Modeling the Effects of Module Size and Material Property on Thermoelectric Generator Power

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ABSTRACT: It is known that thermoelectric power generators (TEGs) can utilize geothermal resources and recycle waste heat. It is vital to improve the thermoelectric power generation efficiency to economically and efficiently use these thermal resources. In this paper, ANSYS was used to build a three-dimensional model of a very simple TEG with only one pair of p- and n-legs (1-PN-TEG) to find the optimal design. The thickness of the semiconductor elements, the cross-sectional area of p- and n-type semiconductor elements, the heat insulation material, the thickness of copper sheet, and other factors were analyzed to study their effects on the power output of 1-PN-TEG. The results show that the power of TEG increases first and then decreases with the thickness of p- and n-legs (H); the maximum power existed at a specific value of H. The power increases when the cross-sectional areas of p- and n-type semiconductor elements become more extensive, but the power per area decreases. Furthermore, the power increases with the volume of p- and n-type semiconductor elements and tends to be stabilized finally. This observation may be used to estimate how much thermoelectric material is required to generate a specific value of TEG power. The gaps between p- and n-type semiconductor elements were filled with different heat insulation materials. The heat insulation material with lower thermal conductivity had a greater power output. The thickness of the copper sheet, as a conductor between p- and n-type semiconductor elements, was also investigated. The maximum power value was reached when the thickness of the copper sheet was equal to about 1.0 mm. All of the results obtained in this paper might provide a theoretical basis for the configuration and design optimization of a thermoelectric generator, making more efficient use of geothermal resources and the waste heat.

1. INTRODUCTION

According to the World Energy Assessment, geothermal energy is one of the largest sources of renewable energy.1 In many geothermal resources, low temperature (<150 °C) accounts for a large proportion. Besides, many factories produce a large amount of waste heat in the operational process. The waste heat resource is vibrant, especially the waste heat with relatively low temperatures. Although many companies have taken some measures to recycle these waste heats, the efficiency is still low.² Compared with high-grade energy sources, such as coal, oil, and natural gas, it is challenging to use low-grade energy sources. However, low-grade energy sources still have great potential. A series of studies have been carried out on thermoelectric generation to use geothermal energy and other low-grade energy sources.³,⁴ Full utilization of these low-temperature geothermal resources can effectively solve the shortage of energy nation-wide and alleviate the status of environmental pollution.⁵

A thermoelectric generator is a device that converts thermal energy into electrical energy directly, without mechanical work. It has obvious advantages in using geothermal energy, waste heat, and other low-grade thermal sources.⁶ Weber et al. prepared a small thermal power generator that could be used in low-power-consumption devices such as watches.⁷ Huesgen et al. proposed a new method for manufacturing thermoelectric generators to maximize the thermal contact area while preparing highly integrated thermocouples.⁸ Maneewan and Chindaruksa produced a thermoelectric generation system that could generate electricity from waste heat from biological dryers, which had a conversion efficiency of around 4.08%.⁹ Niu et al. combined the thermoelectric module and the parallel-plate heat exchanger. The effects of temperature, flow rate, and load size on thermoelectric generation were measured experimentally. The results were compared with the previous numerical simulation results.¹⁰ Hsu et al. constructed a thermoelectric generation system consisting of 24 thermoelectric power generators (TEGs) to recover waste heat from the automobile exhaust gas and carried out numerical simulations.¹¹ Molina et al. proposed a three-phase TEG scheme and verified the experimental results by numerical simulation.¹² Chen et al. reviewed the research progress of nanostructured thermo-
electric materials and described the basis of innovative breakthroughs in nanostructured thermoelectric materials. In the last decade, they proposed that high-performance thermoelectric properties depend on nanostructures, synthetic methods, and device assembly.\textsuperscript{13} Liu et al. designed a thermoelectric generation system using TEG and conducted an experimental study. It was found that the power could reach 500 W at a temperature difference of 200 °C.\textsuperscript{3} Purohit et al. developed an analytical model of TEG based on thermodynamic theory, semiconductor thermoelectric theory, the law of conservation of energy, power output equations, and current of TEG. According to the analysis, the power output per area is independent of the legs’ number and cross-sectional area.\textsuperscript{14} Yavuz et al. designed a new type of thermoelectric generator for industrial waste heat recovery, which achieves 14 W of power when the temperature difference reaches 109 °C.\textsuperscript{15} Barset et al. combined field experiments and mathematical models to study a 0.25 m\textsuperscript{2} TEG, which achieves a maximum power of 160 W/m\textsuperscript{2} at a maximum temperature difference of 100 K, and proved that improving the efficiency of thermoelectric power generation has great potential.\textsuperscript{16}

