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Numerical simulation of thermoelectric performance of linear-shaped thermoelectric generators under transient heat supply

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ABSTRACT

A two-dimensional, dynamic finite element model is developed to study the transient characteristics of linear-shaped thermoelectric generators (L-TEG) in this paper. The model considers the effect of an unsteady heat source, which is regarded as a time-varying thermal boundary condition. The temperature-dependent TE material properties are also taken into account. For two loading processes (i.e. heating process and cooling process), we investigate transient TE behaviors of L-TEG under different loading ways and duration of thermal load as well as geometric dimensions of the TE legs, individually. The results indicate that, in heating process, the responses of the power and the absorbed heat to the thermal load present obvious time delay under some certain conditions; in the cooling process, interestingly, an internal heat source emerges in the L-TEG, caused by the delay of thermal diffusion from the hot end of the TE legs to cold end. This heat source renders a heat release from the generator to the ambient. A process relying on its own heat to generate electricity is thus formed. This study further helps the understanding of TE behavior of TE generators in service.

1. Introduction

Thermoelectric (TE) generator is a kind of clean solid-state energy conversion device due to no working medium leaking and no fossil fuel consumption, which can realize directly the conversion between thermal energy and electric energy [1,2]. Regarding their unique features including long lifetime, no vibration and noise, small volume and light weight, and low maintenance cost, it has shown a broad application prospect in medical treatment, communication, electronic equipment, military, space flight and aviation [3–9].

As for practical application, it is necessary to develop a high-performance TE generator [10–12]. High-performance TE generators mainly rely on the availability of high-quality TE materials [13–17]. Up to now, the researches on the high-performance TE generator are still not sufficient. So it is important to design more reasonable and efficient structure of the device using those existing TE materials to improve the performance of TE devices. Based on a finite element method, Erturun et al. [18] investigated the power generation performances of TE devices with various TE leg geometries (including rectangular prism, trapezoidal prism, cylindrical and octagonal prism). They reported that the power outputs just are slightly affected by geometrical differences due to the same Seebeck coefficients, temperature gradients and heights of the TE leg. Mu et al. [19] carried out a numerical simulation on the effect of geometric dimensions on TE performance for Mg_2Si-based TE generator. The results indicated that the output power and conversion efficiency increase significantly with the increasing length of TE leg; the power also increases greatly with the increasing width, while the efficiency shows the opposite changing tendency. Rezania et al. [20] attempted to build a high-performance and lower material consumption of TE generator. Numerical results indicated that the footprint of n-/p-type TE legs has an optimal ratio with the maximum power output and maximum cost-performance. A TE material operates at its maximum figure-of-merit at a specific temperature. When operating over a large temperature range, the majority of TE material is consequently operating below its potential maximum performance. The fabrication of segmented TE leg structure [21–24] or multistage TE structure [25–27] is one of effective methods to improve the TE performance. However, it can be noted that all these works investigated the TE performance under idealized steady-state operating conditions.

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Nomenclature

C	specific heat, J kg^{-1} K^{-1}
$\mathbf{D}$	electric displacement vector, C m^{-1}
$\mathbf{E}$	electric field intensity vector, V m^{-1}
I	current, A
$\mathbf{J}$	electric current density vector, A m^{-2}
L	total length of p- and n-thermoelements, m
L_p	length of p-type thermoelement, m
L_n	length of n-type thermoelement, m
P	power, W
$\mathbf{q}$	heat flux vector, W m^{-2}
$\dot{q}$	heat generation rate per unit volume, W m^{-3}
Q_h	heat inputted in the hot junction, W
Q_H	heat absorbing from heat source, W
Q_C	heat released to heat sink, W
R_L	external load resistance, Ω
t_0	beginning time of transient process, s
t_e	time to reach steady, s
T_h	reference temperature of hot junction, K
T_c	temperature of cold junction, K
T_H	temperature of heat source, K
T_C	temperature of heat sink, K
T_∞	ambient temperature, K
θ	geometric parameter L_p/L
α	Seebeck coefficient, V K^{-1}
ρ	density, kg m^{-3}
λ	thermal conductivity, W m^{-1} K^{-1}
σ	electrical conductivity, S m^{-1}
ε	dielectric constant,
Π	Peltier coefficient, V
η	Efficiency, –
η_C	Carnot efficiency, –
φ	electric potential, V

