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Characteristics analysis and parametric study of a thermoelectric generator by considering variable material properties and heat losses

Jing-Hui Meng [a], Xin-Xin Zhang [a], Xiao-Dong Wang [b,c,*]

[a] School of Mechanical Engineering, University of Science and Technology Beijing, Beijing 100083, China
[b] State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China
[c] Beijing Key Laboratory of Multiphase Flow and Heat Transfer for Low Grade Energy, North China Electric Power University, Beijing 102206, China

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ABSTRACT

The output power and conversion efficiency of the thermoelectric generator (TEG) are closely related to not only the materials properties but also the geometric structure. This paper developed a multi-physics, steady-state, and three-dimensional numerical TEG model to investigate the TEG performance, and then the model is compared with the classical thermal resistance model. Bismuth-telluride are used as p- and n-type materials. The comparison reveals that the assumption of constant material properties leads to underestimated inner electrical resistance, and overestimated thermal conductance and Seebeck coefficient, so that the thermal resistance model predicts unrealistically high performance than the present model. The results also indicate that when heat losses exist between the TEG and the ambient, although the output power is slightly elevated, the conversion efficiency is significantly reduced, hence, improvement of the heat insulation effect is critically important for high-temperature TEGs. Furthermore, the TEG geometry also affects its performance significantly: usage of thin ceramic plates increases the junction temperature difference, and hence enhances the TEG performance; there are two optimal leg lengths which correspond to the maximum output power and the maximum conversion efficiency, respectively; when heat losses are not ignorable, a large semiconductor cross-sectional area remarkably reduces the ratio of the heat liberated to the ambient to the heat absorbed from the high-temperature heat source, and hence improves the conversion efficiency.

1. Introduction

Energy conservation and emissions reduction issue has become a global consensus due to the serious greenhouse effect and climate change. Hence, renewable energy sources, such as wind, solar, hydro and geothermal energy, have made a considerable development and progress in the last decades. As one of such alternatives, thermoelectric generator (TEG) directly converts heat into electricity by Seebeck effect of thermoelectric materials. The TEG is more robust, flexible and reliable when compared with convectional power generators, because it requires neither real working fluids nor moving parts, so that it is attracting more and more attention [1–12].

The output power and conversion efficiency as indicators for evaluating the TEG performance are closely related to the figure-of-merit of thermoelectric materials, $ZT = \alpha^2\sigma T/\lambda$, 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 [13–15]. Thermoelectric materials with larger ZT can improve the TEG performance. Previous research has demonstrated that α, σ, and λ for most thermoelectric materials are all strongly temperature-dependent. It should be noted that the TEG generally works at a higher temperature difference than the thermoelectric cooler (TEC), such as the recycling of waste heat for iron and steel industry. Thus, it is expected that the temperature-dependent materials properties have much significant effect on the TEG performance. In the previous research, the thermal resistance model was widely used to investigate the TEG performance, and the model is still most frequently adopted so far. This kind of model can derive analytical expressions of the output power and conversion efficiency, so that it can be applied for preliminary screening of TEG design and performance estimation. However, the model accounts for energy balances only at the hot end and the cold end of the TEG. As a result, the constant [1–4,6,8,10–12], or temperature-averaged [5] materials properties

* Corresponding author at: State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China. Tel./fax: +86 10 62321277.

E-mail address: wangxd99@gmail.com (X.-D. Wang).

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must be assumed. Recently, Chen et al. [9] proposed and implemented a 3D numerical model for TEG in FLUENT UDS (User Defined Scalar) environment. Using the same model, Reddy et al. [16] investigated the performance of a novel composite thermoelectric device where a major part of the semiconductor is replaced with a conductor such as copper. In their studies [9,16], the great influence of materials properties are emphasized on the TEG performance. We also developed general, steady-state or transient, 3D numerical models of thermoelectric devices [17–19], in which the heat conduction equation and the electric potential equation were solved coupled and all thermoelectric effects were taken into account, including Seebeck effect, Peltier effect, Thomson effect, Joule heating, Fourier's heat conduction, and heat loss to the ambient. The materials properties were proven to have significant effect not only on the steady-state performance but also on dynamic characteristics for TEC. However, there is no detailed explanations in the literature how materials properties affect the TEG performance.

In addition to the materials properties (α, σ, λ, or ZT), the geometric structure of the TEG also significantly affects its performance. By optimizing the ceramic plate thickness, the leg length and the cross-sectional area of semiconductors, a high-performance TEG can be designed. Some research has already studied the geometric-dependent TEG performance using the thermal resistance model [20–22], or one-dimensional model [23,24]. However, the three-dimensional temperature effect cannot be ignored when there exist significant heat losses from the TEG to the ambient. Recently, Jang et al. [25] investigated the optimal structure of high-performance micro-TEG at room temperature using a three-dimensional model. However, constant materials properties are adopted in their work, because the TEG operates with only a 15 K temperature difference.

This work develops a multi-physics, steady-state, and three-dimensional numerical TEG model to investigate the optimal TEG geometric structure. The proposed model is compared with the classical thermal resistance model to demonstrate the effects of temperature-dependent materials properties and heat losses on the accurate prediction of the TEG performance. Especially, this paper will explain from the heat transfer mechanism why the thermal resistance model predicts unrealistically high performance of TEG. The article structure arrangement is organized as follows. Sections 2 and 3 describe and validate the new three-dimensional TEG model. Section 4 compares the new model with the conventional thermal resistance model to highlight the effect of temperature-dependent materials properties. Section 5 reveals the reduction in the TEG performance due to its heat losses to the ambient. Finally, the optimal structure parameters of the TEG are discussed in Section 6, including the ceramic plate thickness (Section 6.1), the leg length (Section 6.2), and the cross-sectional area (Section 6.3) of semiconductors.

2. Model

2.1. Numerical model

As the basic element of a practical TEG, the p–n junction is formed by connecting two different types of thermoelectric materials (the hole-rich p-type semiconductor and the electron-rich n-type semiconductor) together. When a temperature difference is supplied to the two sides of the junction, the thermal excitation causes migration of carriers from the hot side to the cold side, so that a Thomson electromotive force will be created. In addition, there exists a concentration difference of carriers between p- and n-type materials, which activates the electrons diffusion from the n-type material to the p-type material and the back diffusion of holes. As a result, a Peltier electromotive force will be constructed. The Seebeck electromotive force is the sum of the Thomson and Peltier electromotive forces, which is a maximum electric potential produced by the junction and is also referred as to the open-circuit voltage. However, when a load is connected to the junction, the junction cannot produce the electric potential difference as large as the open-circuit voltage because of the electric potential drop caused by inner electrical resistance of the junction. To obtain a higher output voltage, many p–n junctions need to be connected in series to form a TEG.

Fig. 1 shows the schematic of a TEG unit, where a p–n junction (n-doped and p-doped bismuth-telluride legs) is connected electrically in series by copper connectors, and is sandwiched between two same ceramic plates (silicon). As electrical insulation layer, the ceramic plate plays a role in thermal conduction from outer heat sources and cooling parts to p–n junction.

The three-dimensional, steady-state TEG model developed here solves heat and electricity conductions simultaneously. The governing equations and boundary conditions are as follows.

2.1.1. Heat conduction equations

$$\nabla \cdot (\lambda_i \nabla \mathrm{T}) + \frac{J^2}{\sigma_i} - \beta_i \vec{J} \cdot \nabla T = 0 \tag{1}$$

where λ is the thermal conductivity, σ is the electric conductivity, and β is the Thomson coefficient. The subscript i denotes conn for the connectors, p for the p-type semiconductor, n for the n-type semiconductor, cer for the ceramic plates, respectively. $\vec{J}$ is the local current density vector and equals zero for the ceramic plates. The first term on the left side in Eq. (1) denotes the Fourier heat conduction, and the second and third terms denote the Joule heating and Thomson effect, respectively.

2.1.2. Electric potential equation

$$\nabla \cdot (\sigma(\nabla \phi - \alpha \nabla T)) = 0 \tag{2}$$

where α is the Seebeck coefficient of semiconductors, ϕ is the electric potential, $\alpha\nabla T$ is Seebeck electromotive force coming from the Seebeck effect.

The Thomson coefficient is proportional to the first derivative of the Seebeck coefficient versus temperature, or:

$$\beta = T\frac{\mathrm{d}\alpha}{\mathrm{d}T} \tag{3}$$

Once the electric potential is obtained, the current density vector can be calculated by the following equation:

$$\vec{J} = \sigma\vec{E} = \sigma(-\nabla\phi + \alpha\nabla T) \tag{4}$$

2.1.3. Boundary conditions

The boundary conditions are described in Fig. 1. The temperatures at the top of the upper ceramic plate and the bottom of the lower ceramic plate are 450 K and 300 K, respectively. At the interfaces between different materials, temperature and heat flux are all assumed continuous. The side surfaces of n- and p-type semiconductors are convective boundary conditions, or:

$$-\lambda\frac{\partial T}{\partial n} = h(T - T_\infty) \tag{5}$$

where h is the convective heat transfer coefficient, T_∞ is the ambient temperature assumed to be 300 K. The boundary conditions for electric conduction include: (1) at the side surface of the connector under the n-type semiconductor: $J = I/A_c$ = constant, where I is the load current and A_c is the side surface area of the