In addition to studying thermoelectric generation equipment, many have also carried out many numerical simulations, providing theoretical guidance for the experimental design. Freunek et al. proposed a TEG model with heat conduction with Seebeck, Peltier, Thomson, and Joule effects.\textsuperscript{17} Ebling et al. used finite element analysis (FEA) to model the effect of the thickness of thermocouple and the effect of the contact resistance on the ZT value of the element based on theoretical calculation. The simulation results demonstrated that the presence of the contact resistance negated the ZT value of the thermocouple and the power of the TEG was reduced.\textsuperscript{18} Lavric established a one-dimensional model to analyze the effect of geometrical elements of TEG on power and efficiency, and analyzed the effect of thickness and cross-sectional area on power.\textsuperscript{19} Suter et al. conducted a numerical simulation of a 1 KW thermoelectric module and discussed the effect of different factors on power output of the TEG.\textsuperscript{20} Gou et al. established a TEG dynamic model, which could be used in the design and operation analysis of TEGs. The results showed that enhancing heat dissipation on the cold side generates a more remarkable improvement on TEG output performance compared with enhancing heat transfer on the hot side.\textsuperscript{21} Luo et al. revealed a new TEG structure in which the cross-sectional area of the thermal element gradually increased as the hydrothermal fluid flows downward. The performance of the new TEG was evaluated using a steady-state, three-dimensional, fluid—thermal—electric multiphysical model. The paper pointed out that the maximum output power of the TEG appears when the load resistance is slightly greater than the internal resistance of the TEG.\textsuperscript{22} Cheng et al. established a three-dimensional structural model to determine the effects of structural parameters like length, cross-sectional area, and other factors. They carried out numerical modeling to obtain the effects of these structural parameters on the power. The optimal value of the length is between 0.075 and 0.125, and the power per area decreases slowly with the increase of the cross-sectional area. Moreover, the power output and energy conversion efficiency decrease with the increase of the thermal conductivity substrate.\textsuperscript{23,24} Brito et al. simulated the effects of the thickness of thermoelectric element, contact resistance, and other factors on the power output of thermoelectric generation. The simulation results indicated that the thickness of the thermocouple has an optimal value and that the presence of the contact resistance reduces the power.\textsuperscript{25} Ming et al. established a mathematical model for analyzing TEG heat conduction and thermal stress. They suggested that thermal stress in the horizontal direction is the main reason for the fatigue of the thermoelectric sheet.\textsuperscript{26} Ji et al. built a simulation model to predict the performance of TEG installed in a ship exhaust system. The model results estimate that 9.97 kW power output can be generated in a ship engine with a rated power of 1 MW. Nearly 1% of rated power was generated by TEG.\textsuperscript{27} Howard et al. outlined the application of modeling and simulation to estimate the usable electric power produced by a TEG array on the exhaust muffler of a small fossil fuel generator. The simulation results give information for the design, construction, and testing of an initial prototype.\textsuperscript{28} Naveen et al. studied geometry optimization for structural reliability and the influence of TEG, leg length, and p- and n-type leg areas on performance.\textsuperscript{29} Mamur et al. utilized maximum power point tracking (MPPT) algorithms for modeling both TEGs and a boost converter with MPPT together. Detailed modeling, simulation, and verification of TEGs depending on the Seebeck coefficient, the hot/cold side temperatures, and the number of modules in MATLAB/Simulink were carried out.\textsuperscript{30} Luo et al. presented a comprehensive model to predict the performance of thermoelectric generators and coolers, and investigated the effects of height, cross-sectional area, coupling number, ceramic plates, and heat loss on generators and coolers.\textsuperscript{31} Besides, a multiphysics numerical model of fluid—thermoelectric coupled field was proposed to simulate the behavior of the thermoelectric generator system. The results showed that the output power of the converging thermoelectric generator system was 5.9% higher than that of the conventional system when the air temperature is 550 K and the air flow rate is 60 g/s.\textsuperscript{32} Huang et al. developed a combined RSM—GA optimization method based on numerical models of TEGs. The optimization algorithm improves the rigor of the actual design of the test error and the efficiency of the direct search of the design space.\textsuperscript{33} Eddine et al. developed a dynamic model to investigate the application of a thermoelectric generator in the recovery of exhaust heat from automobile engines. The converted electrical energy was used to charge a 12 V battery.\textsuperscript{34} Li et al. designed a five-layer TEG module for power generation and measured the influence of flow rate, temperature, and temperature difference between hot and cold sides on power output and efficiency.\textsuperscript{35} One can see that many papers have been published in this area of TEG modeling. However, different researchers’ data and results are not consistent, and some are even conflicting with each other. How to estimate the mass of bismuth telluride required to generate a specific TEG power value is still a question. The power output under different configuration parameters of 1-PN-TEG was investigated in this paper to solve some of the above problems and achieve optimal design of TEG. ANSYS was used to model the performance of the 1-PN-TEG in a steady state.

