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Transient modeling and dynamic characteristics of thermoelectric cooler

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HIGHLIGHTS

- A complete three-dimensional TEC transient model was proposed.
- The model couples heat conduction and electric conduction.
- Dynamic behaviors are studied at extensive operating conditions.
- Temperature-dependent material properties have strong effect on dynamic behaviors.

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ABSTRACT

Dynamic characteristics are extremely important for design and operation of thermoelectric coolers (TECs). This paper develops a three-dimensional transient TEC model based on the coupling of heat transfer and electric conduction within semiconductors. The model takes into account all thermoelectric effects, including Joule heating, Thomson effect, Peltier effect and Fourier's heat conduction. For most of semiconductor materials, Seebeck coefficient, electric conductivity and thermal conductivity are strongly temperature-dependent. Therefore, the present transient model is used to compare dynamic temperature variations at the cold and hot ends with constant and variable material properties. Small, medium, and large applied currents with various cooling loads are adopted as operating conditions. The results show that, at small currents, constant property model developed by this work can predict accurately the dynamic characteristics, however, with the increase in current, the temperature-dependence of properties have more and more remarkable effect on the dynamic temperature variations, especially for high cooling loads. When the current is larger than a specific value, the heat transferred from the hot end to the cold end by Fourier's heat conduction will exceed the heat adsorbed at the cold end by Peltier effect, thus, the temperatures at the cold and hot ends increase continuously, the TEC cannot reach the steady-state. This phenomena is predicted exactly by the variable property model, oppositely, the constant property model predicts that the TEC still supply refrigeration.

1. Introduction

In recent years, TECs have attracted more and more attention due to their features of no compressors and refrigerants, large operating temperature range, easy to control, reliable operation, layout flexibility, adaptability and other characteristics [1–3]. The TEC has been frequently used for the cooling of electric devices such as CPU, infrared sensor, ice-point reference in thermocouple thermometry, and refrigerators [4]. Generally, the TEC includes a number of thermoelectric elements, which are connected electrically in series and thermally in parallel. The thermoelectric elements are composed of a pair of p- and n-type semiconductors. When electric current flows across the thermoelectric elements, the heat is transported from the cold end to the hot end caused by the Peltier effect.

A large amount of works considered the TEC performance [5–13] and the TEG performance [14–22] under steady-state condition, while few works [4,23–29] investigated its transient or dynamic characteristics. Actually, transient characteristics are also extremely important in practical TEC operation. First, cooling load at the cold end and/or cooling capacity of heat sink and ambient temperature at the hot end may be variable [24]. Second, the start up and shut down characteristics of TECs are also a major concern for cooling purpose [25,26]. For example, for a fixed cooling load at the cold end and a fixed cooling capacity of heat sink at the hot end, when a specific current is applied to the TEC, how much is the consuming for the TEC to reach the steady-state and what

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are the corresponding steady-state temperatures of cold and hot ends. In addition, as a current pulse with a magnitude of several times higher than the steady-state optimum current is applied to a TEC, the transient lower temperature than that reachable at the steady-state can be achieved at the cold end due to the delay of the thermal diffusion of the volumetric Joule heat, which is referred to as the transient thermoelectric effect [27,28].

Up to now, some transient models have been developed to understand the dynamic behaviors of TEC. Mostly the previous transient models were limited to one-dimensional problems [4,24,28], where the Thomson effect was ignored and constant material properties were used because small temperature difference between the cold and hot ends was assumed. In addition, as mentioned by Cheng et al. [26], in the existing models, the p-n element pair was simply treated as a single bulk material so that the difference in thermal behavior between the two semiconductor elements was not possible to evaluate. Hence, Cheng et al. developed a three-dimensional model with p-type and n-type semiconductors as two separate parts and the Thomson effect was taken into account. However, the material properties were still assumed to be constants in the Cheng's model.

Recently, we proposed a general, three-dimensional TEC steady-state model [29], which is different from previous models [5–13] in which only heat conduction equation with Joule heat and/or Thomson heat as internal heat sources is solved. Our model introduced the coupling of heat conduction and electrical conduction, and considered all the effects occurred in the TEC. The model was used to figure out the performance of TECs with the temperature-dependent material properties. The predictions showed that the variable properties and the heat losses to the ambient gas have significant effects on the cooling capacity and the coefficient of performance (COP) of the TEC. Three-dimensional temperature distributions within semiconductors was observed and it became more remarkable at large temperature differences and high currents.

The purpose of this work reaches the following targets: (1) extending our previous steady-state model [29] to a transient one; (2) employing the developed transient model to investigate the dynamic characteristics of TECs under various operating conditions. The dynamic behaviors for TECs with temperature-dependent properties are analyzed and compared with those constant properties.

