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Research Paper

A three-dimensional model for thermoelectric generator and the influence of Peltier effect on the performance and heat transfer

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HIGHLIGHTS

- A 3-D model for thermoelectric modules which consisting of 127 thermocouples is developed.
- An experiment was carried out to validate the simulation.
- Influence of Peltier effect on the performance and heat transfer is investigated.
- The Peltier effects are proved to be more remarkable for weak heat transfer boundary conditions.

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ABSTRACT

Thermoelectric generator has been considered as a promising device to recover industrial waste heat for electricity generating. To figure out the heat transfer and electric conduction processes in thermoelectric generator, a three-dimensional numerical model has been built up which consists of 127 thermocouples. The open-circuit voltage, internal resistance, and output power have been studied by numerical simulation. All calculation results are in good agreement with the experimental results, and the maximum deviation is less than 6%. Due to the influence of Peltier effect, both heat flow and equivalent thermal conductivity increases by 30.2% when temperature difference between the hot and cold side is 170 °C and the thermoelectric generator reaches its maximum power output. In addition, the Peltier effect has been investigated when the convective heat transfer boundary conditions are applied. The results showed that the effective temperature difference was raised to 13.6 °C (a 10.2% increase) and maximum output power was raised to 0.59 W (a 14.8% increase) for the thermoelectric generator model with a fin height of 100 mm when compared with that without fins. Besides that, the radio of load resistance to internal resistance decreased from 1.31 to 1.14.

1. Introduction

In recent years, thermoelectric generator (TEG) is attracting more and more attention due to its ability to generate electricity from waste heat [1,2]. TEG has many advantages, such as no moving parts, no chemical reaction, no pollution, no noise and a longer lifespan [3–5]. Moreover, as a solid-state heat engine, TEG generates a voltage whenever there is a temperature gradient. Therefore, TEG can be used to recover the energy in many processes in which heat is released directly to the atmosphere. Therefore, TEG is recognized as one of the most potential energy technologies in the 21st century [6].

Thermoelectric effects have been discovered for more than 40 years and many researchers have been concentrating on the investigations of improving the thermoelectric properties of materials [7,8]. In addition, optimizing the structure of thermoelectric devices based on thermal analysis is also an important way to improve the performances of TEG. Consequently, precise, complete description of the thermoelectric coupling process in the thermoelectric devices and analysis of the influence of various factors on the output index are vital for the amelioration of TEG's performance.

So far, computation tools have been used to build one-dimensional [9,10] or three-dimensional [11,12] heat transfer model, and the performances of TEG can be obtained by solving electric potential distribution and temperature distribution. More recently, Kossyvakis et al.

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[13] investigated the temperature distribution on the hot side and performance reduction by thermal losses based on a finite element model which consists of 71 thermocouples. The discrepancy between computation and measurements is acceptable, which indicates that the model can be used in the evaluation of TEG's performances.

However, accurate prediction of the power production can be difficult because many heat transport mechanisms occur simultaneously in TEG. In early attempts, the numerical and experimental results were compared using single thermocouples [14,15]. It indicated that the temperature dependence properties of materials have a significant impact on calculation results and the contact thermal resistance should not be neglected [16]. In general, p-type and n-type thermoelectric material have the similar index called the figure of merit (ZT). So the p-type and n-type elements have the same geometric size and the devices can be assembled more conveniently. However, the similar ZT does not mean the same material properties such as the similar thermal conductivity and resistivity. So the p-type and n-type elements were treated as two separate parts and the differences in thermal behavior between the two elements are distinguished and evaluated [12]. Later, the influences of size effect on the power generation and thermal stresses were investigated based on a model which consists of two thermocouples. The results indicated that the power outputs and the efficiencies are related to the leg size and spacing [17]. More recently, Li et al. [18] pointed out that attention should be paid to the contact electrical resistance induced by welding. However, the studies mentioned above are limited to the investigation of single or a few thermocouples behaviors. In real situations, a commercial TEG module usually consists of a large number of thermocouples. Chen et al. [12] mentioned that the number of thermocouples has a significant impact on the TEG devices' cooling power. And they also [19] pointed out that the number of thermoelectric elements affects the power output and efficiency. Thus, a new holonomic model is needed for the full analysis of heat transfer and electric conduction processes in TEG.

As mentioned above, the computational method is a reliable tool to predict the performances and optimize the geometry structure of TEG. Besides, a precise and complete model must contain the following features: (1) the p-type and n-type must be treated as two separate parts and all the material properties are temperature-dependent; (2) the model must contain, besides P/N junction and conductive strips, a solder layer and ceramic plates; (3) the model should contain enough P/N junction if the computation conditions are allowed.

