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DESIGN OF SEGMENTED THERMOELECTRIC GENERATOR OPTIMIZED BY MULTI-OBJECTIVE GENETIC ALGORITHM

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ABSTRACT

This study focuses on the design of segmented thermoelectric generator (STEG) system to achieve the system maximum output power. Multi-objective genetic algorithm (MOGA) design was applied to increase the output power. The STEG structure was optimized by altering the length of the cold side thermoelectric materials. The results showed that the optimized STEG module has the maximum output power when the lengths of p-type and n-leg cold side thermoelectric material are 0.78 mm and 0.5 mm. The cold side length which is not in the range of optimized value will reduce the maximum output power. In addition, the heat transfer rate and power generation of the STEG model was optimized. The most suitable length of the cold side thermoelectric material was found by MOGA. The output power of the optimized STEG compared with half in leg length of the segmented STEG was increased 21.94 % at ΔT= 400 K. Therefore, MOGA was an effective tool for designing STEG geometries.

Keywords: Segmented; Thermoelectric generators (TEG); Impedance matching; Optimization; Multi-objective genetic algorithm (MOGA); Output power.

1. INTRODUCTION

Thermoelectric (TE) was a friendly and reliable alternative energy. This technology could be applied in many fields, including aerospace, industrial waste heat recovery, petrochemical, etc [1]. Thermoelectric generator (TEG) directly generates electricity using temperature gradients, unlike thermal engines which needed to transform thermal energy into mechanical energy. Special segmented structures by dividing thermoelectric material into hot and cold end were applied in the recent studies to improve the power efficiency [2, 3]. The thermoelectric materials could have the maximum efficiency in the effective temperature range which had the high ZT value.

Based on the literature reviews, it could be found out that the best solution was obtained quickly and conveniently by optimization analysis [4, 5], especially the geometric analysis was the most effective way. This study used artificial intelligence optimization methods to determine the optimal length of TEG and explored the possible effects of temperature differences on the optimization method.

From the literatures, it has been known that the STEG was helpful for improving performance, but it could be further optimized. In the optimization, the accuracy and convenience of solving problems directly was important. MOGA is better than the general method to obtain high performance results. Previous STEG research did not specifically emphasize on the effects of temperature difference. This study proposes to determine the length of a STEG with the optimal ratio. In addition, particular attention also paid to the heat transfer rate and power generation in the thermoelectric couple. The optimized results facilitated the development and manufacturing consults of TEG components, thereby enhancing their performance.

2. PAPER STRUCTURE

2.1 Physical model

Thermoelectric generators with 127 pairs of thermocouples were a common design in industrial TEG [6]. Therefore, it was the basis of this research. Each thermocouple consisted of a pair of p-type and n-type semiconductors. The length and width of the thermoelectric wafer were 4.0 cm and 4.0 cm [7], respectively. The geometry of the p-type and n-type semiconductors was homogeneous. The length, width, and depth each element were 3 mm, 1.056 mm and 1.056 mm, respectively. The thickness of the substrate on the upper and lower sides of the p-type and n-type electrodes was 3 mm by copper [8].

During the simulation, one pair of thermoelectric elements was used as a research basis. The thermoelectric materials used in this study were from previous literature [9, 10]. Skutterudite (n-type (Sr, Ba, Yb)$_yCo_4Sb_{12}$ with 9.1 %$In_{0.4}Co_4Sb_{12}$, p-type $DD_{0.59}Fe_{2.7}Co_{1.3}Sb_{11.8}Sn_{0.2}$) was used as the hot side semiconductor element, and hydrothermal synthesized nanostructure thermoelectric material ($Bi_{0.4}Sb_{1.6}Te_3$) was chosen as the cold side semiconductor element [11].

2.2 Boundary conditions

Consider the model with hot, cold and lateral side as thermal boundary conditions. During the simulation, the hot surface temperature was manipulated between 400 and 700K and the cold surface temperature was generally room temperature. Apart from this, the adiabatic state was considered on the lateral surfaces [12]. The inlet and outlet of the metal substrate were subjected to constant current and zero potential as electrical boundary conditions, respectively. Therefore, assume they were ϕ = 0 and $\overrightarrow{J} \cdot \vec{n} = 0$. ϕ, $\vec{J}$, $\vec{n}$ were an electric scalar potential, the current density vector, and normal vector. In order to reduce the time for processing physical problems, the assumptions included: (1) considering the typical heat transfer of the hot rod, but the simulation did not include the actual geometry of the hot rod; (2) the heat flux and current at the interface between the element and the electrode were not exposed to heat of contact resistance and contact resistance; (3) There was no current and heat transfer on the lateral surface.

