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Thermal design and management for performance optimization of solar thermoelectric generator

Jinsheng Xiao [a,b,*], Tianqi Yang [a], Peng Li [b], Pengcheng Zhai [b], Qingjie Zhang [b]

[a] School of Automotive Engineering, Wuhan University of Technology, Hubei 430070, China
[b] State Key Laboratory of Advanced Technology for Materials Synthesis and Processing, Wuhan University of Technology, Hubei 430070, China

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ABSTRACT

We established a three-dimensional finite element model of thermoelectric module based on low-temperature thermoelectric material bismuth telluride and medium-temperature thermoelectric material filled-skutterudite. The material properties of the thermoelectric materials such as the Seebeck coefficient, thermal conductivity, and electrical conductivity are temperature dependent. Based on the formal model, multi-stage models consist of low- and medium-temperature thermoelectric modules are proposed. The effect of input energy on performance of solar thermoelectric generator is considered according to the real operating condition. Results show that, reasonable thermal design of solar thermoelectric generator can take full advantage of the characteristics of thermoelectric materials and effectively improve the performance of power generation.

1. Introduction

Solar thermoelectric generator, which uses concentrated solar radiation as heat source, has been studied for many years. Chen developed a thermodynamic model for discussing the performance of solar-driven thermoelectric generator [1]. Scherrer et al. developed a numerical model of solar thermoelectric generator base on skutterudite for satellite [2]. Omer and Infield presented an improved theoretical model of solar thermoelectric generator which includes all parameters that have an influence on the heat transfer process, and the modeling results are compared with experimental data of the commercial thermoelectric module in power generation mode [3]. Li et al. presented a prototype concentration solar thermoelectric generator (CTG) and a discrete numerical model for the evaluation of the whole system [4]. All these theoretical and experimental studies lay a foundation for the development of solar thermoelectric generator.

There are many advantages of solar thermoelectric generator, such as endless shelf life, simple structure, no moving parts, silent in operation and no pollution. However, the low conversion efficiency makes it hard to be widely used. The conversion efficiency of solar thermoelectric generator is mainly restricted by thermoelectric materials. Over the past several years, a number of high performance thermoelectric materials have been developed [5,6], and some of them are available commercially. Bismuth telluride is a favorable low-temperature thermoelectric material, which exerts better property at low temperature (25–225 °C) [7,8]. While filled-skutterudite is a good medium-temperature thermoelectric material, that can be used for wide temperature range generation (25–525 °C) [9].

In addition to the research of thermoelectric materials, reasonable thermal design and management of thermoelectric generator is equally important for improving the generating performance. Chen et al. established a theoretical model of a two-stage semiconductor thermoelectric generator [10]. El-Genk and Saber presented a 1-D analytical model of segmented thermoelectric unicouple for operation between 973 and 300 K [11]. In the present paper, we construct a three-dimensional finite element model [12,13] for discussing the performance characteristics of low- and medium-temperature thermoelectric modules. The material properties of the thermoelectric materials such as the Seebeck coefficient, thermal conductivity, and electrical conductivity are temperature dependent. Based on the singe-stage models, we present two- and three-stage models of the solar thermoelectric generator to discuss its performance characteristics. The effect of input energy on performance of solar thermoelectric generator is considered according to the real operating condition.

* Corresponding author at: School of Automotive Engineering, Wuhan University of Technology, Hubei 430070, China.

E-mail addresses: jsxiao@whut.edu.cn (J. Xiao), tqyang@whut.edu.cn (T. Yang), lpwhut@live.whut.edu.cn (P. Li), pczhai@whut.edu.cn (P. Zhai), zhangqj@whut.edu.cn (Q. Zhang).

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Nomenclature

C	specific heat capacity (J/kg K)
T	temperature (°C)
$\dot{q}$	heat generation rate per unit volume (W/m^3)
$\vec{q}$	heat flux vector (W/m^2)
$\vec{J}$	electric current density vector (A/m^2)
$\vec{D}$	electric flux density vector (C/m^2)
$\vec{E}$	electric field intensity vector (V/m)
I	load current (A)
R_L	electric load (Ω)
P	output power (W)
Q_{in}	input power (W)
q_{solar}	solar radiation flux density, 1000 W/m^2
C_g	total concentration ratio of optical focusing system

Greek symbols

ρ	density (kg/m^3)
$[\lambda]$	thermal conductivity matrix (W/mK)
$[\sigma]$	electrical conductivity matrix, S/m
$[\alpha]$	Seebeck coefficient matrix (V/K)
$[\varepsilon]$	dielectric permittivity matrix (F/m)
φ	electric scalar potential (V)
η_{STEG}	total efficiency of solar thermoelectric generator
η_{TE}	thermo electric conversion efficiency
η_{opt}	optical focusing efficiency
η_a	absorptivity of the heat collector

2. Mathematical model of solar thermoelectric generator

2.1. Governing equations of coupled thermoelectricity

The heat flow equation in thermoelectric analysis can be expressed as:

$$\rho C \frac{\partial T}{\partial t} + \nabla \cdot \vec{q} = \dot{q} \tag{1}$$

where ρ, C, T, $\dot{q}$ and $\vec{q}$ stand for density, specific heat capacity, temperature, heat generation rate per unit volume and heat flux vector, respectively.

The continuity equations of electric charge is

$$\nabla \cdot \left(\vec{J} + \frac{\partial \vec{D}}{\partial t} \right) = 0 \tag{2}$$

where $\vec{J}$ is the electric current density vector, $\vec{D}$ is the electric flux density vector.

Above two equations are coupled by the set of thermoelectric constitutive equations [12],

$$\vec{q} = T[\alpha] \cdot \vec{J} - [\lambda] \cdot \nabla T \tag{3}$$

$$\vec{J} = [\sigma] \cdot (\vec{E} - [\alpha] \cdot \nabla T) \tag{4}$$

where $[\lambda]$ is the thermal conductivity matrix, $[\sigma]$ is the electrical conductivity matrix, and $[\alpha]$ is the Seebeck coefficient matrix. $\vec{E} = -\nabla\varphi$ is the electric field intensity vector, where φ is the electric scalar potential.

The coupled equations of thermoelectricity can be obtained from above equations,

$$\rho C \frac{\partial T}{\partial t} + \nabla \cdot (T[\alpha] \cdot \vec{J}) - \nabla \cdot ([\lambda] \cdot \nabla T) = \dot{q} \tag{5}$$

$$\nabla \cdot \left([\varepsilon] \cdot \nabla \frac{\partial \varphi}{\partial t} \right) + \nabla \cdot ([\sigma] \cdot [\alpha] \cdot \nabla T) + \nabla \cdot ([\sigma] \cdot \nabla \varphi) = 0 \tag{6}$$

where $[\varepsilon]$ is the dielectric permittivity matrix.

In the present steady-state model, material properties of all components are considered to be isotropic. The coupled equations of thermoelectricity can be written as follows:

$$\nabla \cdot (T\alpha\vec{J}) - \nabla \cdot (\lambda \nabla T) = \dot{q} \tag{7}$$

$$\nabla \cdot (\sigma\alpha\nabla T) + \nabla \cdot (\sigma\nabla\varphi) = 0 \tag{8}$$

The equations described in the previous section are solved using the ANSYS which is the commercial software based on the finite element method and is applicable to multiphysics problems [13].

2.2. Model parameters of solar thermoelectric generator

2.2.1. Geometric model

A typical solar thermoelectric generator consists of an optical focusing system, heat collector, thermoelectric module, and cooling plate. The thermoelectric module is the major component of the solar thermoelectric generator. As shown in Fig. 1a, the

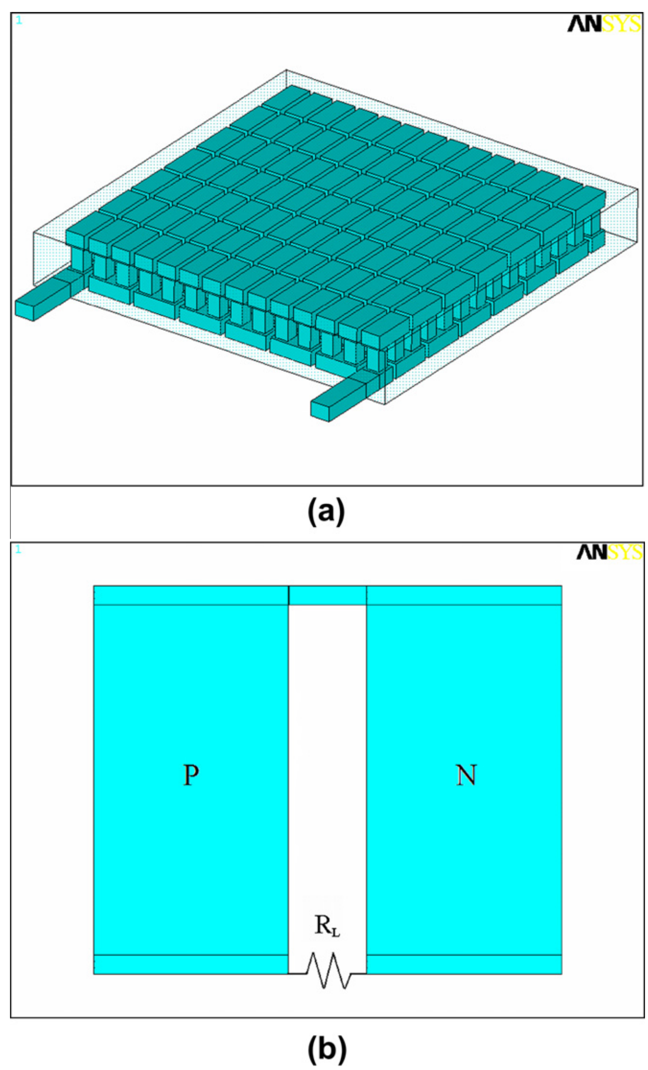

Fig. 1. Geometric model of thermoelectric module and thermoelectric unicouple.