Moreover, there are still some difficulties in establishing a finite element model that couple with heat, electricity, and fluid flow at the same time. Thus, the following two methods are often used to calculate the output performance when TEG operating in fluids with temperature difference: (1) Firstly the liquid-solid conjugate heat transfer is calculated to determine the temperature field. Then the TEG's temperature of the hot and cold sides are used as the boundary condition for the calculation coupled with heat and electricity [18]; (2) Only the temperature field is calculated by simplifying the TEG model and the electric energy output is approximated by zero-dimensional model according to the obtained temperature field [20]. Both these two methods are based on the assumption that TEG is in an open-circuit state. However, when TEG is in a closed state, the Peltier effect produced by the current usually transfers extra dozens W of heat flow from the hot side [21]. The temperature field previously established may be changed significantly, especially when the heat transfer condition is weak such as the convective heat transfer with air. Under these conditions, the temperature difference between the two sides of TEG will be directly reduced and a relatively large deviation will appear in the final results. Nevertheless, there are few articles that discuss the extent of the influence of Peltier effect on different heat transfer conditions.

In this paper, a new complete TEG model consisting of 127 thermocouples has been developed and a laboratory TEG system has been built to verify the accuracy of the model. The open circuit voltage, internal resistance and maximum output power have been studied by numerical simulation and experiment. The p-type and n-type are treated as two separate parts and are based on temperature-dependent properties. In addition, the performance of TEG in a closed state, not in an open circuit state as previously done, has been investigated and the influences of Peltier effect on the performances, the temperature distribution and the equivalent thermal conductivity of the TEG under the convective heat transfer boundary conditions have been analyzed.

2. Theoretical model

TEGs' operation bases on the Seebeck effect: when two dissimilar conductors join together and form a closed loop, a voltage is produced due to a temperature difference between the two junctions. To obtain a greater voltage, a certain amount of thermoelement pellets are connected in series through copper strips and are sandwiched between two ceramic plates. The TEG module is connected to a load resistance to output electric energy during operation.

When the electric field and temperature field exist simultaneously, all processes occurring in the thermoelectric element can be expressed as:

$$\vec{j} = \frac{1}{\rho}(\vec{E} - \alpha\nabla T)$$

$$\vec{q} = \alpha T\vec{j} - \kappa\nabla T$$

where $\vec{E}$ is the electric field intensity; $\vec{j}$ is current density; $\vec{q}$ is heat flux; T is temperature; α, ρ, and κ are the Seebeck coefficient, electrical resistivity and thermal conductivity of a thermoelectric element, respectively.

An energy balance analysis for the p and n thermoelements leads to the energy equation [22]:

$$C_p a_p \frac{\partial T_p}{\partial t} = \nabla^2\kappa_p(x,y,z,T)\cdot T_p - jT_p\alpha_p(x,y,z,T) + j^2\rho_p(x,y,z,T)$$

$$C_n a_n \frac{\partial T_n}{\partial t} = \nabla^2\kappa_n(x,y,z,T)\cdot T_n + jT_n\alpha_n(x,y,z,T) + j^2\rho_n(x,y,z,T)$$

In which, subscripts p and n represent the materials p and n, respectively; C denotes the specific heat and a is density.

In steady state, the heat loss along the side of thermoelectric elements and Thomson effect are ignored. Taking into account the temperature dependence of material properties α, ρ, and κ, the steady-state heat transfer equation can be written as:

$$Ca\frac{\partial T}{\partial t} = 0 = \nabla^2\kappa(x,y,z,T)\cdot T - jT\alpha(x,y,z,T) + j^2\rho(x,y,z,T)$$

The electric potential equation can be written as [23]:

$$\nabla^2\phi(x,y,z) = -\alpha\nabla^2 T$$

where φ is the electric scalar potential.

3. Performance of TEG

The open circuit voltage (U_0) is calculated as [24,25]:

$$U_0 = \mathrm{n}\cdot(\alpha_p + |\alpha_n|)\cdot(\mathrm{T}_h - \mathrm{T}_c)\cdot\left(\frac{R_i}{R_i + R_l}\right) = \mathrm{n}\cdot\alpha_{pn}\Delta T\cdot\left(\frac{R_i}{R_i + R_l}\right)$$

where n is the number of thermocouples in TEG module; T_h is the temperature of hot side; T_c is the temperature of cold side; R_i is the thermal resistance of thermocouples; R_l is the total contact thermal resistance of TEG module.

The output power gets the maximum value (P_{max}) when the load resistance r_l value is equal to the internal resistance r_i:

$$m = \frac{r_l}{r_i} = 1$$