2. Model development

The schematic of a TEC device containing one semiconductor element pair (referred to as TEC element hereafter) is shown in Fig. 1. A TEC device consists of a number of TEC elements. In consideration that the thermal characteristics among the TEC elements are periodic, hence, only one element is considered here. The TEC element includes a pair of p- and n-type semiconductor columns, three metallic connectors, and two electrically insulating ceramic plates. The ceramic plate, connector, and semiconductor columns have thicknesses of H_0, H_1, and H_2, respectively. The semiconductor columns have square cross-section with the side length of L_2. The distance between p- and n-type semiconductors is L_1. A heat sink with the thickness of H_s is attached on the hot end of the TEC element for heat dissipation. The geometric parameters of the TEC element simulated in the present work are as follows, L_1 = 0.2 mm, L_2 = 0.5 mm, H_0 = 0.2 mm, H_1 = 0.1 mm, H_2 = 1.0 mm, and H_s = 0.2 mm.

When applied current flows from the p-type semiconductor to n-type semiconductor, the holes in the p-type semiconductor and the electrons in the n-type semiconductor migrate from the cold end to the hot end, the corresponding Peltier heats will be generated at the interface between connectors and semiconductors. The heat is adsorbed at the cold end and liberated at the hot end caused by the Peltier effect, forming a temperature difference $\Delta T = T_H - T_L$. With the temperature difference, the heat will be transferred from the hot end to the cold end due to Fourier's heat conduction. In the role of the current and temperature gradient, the Joule heat and the Thomson heat will be generated within semiconductors. Thus the final cooling capacity of the TEC, Q_L, is determined by cooperative effect of Peltier heat, Fourier's heat conduction, Joule heat, and Thomson heat.

2.1. Governing equations

The transient TEC model is developed from our previous steady-state model [29] by adding a transient term. The basic governing equations include the energy equations and the electric potential equations. The energy equations of connectors, p- and n-type semiconductors, ceramic plates, and heat sink are as follows:

$$(\rho c_p)_{\text{conn}} \frac{\partial T}{\partial \tau} = \nabla \cdot (\lambda_{\text{conn}} \nabla \mathrm{T}) + \frac{J^2}{\sigma_{\text{conn}}} - \beta_{\text{conn}} \vec{J} \cdot \nabla T \quad (1)$$

$$(\rho c_p)_p \frac{\partial T}{\partial \tau} = \nabla \cdot (\lambda_p \nabla T) + \frac{J^2}{\sigma_p} - \beta_p \vec{J} \cdot \nabla T \quad (2)$$

$$(\rho c_p)_n \frac{\partial T}{\partial \tau} = \nabla \cdot (\lambda_n \nabla T) + \frac{J^2}{\sigma_n} - \beta_n \vec{J} \cdot \nabla T \quad (3)$$

$$(\rho c_p)_{\text{cer}} \frac{\partial T}{\partial \tau} = \nabla \cdot (\lambda_{\text{cer}} \nabla T) \quad (4)$$

$$(\rho c_p)_{\text{sink}} \frac{\partial T}{\partial \tau} = \nabla \cdot (\lambda_{\text{sink}} \nabla T) \quad (5)$$

where ρ is the density, c_p is the specific heat, λ is the thermal conductivity, σ is the electric conductivity, and β is the Thomson coefficient. The subscripts conn, p, n, cer, and sink denote connector, p- and n-type semiconductors, ceramic plate, and heat sink, respectively. The first terms on the right side in Eqs. (1)–(5) denote Fourier's heat conduction, the second and third terms denote internal heat sources due to Joule heating and Thomson effect, respectively. $J(x, y, z)$ is the local current density, which is assumed to be constant and equal to I/A in the previous models [4–13,23–28], where I is the total applied current, and A is the cross-sectional area of semiconductors. The Thomson coefficient can be derived from Seebeck coefficient, or:

$$\beta = T \frac{\mathrm{d}\alpha}{\mathrm{d}T} \quad (6)$$

where α is the Seebeck coefficient. The electric potential is the driving force of the electrons and holes in the semiconductor, which can be obtained by solving the following equation:

$$\nabla \cdot (\sigma(\nabla \phi - \alpha \nabla T)) = 0 \quad (7)$$

where ϕ is the electric potential, $\alpha \nabla T$ is Seebeck electromotive force coming from Seebeck effect. Once ϕ is determined, the electric field can be calculated by the following equation:

$$\vec{E} = -\nabla \phi + \alpha \nabla T \quad (8)$$

Finally, the current density vector in Eqs. (1)–(3) can be calculated as follows: