pronounced for the large values of the external load parameter. Optimizations were carried out for the two-stage TE coolers with two design configurations, i.e., the pyramid-styled and cuboid-styled ones by Xuan et al. [15], the optimum number ratio of TE modules between two stages for the first design and the optimum electric current ratio between two stages for the second design were finally obtained.

In all the single-parameter optimization studies [10–15], the optimal value for a specific parameter is obtained by searching this parameter to reach the optimal TE performance while keeping the other parameters unchanged. However, because all the parameters have coupled effects on the TE performance, the optimal TE performance cannot be reached only by searching a specific parameter. Fortunately, a few studies [16–19] have made attempt to develop TEC (thermoelectric cooler) multi-parameter optimization methods by combining the various optimization algorithms and the TEC analytical/numerical model. Cheng et al. combined a TEC model and a genetic algorithm to optimize of the geometry of single- [16] and double-stage [17] TEC. In their study, the maximum cooling capacity was defined as the objective function under the requirement of minimum coefficient of performance and the constraint of maximum material cost. The leg length, the leg area and the number of legs were taken as search variables and were optimized simultaneously. Rao and Patel [18] developed a modified version of the teaching–learning-based optimization algorithm and incorporated this algorithm into the TEC model to optimize the performance of double-stage TEC. The cold stage current, hot stage current, and number ratio of thermoelectric elements between the two stages were three search variables. Thermal resistance model was adopted as the direct problem solver in Refs. [16–18]. Due to grossly simplifying assumptions, such as that only the energy balance equations at the hot and cold ends were solved, only constant or temperature-averaged properties can be used, the current density vector was simplified as a constant scalar, etc., the thermal resistance model, however, cannot predict the TE performance accurately, and therefore is not appropriate as the direct problem solver for TE optimization. Recently, we combined a multi-physics TEC model [19] and a SCG algorithm to optimize the cooling capacity of a TEC module. A value of COP (coefficient of performance) that was not lower than 70% COP of the initial TEC geometry was chosen as the constraint condition, and the semiconductor pair number, the leg length, and the base area ratio of semiconductor columns to TEC were taken as search variables. The optimal geometry corresponding to the maximum cooling capacity was successfully obtained, however, the COP of the optimal geometry was reduced as compared with the initial geometry.

The motivation of the present work is based mainly on the following three points: 1) the effect of the TEG geometry on its performance is also very significant, however, the TEG multi-parameter optimization has not been reported so far; 2) as two important evaluation indexes for the TEG performance, P and η cannot reach the extreme value simultaneously when using the single-objective optimization, hence, multi-objective optimization needs to be carried out; 3) it is well known that the direct problem solver is very critical for the optimization, due to the limitation of