2. PHYSICAL MODELS

2.1. Basic Structure of 1-PN-TEG. 1-PN-TEG is composed of only one pair of p- and n-type semiconductor elements, a copper sheet (serving as a bridging conductor between p- and n-type semiconductor elements), and a thermally conductive ceramic chip. The p- and n-type
semiconductor elements have the same size and square-shaped cross-sectional area. The hot and cold sides of 1-PN-TEG provide a temperature difference, \( T_p \) represents the thickness of the p-type semiconductor element, \( L_n \) represents the thickness of the n-type semiconductor element, \( W_p \) represents the width of the p-type semiconductor element, and \( W_n \) represents the width of the n-type semiconductor element. The thickness of the thermally conductive ceramic chip is constant, which equals 0.5 mm in this paper (Figure 1).

![Figure 1. Schematic diagram of 1-PN-TEG.](Image)

All of the parameters are presented in Table 1.

| parameters                     | symbol | standard       | range     |
|--------------------------------|--------|----------------|-----------|
| temperature of hot side        | \( T_h \) | (100, 250 K)   |           |
| temperature of cold side       | \( T_c \) | 50 K           |           |
| Seebeck coefficient of p-type  | \( \alpha_p \) | 0.00019 V/K    | standard  |
| semiconductor element         |        |                | value     |
| Seebeck coefficient of n-type  | \( \alpha_n \) | -0.00019 V/K   | standard  |
| semiconductor element         |        |                | value     |
| thermal conductivity of p, n-type semiconductor element | \( k \) | 1.2 W/(m·K)    | standard  |
| resistivity of p, n-type       | \( \rho \) | 1.5 \times 10^{-5} Ω·mm | standard value |
| semiconductor element         |        |                | range     |
| thickness of the semiconductor element | \( L_p/L_n \) | (0, 2 mm) & 0.5 mm | standard value |
| thickness of the ceramic chip  | \( L_c \) | 0.5 mm         | standard  |
| thickness of the copper sheet  | \( L_{cu} \) | (0.01, 0.05 mm) | standard  |
| width of the semiconductor element | \( W_p/W_n \) | (0.3, 0.40 mm) | standard value |

2.2. Basic Principle. There are three primary effects in thermoelectric generation: Seebeck, Peltier, and Thomson effects. The fundamental principle of the model includes the conservation equations both thermal field and electric field, as follows:

The energy conservation of p-type and n-type semiconductor elements is expressed by eqs 1 and 2, respectively:

\[
\nabla \cdot (\lambda_p(T) \nabla T_p) = -\sigma_p^{-1}(T))^2 + \nabla \alpha_p(T) J T_p
\]

\[
\nabla \cdot (\lambda_n(T) \nabla T_n) = -\sigma_n^{-1}(T))^2 + \nabla \alpha_n(T) J T_n
\]

where \( \lambda_p \) and \( \lambda_n \) are the thermal conductivities of the p- and n-type semiconductor elements, respectively, W/(m·K). The Seebeck coefficients of the p- and n-type semiconductor elements are \( \alpha_p \) and \( \alpha_n \), respectively, V/K. \( \sigma^{-1} \) is the electrical resistivity, 10^{-5} Ω·m, and \( J \) is the current density vector, A/mm².

Equations 3 and 4 are the energy conservation of copper sheets and ceramic chips, respectively.

\[
\nabla \cdot (\lambda_e(T) \nabla T) = -\sigma_e^{-1} J^2
\]

\[
\nabla \cdot (\lambda_e(T) \nabla T) = 0
\]

where \( \lambda_e \) and \( \lambda_e \) are the thermal conductivities of the copper sheets and ceramic chips, respectively, W/(m·K).

The electric field density vector can be regarded as the sum of electric potential difference and Seebeck voltage, as shown in eq 5. The current density vector equals electric conductivity times electric field density vector, as shown in eq 6. Also, the current continuity can be expressed as eq 7:

\[
E = -\nabla \phi + \sigma \nabla \varphi
\]

\[
J = \sigma \nabla \varphi
\]

\[
\nabla \cdot J = 0
\]

where \( E \) is the electric field intensity vector, V/mm², and \( \varphi \) is the electric potential, V.

The Seebeck coefficients of the p- and n-type semiconductor elements are \( \alpha_p \) and \( \alpha_n \), respectively, and the relative Seebeck coefficient of p- and n-type semiconductor is: \( \alpha_{p,n} = \alpha_p - \alpha_n \) (V/K). The temperature difference between the two sides of the TEG is \( \Delta T = T_h - T_c \). The total voltage generated in the TEG is expressed as follows:

\[
U_0 = \alpha_{p,n} \Delta T
\]

The internal resistance of 1-PN-TEG is \( R_m \) which is expressed as \( R_m = R_p + R_n + R_{cu} \) where \( R_p \) is the resistance of the p-type semiconductor element, \( R_n \) is that of n-type semiconductor element, and \( R_{cu} \) is the copper sheet’s resistance (all of the formulas and simulations in this paper are carried out under the condition of neglecting the contact resistance between copper and semiconductor elements). If the load resistance is \( R_l \), the total current \( (I) \) in the circuit can be calculated by eq 9:

\[
I = \frac{\alpha_{p,n} \Delta T}{R_p + R_m}
\]

The power output \( (P) \) of 1-PN-TEG can be calculated by eq 10:

\[
P = \frac{(\alpha_{p,n} \Delta T)^2 R_m}{(R_p + R_m)^2}
\]

The expression for efficiency \( (\eta) \) is:

\[
\eta = \frac{P}{Q_{in}}
\]

where \( Q_{in} \) is the inflow heat at the hot side of 1-PN-TEG.

All of the simulation results in this paper are obtained under the condition that the load resistance is equal to the internal resistance. The power at this point was defined to be \( P_{in} \).

3. RESULTS AND DISCUSSION

3.1. Cross-Sectional Shape of p, n-Type Semiconductor Elements. At the temperature difference of 200 K, the cross-sectional area of p, n-type semiconductor elements.
is kept at 16 mm², the thickness of P and N is 0.8 mm, the shape of the p, n-type semiconductor elements changed, and three different cross-sectional shapes are modeled: square, rectangle, and circular. Moreover, 1-PN-TEG is simulated by ANSYS. The results are shown in Figure 2.

The results listed in Figure 2 show that the power output of 1-PN-TEG is not affected by the shape of p, n-type semiconductor elements when the cross-sectional area is constant.

3.2. Thickness of p, n-Type Semiconductor Elements.
At the temperature differences of 200, 150, 100, and 50 K, the cross-sectional shape of p, n-type semiconductor element is square with a side length of 4 mm. By changing the thickness of p, n-type semiconductor elements, ANSYS is used to conduct the numerical simulation for 1-PN-TEG. The results are demonstrated in Figure 3.

The power output of 1-PN-TEG increases first and then decreases with the increasing thickness varying from 0.1 to 2 mm, as shown in Figure 3. The observation is near-consistent with the results of Brito et al.25 The simulation results are shown in Figure 3 (ΔT = 200 °C), which indicates how the power output of 1-PN-TEG varies with the thickness of semiconductor elements at the temperature difference of 200 °C. Although the values of parameters such as configuration parameters and resistivity are different, there is a particular difference in the power output obtained by simulation; the variation of power output with the thickness of semiconductor elements is consistent. The explanation of this modeling phenomenon is described briefly in the following.

The thermal resistance of ceramic plates causes the power to increase first and then decrease with the thickness of the semiconductor elements. When the thickness of the semiconductor elements is relatively small, the thermal resistance of ceramic plates accounts for a large part of the overall thermal resistance of 1-PN-TEG, which causes a large temperature drop in the ceramic plate.

It can also be seen from Figure 3 the effect of temperature difference on power. The high-temperature difference leads to a high power output. According to the thermoelectric power generation principle, the Seebeck voltage and power increase with the increase in temperature difference.

The change of power output and efficiency with the thickness of semiconductor elements at a temperature difference of 200 K is presented in Figure 4. It can be seen from the figure that, although the efficiency (calculated using eq 11) increases gradually with increasing thickness, the power decreases with the increase in thickness. Higher efficiency does not guarantee a greater power output. After reaching a specific thickness, the efficiency increases, but the power decreases. In a specific temperature difference, efficiency will reach a limit, i.e., the Carnot efficiency. According to the relevant laws of thermodynamics, the calculated Carnot efficiency agrees well with the simulation results, which further proves the accuracy of the experimental result. As shown in Figure 4, the intersection points of power and efficiency are not the same under different temperature conditions.

As shown in Figure 4, the efficiency increases with the thickness of the semiconductor elements with lower power and increased material cost. Low-temperature energy utilization maximizes the power output and not the efficiency, even at the expense of higher thermal loss. The lower thickness of the semiconductor elements will increase the heat, but the power will increase when a certain threshold is reached.25 To ensure both thermal efficiency and power output, the intersection of power and efficiency is considered to be the optimum thickness of the semiconductor elements. The optimum thickness of the semiconductor elements is varied at different temperature conditions. When the temperature differences are 50, 100, 150, and 200 K, the best thicknesses of the semiconductor elements are 0.1, 0.2, 0.4, and 0.6 mm, respectively.
respectively. This is because both the power output and efficiency can be guaranteed at the power vs efficiency curve.

Numerical simulation is conducted to model the temperature and voltage field distribution inside the TEG. When the thickness of the semiconductor elements is 0.8 mm, the temperature of the hot side is 250 K and that of the cold side is 50 K. The changes in temperature and voltage field of 1-PN-TEG from the hot side (top) to the cold side (bottom) can be calculated, and the results are shown in Figures 5 and 6. Figure 5 shows that the temperature decreases slowly in the thermally conductive ceramic sheet and the copper sheet, and the temperature drop in 1-PN-TEG is mainly distributed in bismuth telluride. Figure 6 shows the voltage distribution within the 1-PN-TEG.

3.3. Cross-Sectional Area of p, n-Type Semiconductor Elements. At the temperature difference of 200 K, the cross-sectional shape of p, n-type semiconductor elements is square, the thickness of p, n-type semiconductor elements is 0.8 mm, and the thickness of the copper sheet is 0.05 mm; by changing the width of p, n-type semiconductor elements, and the change of power output with the cross-sectional area was obtained.

The concept of duty cycle is introduced here. The module duty cycle ($r$) is defined as the ratio of the cross-sectional area of p, n-type semiconductor elements to the module area.\(^3\,4\) If the width of the p, n-type semiconductor elements is 4 mm, the distance between p- and n-type semiconductor elements is 2 mm, $r = (4 \times 4 \times 2)/(4 \times 10) = 0.8$. In this paper, the module duty cycle has been kept at 0.8. The variation of power with area and power per unit area is shown in Figures 7 and 8.

Figure 7 shows that the power output of 1-PN-TEG increases with the cross-sectional area until the latter reaches 100 mm\(^2\). It can be seen from Figure 8 that the power per area decreases with the increase of the cross-sectional area until the latter reaches 100 mm\(^2\). The phenomenon observed in Figure 7 is explained as follows:

Generally, the heat transfer rate through a material is proportional to the negative gradient in temperature and area, at right angles to that gradient, through which the heat flows, as shown in eq 12.
\[ Q = -\lambda A \frac{\Delta T}{\Delta x} \]  

(12)

where \( Q \) is the heat transmitted in unit time, W; \( A \) is the cross-sectional surface area, \( m^2 \); \( \lambda \) is the coefficient of thermal conductivity, \( W/(m \cdot K) \); and \( \frac{\Delta T}{\Delta x} \) is the temperature gradient.

According to eq 12, when the sectional area increases, conduction heat flow from the hot side increases, so the power output will increase. The increase in section area will lead to smaller internal thermal resistance, energy conversion efficiency, and reduced power per unit area. When the internal resistance is equal to the load resistance, the power is expressed as

\[ P_m = \frac{(\alpha_{pN} \Delta T)^2}{(4R_g)} \]  

(13)

where \( R_g = R_p + R_n + R_{cu} \) the cross section of p, n-type semiconductor elements is denoted by \( S \), and according to the formula \( R = \frac{\rho L}{S} \), eq 13 can be transformed into

\[ P_m = \frac{(\alpha_{pN} \Delta T)^2}{(R_{cu} + R_p + R_n)} = \frac{(\alpha_{pN} \Delta T)^2}{\left( \frac{\rho_{pL}}{S_p} + \frac{\rho_{nL}}{S_n} + \frac{\rho_{cu}}{S_c} \right)} \]  

(14)

Taking known parameters into account, they can be reduced to

\[ P_m = \frac{a}{b + c} \]  

S  

(15)

where \( a, b, \) and \( c \) are constants, and \( S \) is the cross-sectional area of p, n-type semiconductor elements. According to eq 15, the power output of 1-PN-TEG increases with an increase in the cross-sectional area, but the growth rate becomes smaller and smaller. This phenomenon explained the observation shown in Figure 7.

When \( S \) approaches infinity, eq 15 is reduced to eq 16

\[ \lim_{S \to \infty} P_m = \frac{a}{b} \]  

(16)

Therefore, when the cross-sectional area becomes more extensive, \( P_m \) gradually increases until it becomes a constant value. The power per area, \( P_{ms} \), can be expressed by eq 17.

\[ P_{ms} = \frac{a}{bS + c} \]  

(17)

where \( a, b, \) and \( c \) are constants, and \( S \) is the cross-sectional area of p, n-type semiconductor elements. When \( S \) approaches infinity, eq 17 is reduced to eq 18

\[ \lim_{S \to \infty} P_{ms} = 0 \]  

(18)

The cross-sectional area gradually increases and \( P_{ms} \) approaches 0. Equations 17 and 18 show that the power per area decreases with an increase in the cross-sectional area. These results are shown in Figure 8.

Figures 7 and 8 show that the power output increases as the area increases and the power per unit area decreases as the area increases. Figure 9 demonstrates the modeling data from both Figures 7 and 8. The intersection of the curve of power output and the power output curve per unit area (Figure 9) ensures that 1-PN-TEG has higher power output and efficiency.

To further show the effect of cross-sectional area and thickness on the power output of 1-PN-TEG, a diagram of the variation of power with the ratio of area to thickness is plotted (see Figure 10). The power change with the area and thickness product and the power change per unit area are shown in Figures 11 and 12, respectively. Figure 13 shows the change of power per unit area with a product of area and thickness. As shown in Figure 10, when the ratio of area to thickness is relatively small, the power of different thicknesses of 1-PN-TEG is close to each other. However, when the ratio of area to thickness increases, the power increases with the thickness of semiconductor elements. Similar to the thickness of the semiconductor elements, the power output increases as the ratio of area increases.

With increasing area and thickness, the power increases gradually and finally tends to be stable (see Figure 11).
phenomenon is interesting and may be used in designing TEG systems. For example, one may estimate the mass of bismuth telluride required to generate a specific TEG power value.

The power per unit area decreases gradually with the increase of the ratio of area to thickness, as shown in Figure 12.

Figure 13 shows that the power per unit area decreases gradually with the product of area and thickness. The power per unit volume decreases with the increase of the area, and the data are shown in Figure 14. The larger thickness of the semiconductor elements leads to the smaller power per unit volume for the same cross-sectional area.

3.4. Effect of Heat Insulation Material. When the temperature of the hot side is 250 K, the temperature of the cold side is 50 K, and width of p, n-type semiconductor elements is 4 mm, the effect of heat insulation material is simulated by only changing the thermal conductivity of the heat insulation material filled between the p- and the n-type semiconductor elements. The results are shown in Figure 15.

It can be seen from Figure 15 that power output increases with the decrease in thermal conductivity of the heat insulation material.

Simultaneously, the temperature field distribution and the voltage field distribution inside 1-PN-TEG after filling the insulating material are simulated. Figure 16 shows the temperature field change from the hot side (top) to the cold side (bottom) with a thickness of 0.8 mm. Different temperature drops can be observed in materials with different thermal conductivities. Compared with Figure 5, it can be seen that heat insulation material affects the temperature distribution inside one unit of TEG. Figure 17 demonstrates the voltage field distribution.

3.5. Effect of Heat Convection. The convective heat transfer between the top and bottom ceramic walls is proportional to the temperature difference, which is

\[ q = h(t_w - t_\infty) \]  
\[ Q = h(t_w - t_\infty)A = Aq \]

where \( q \) is the quantity of heat exchanged between solid surface and fluid (W/m²), \( t_w \) and \( t_\infty \) are the temperatures of solid surface and fluid (K), respectively, \( A \) is area (m²), \( Q \) is the heat transfer heat per unit area (W), and \( h \) is the surface convection heat transfer coefficient (W/(m²·K)).

At the temperature difference of 200 K, the cross-sectional shape of p, n-type semiconductor elements is square, the thickness of p, n-type semiconductor elements is 0.8 mm, and the copper sheet’s thickness is 0.05 mm. The convection heat transfer coefficient is changed in simulation. The results are shown in Figure 18.

Figure 18 shows the change of the power output with the convection heat transfer coefficient.

As shown in Figure 18, with the increase of convection heat transfer coefficient, the 1-PN-TEG power also increases, as foreseen by eqs 19 and 20.

3.6. Effect of the Thickness of the Copper Sheet. Copper sheets are often used as a bridging conductor between p- and n-type semiconductor elements. The thickness of the copper sheet is investigated, and the results are shown in Figure 19. The temperature difference is 200 K. The cross-sectional area of the p, n-type semiconductor elements is kept constant, the thickness of the p, n-type semiconductor
elements is 0.8 mm, and the width of the p, n-type semiconductor elements is 4 mm.

Figure 19 illustrates that decreasing the copper sheet’s thickness initially has a positive effect on power, but a negative effect later. When the copper sheet thickness is about 1 mm, the power reaches the optimum value in the case studied. This phenomenon is explained as follows. When the internal resistance is equal to the load resistance, the calculation formula of output power is shown in eq 13.

\[ R_l = R_P + R_N + R_{cu}, \text{ the thickness of the copper sheet is } H_{cu}, \]

and according to the formula \( R = \frac{\rho L}{S} \), eq 13 can be transformed into

\[ \alpha = \frac{(a_{PN}\Delta T)^2}{(R_{cu} + R_P + R_N)} = \frac{(a_{PN}\Delta T)^2}{\rho_c L_{cu} + \rho_p L_P + \rho_N L_N} \]  

(A21)

Using the known parameters, eq 21 may be reduced to

\[ P_m = \frac{m}{n + \frac{k}{H_{cu}}} \]  

(A22)

where \( m, n \), and \( k \) are constants, and \( H_{cu} \) is the thickness of the copper sheet.