In practical applications, the TE generator works under transient operating condition mainly due to the transient behavior of the imposed heat sources. Examples of the heat source are waste heat from the automobile exhaust, the engine of aircraft and the cooking stove in a house [6]. As far as the automobile is concerned, it goes through different driving behaviors (acceleration, brake and stop) and varying road conditions (steep and bumpy) which make exhaust system works in a varying condition to accommodate the changes. So it is not easy for heat sources to provide a long-time sustainable and stable hot temperature. In addition, the hot temperatures also vary with time during the start-up and shut-down periods. It is therefore very important to develop a transient model to understand the dynamic characteristics of the TE devices. This satisfies the demand of complicated application conditions and environments. In recent years, some typical works have focused on this issue. Meng et al. [28] established a complete three-dimensional transient TE cooler model which takes into account all TE effects. Based on the model, they predicted the dynamic characteristics of TE cooler under various applied currents, and analyzed the difference of dynamic behaviors with temperature-dependent properties and constant properties. For TE generators, Montecucco et al. [29] presented a one-dimensional analytical model to study the transient behaviors of the device with dynamic exchanges of heat through the hot and cold sides. Meng et al. [30] deeply investigated the TE behavior of TE generator under transient operating conditions (including variations of two end temperatures of the device, cold end temperature and load current) using a three-dimensional thermal-electricity coupled model, and obtained some very useful results. However, the effects of the temperature-dependent properties of TE materials and geometric dimensions of the device were investigated insufficiently in their study.

It can be shown that whether studying on the steady-state behavior or transient behavior, the TE device is usually considered as a π-shaped structure. The traditional devices require the same lengths of n- and p-type TE legs when assembled into a TE module, so that the performance of TE materials somewhat are lowered. Recently, we improved linear-shaped thermoelectric generators (L-TEG) [31]. Such devices can exhibit more flexibility and better performance than traditional π-shaped devices because its unique structure makes n- and p-type TE legs can be optimized independently.

In this study, the pervious steady-state L-TEG finite element model is further extended to a transient one. The model is developed to describe the transient TE behaviors of the L-TEG, subjected to dynamic heat supply. The effects of unsteady heat source are treated as time-varying thermal boundary conditions which designed as the exponential variation and linearity variation patterns. The temperature-dependent TE material properties are also taken into account in this model. For two loading processes (i.e. heating process and cooling process), the influences of loading way and duration of thermal load as well as geometry dimension of the TE legs on the dynamic TE performance of the L-TEG are investigated, individually.

2. Calculation model

2.1. Thermodynamic characteristics of TE systems

A schematic diagram of TE system is shown in Fig. 1. The system consists of the heat source, heat sink and working medium (TE generator). Under an ideal condition, the maximum thermal efficiency of TE system, i.e. the efficiency of Carnot cycle is defined as:

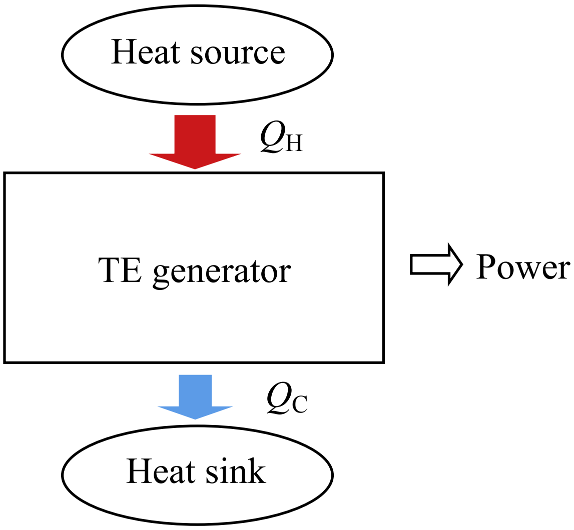

Fig. 1. Schematic diagram of TE system.