2.3 Multi-objective genetic algorithm (MOGA)

This study used MOGA optimization to provide a more accurate method. It worked by several iterations, retaining the "elite" percentage of the sample, and it allowed the retained samples to "genetically" evolve until the optimal value converges to the target value and the analysis was completed. MOGA could be applied globally and locally, and offer several candidates in different regions to find accurate solutions and address multiple objectives. Compared to traditional multi-objective optimization methods, traditional methods typically applied a linear combination of multiple targets or by transforming the target into a constraint with an associated threshold and penalty function. In MOGA, individual groups for optimization problems were gradually moving towards better solutions.

2.4 Objective function and constraints

Performance optimization of segmented thermoelectric elements required consideration of multiple standards. The objective function was F_{obj} = max (P) = I × V, where P was the output power of the segmented thermoelectric generator, I was the induced current, and V was voltage, respectively. In this study, the total height of the element L_{STEG}=3mm (ie, the length is constant) was considered. At the same time, the parameter condition variables were allowed to change within the following ranges: 1.5 A< I < 2.5 A, 0.1 mm<$L_{c,n}$< 1 mm, 0.1 mm< $L_{c,p}$< 1 mm, T_h=700 K, T_c=300 K, where I was the current, $L_{c,n}$ and $L_{c,p}$ were the p-type and n-type cold side length of TEG module.

2.5 Operating conditions

In this study, two different thermal boundary conditions were considered. The process assumed that the temperature was constant at the boundary and had a fixed temperature at the hot side surface (400, 500, 600 or 700K). The cold side surface was fixed at room temperature (300K), and the other assumed that the ambient temperature and heat transfer were constant at the boundary.

3. RESULTS AND DISCUSSION

3.1 Segmented TEG module

In order to understand the impact of the segmented structure on TEG, a TEG model with equal segmented was established. The hot and cold end thermoelectric materials accounted for half the length of the TEG leg and general skutterudite were used. Segmented TEG was compared to general skutterudite. The maximum output power and maximum efficiency of the segmented TEG were 0.0943 W and 14.55 %, whereas 0.0927 W and 10.54 % for general skutterudite. At the maximum output power, the segmented TEG increased by 1.67 %. For the most efficient part, the segmented TEG increased by 38.04 % at I= 1.2A. The thermoelectric properties were further improved after changing the cold-end thermoelectric material. $Bi_{0.4}Sb_{1.6}Te_3$ replaced the lower thermoelectric performance of skutterudite in the low heat temperature range, but the improvement of output power did not achieve good results compared with 21.9 % of the previous paper [8]. Therefore, the segmented

TEG model needed to be further optimized to increase the maximum output power.

3.2 Optimal length ratio by MOGA

Each different numerical point represents a different geometry of the STEG model. Their output power is also different under fixed operating conditions. Mahmud et al. [13] described the hot side heat transfer rate from heat source to STEG model (Q_h) and cold side heat transfer rate from STEG model to environment (Q_c) of the thermoelectric pair equal to the power generated by the system. Multiplying the number of thermoelectric unit couples in one module was the total output power, as shown below:

$$P = n\,(Q_h - Q_c) \tag{1}$$

where n is the number of thermoelectric couples in one module. Eq. (1) is used to calculate the output power during the optimization process. Fig 1a and Fig 1b illustrate the evolutionary process of the n-type and p-type cold side length with fixed total length of segmented components, and the evolution process of the hot side heat transfer rate from heat source to STEG model (Q_h), cold side heat transfer rate from STEG model to environment (Q_c), and output power are shown in Fig 1c, Fig 1d, and Fig 1e. In the 1st generation (numbers ⩽ 5000), the oscillation volatility of length, heat transfer rate and power were extremely large, indicating a large amount of different data counted by the algorithm. In the 2nd generation (5000 ⩽ numbers ⩽ 10000), the change in the quantity became slowly stabilized, and this stage left the value of "elite" for optimization a better value. In the 3rd generation (10000 ⩽ numbers ⩽ 15000), the change began to converge in a single interval, revealing the evolution closed to the desired goal. In the 4th generation (15000 ⩽ numbers ⩽ 20000), a single specific straightness began to change, revealing the genetic evolution to the desired goal after the final iteration. When the temperature difference was 400 K, the optimized n-type cold end material leg height and p-type cold end material leg height were 0.5 mm and 0.78 mm. The highest output power was 0.1154 W, which obtained at the induced current of 1.5 A. The highest power was not obtained at the highest value of the Q_h and Q_c because the heat transfer rate at a certain value allowed the output power to reach the maximum value.

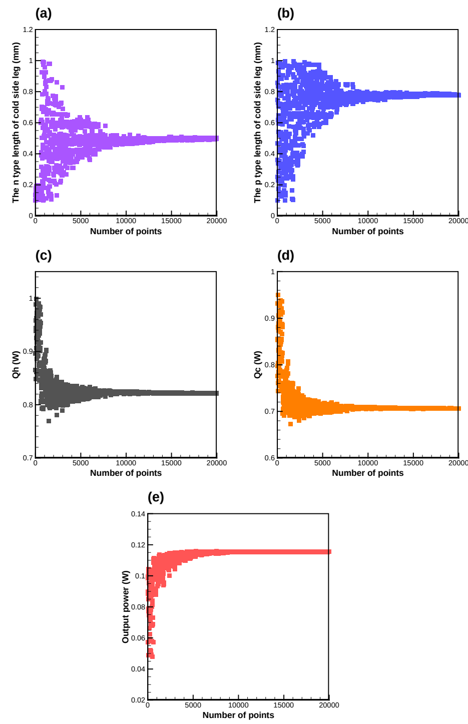

Fig. 1 The process of parameter evolution for the length of segmented TEG at ΔT= 400 K (a) the p type length of cold side leg, (b) the n type length of cold side leg, (c) Q_h, (d) Q_c, and (e) output power.

When the temperature difference was 400 K, the optimization found the n-type cold end material leg height was 0.5 mm and the p-type cold end material leg height was 0.78 mm. The highest output power was 0.1154 W at the induced current of 1.5 A.

The optimization model was compared to the previous part of the equal segmented TEG as shown in Fig 2. The maximum output power was increased from 0.09431W to 0.11501W, but the maximum efficiency was reduced from 14.55% to 14.48%. With the optimization of MOGA, the maximum output power increased 21.94%, but the efficiency dropped 0.48%.

4. CONCLUSIONS

This study proposes to determine the length of a STEG with the optimal ratio. In addition, particular attention also paid to the heat transfer rate and power generation in the thermoelectric couple. The output power and efficiency of a pair of STEG module under operating conditions (ie, fixed temperature difference) and fixed length have been numerically analyzed as heat sources collected by the heat pipe. MOGA was used to optimize the STEG to achieve the maximum output power by varying the STEG length of cold side. The evolution of the p-type and n-type cold side lengths of the TEG was performed as the algorithm proceeds.

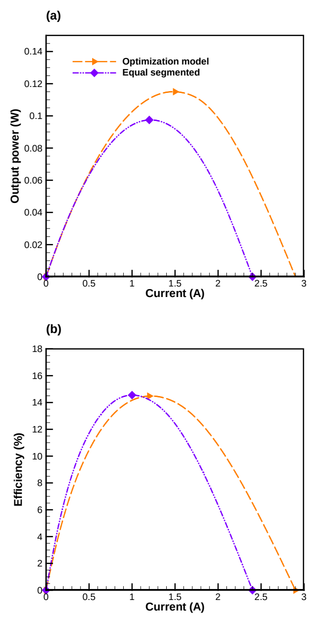

Fig 2 Performance comparison of the equal segmented TEG and optimization module (a) output power, (b) efficiency.

The maximum output power increased by 21.94%, but the efficiency dropped by 0.48% at ΔT=400 K. The optimized STEG model was discussed in detail for its heat transfer. The study examined the effect of the segmented thermoelectric materials on thermoelectric performance and verified the proportion of optimization. The three different leg lengths of the hot-cold-end thermoelectric materials were selected to simulate. The optimal module has maximum value of P which was increased by 3.39 %. The optimized results facilitated the development and manufacturing consults of TEG components, thereby enhancing their performance.

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