Equation 22 shows that the power becomes higher when the thickness of the copper sheet becomes greater. Nevertheless, when the copper sheet thickness increases to a certain extent, the temperature difference will decrease fast so that the generated voltage as well as power will be reduced. Therefore, \( P_m \) increases first and then decreases as the thickness of the copper sheet increases.
3.7. Discussion. Six factors that may affect the power output are simulated in this paper. The shape of p, n-type semiconductor elements has little influence on the power output. The influence of the thickness of p, n-type semiconductor elements on the power output is consistent with the previous simulation results; it is found that an optimized thermoelectric element thickness maximizes the electrical power output. This paper optimizes the previous research results and verifies that the power output slowly increases with the increase of the cross-sectional area. It also concludes that the power output of 1-PN-TEG increases with the cross-sectional area until the cross-sectional area reaches 100 mm². The power per unit area decreases as the area increases. A few studies reported in the literature have investigated heat convection optimization for TEG. This work shows that with the increase of convection heat transfer coefficient, the power of 1-PN-TEG also increases, which is consistent with the actual situation. At present, no study has been found on the numerical simulation of copper sheet thickness, and the numerical simulation results of this paper show that there is an optimal value of copper sheet thickness.

4. CONCLUSIONS
A three-dimensional model of 1-PN-TEG was constructed, and the calculation was conducted using ANSYS. The thickness of semiconductor elements, the cross-sectional area of p- and n-type semiconductor elements, the heat insulation material, the thickness of copper sheet, and other factors were modeled and analyzed to study their effects on the power output of 1-PN-TEG. According to the current modeling data and results, the following conclusions may be obtained:

(1) The power output of 1-PN-TEG increases first and then decreases with the increase in the thickness of the thermoelectric element. It is found that an optimized thickness maximizes the power output.
(2) The power output of 1-PN-TEG increases with the cross-sectional area of p- and n-type semiconductor elements and approaches a constant value finally. The power output per unit area decreases with the increase in the cross-sectional area.
(3) The lower conductivity of the insulating material between p- and n-type semiconductor elements leads to a greater power output.
(4) The power increases first and then decreases with the increase in the thickness of the copper sheets (serving as a bridging conductor between p- and n-type semiconductor elements).
(5) The power increases with the volume of the p- and n-type semiconductor elements gradually and tends to be stabilized ultimately. This observation may be used to estimate how much thermoelectric material is required to generate a specific value of TEG power.
(6) The greater the convection heat transfer coefficient, the higher the power of the 1-PN-TEG.

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Notes
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■ NOMENCLATURE
A cross-sectional surface area
a constant
b constant
c constant
E electric field intensity vector
H thickness of semiconductor elements
Hcu thickness of copper sheet
h surface convection heat transfer coefficient
I total current
J current density vector
k constant
Lp thickness of the p-type semiconductor element
LN thickness of the n-type semiconductor element
m constant
n constant
P power output
Pm power output when the load resistance is equal to the internal resistance
Pms power per area
Q heat transfer per unit area
Qms incoming heat flow at the hot side of 1-PN-TEG
q quantity of heat exchanged between solid surface and fluid
Ri internal resistance of 1-PN-TEG
Rp resistance of the p-type semiconductor
RN resistance of the n-type semiconductor
Rcu copper sheet’s resistance
Rm load resistance
r module duty cycle
S cross-sectional area of p, n-type semiconductor elements
Th temperature of hot side
Tc temperature of cold side
Uo total voltage
Wp width of the p-type semiconductor element
Wn width of the n-type semiconductor element
GREEK SYMBOLS

\( \alpha_p \) Seebeck coefficients of the p-type semiconductor element

\( \alpha_n \) Seebeck coefficients of the n-type semiconductor element

\( \lambda \) coefficient of thermal conductivity

\( \eta \) efficiency

\( \sigma^{-1} \) electrical resistivity

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