Energy Conversion and Management 101 (2015) 713–720

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

A real-sized three-dimensional numerical model of thermoelectric generators at a given thermal input and matched load resistance

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ARTICLE INFO

Article history:
Received 30 April 2015
Accepted 6 June 2015
Available online 20 June 2015

Keywords:
Thermoelectricity
Thermoelectric generator
Finite element analysis
Real-sized three-dimensional model

ABSTRACT

Thermoelectric generators are usually designed and optimized by finite element analysis. For accurate analysis, it is significant to establish a real-sized three-dimensional model of thermoelectric generator under actual application situations. In this paper, a real-sized three-dimensional finite element model of the thermoelectric generator is established and discussed. The height, cross-sectional area, and amount of thermoelectric pairs are alterable and programmable. The thermal input power is constant and the load resistance matches the internal resistance. The average temperature difference, the hot-side temperature distribution, and the output performance of the thermoelectric generator are calculated and discussed. Results indicate that changing the geometry or amount of thermoelectric pairs can influence the average temperature difference and hot-side temperature distribution simultaneously. However, changing the geometry or amount of thermoelectric pairs can only enhance the output voltage or current solely rather than simultaneously.

1. Introduction

The thermoelectric (TE) generator is proposed as one of possible technologies to aid in global efforts for energy conservation and the reduction of pollutants [1]. This technology is widely used in many aspects. Liu et al. [2] designed and fabricated a completed thermoelectric generator (TEG) system to recover waste heat from automotive exhaust. Özdemir et al. [3] designed a new solar based TEG to convert solar heat energy into electric energy. Sion et al. [4] presented an infrared sensor by adopting a planar TE device. And, Yu et al. [5] presented a wearable micro energy capture system by using a micro TEG.

The TEG is mainly composed of thermoelectric modules (TEMs) and heat sinks [6]. It can convert heat energy into electric energy when a temperature difference applied on it [7]. To test and evaluate the performance of TE systems, the temperature difference across the TEM is usually set as constant. For example, Park et al. [8] developed a TEG energy capture system based on the maximum power point tracking technique and evaluated its property under several given temperature differences; Kinsella et al. [9] designed a thermoelectric battery charging system and tested its performance under different constant temperature differences; Mamur and Ahiska [10] designed a DC–DC boost converter for low power thermoelectric generators and tested it under several constant temperature differences; Wu and Yu [11] calculated the performance of TEG by an advanced finite model under the given temperature difference; and, Tian et al. [12] presented a mathematical model to compare and optimize parameters of a segmented thermoelectric generator at constant temperature difference. For these above situations, the output performance of the TEM can be directly estimated and calculated by the established thermoelectric theory, since the temperature difference is set as constant. However, in some applications, the thermal power of the heat source is constant (radioisotope radiation [13]) or nearly constant (solar radiation [14]). For these applications, literatures have already demonstrated that the temperature difference across the TEM is not a constant and will vary with the geometry and amount of TE pairs [15]. As shown in Fig. 1, it is more complex to calculate the output performance of the TEG, because changing the geometry or amount of TE pairs will influence the output performance and the temperature difference simultaneously. Consequently, it is highly desirable to evaluate and optimize the performance of the TE device under a given thermal input power. And, for accurate computation and analysis, it is significant to establish a real-sized model of the TEG.

Recently, much work has been done to evaluate and optimize the performance of TE devices under the constant thermal input

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http://dx.doi.org/10.1016/j.enconman.2015.06.020
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Nomenclature

ρ	density (kg/m^3)	V	output voltage (V)
C	specific heat capacity (J/K/kg)	I	output current (A)
h	convection coefficient (W/K/m^2)	P	output power (W)
t	time (s)	R_L	load resistance (Ω)
P_{in}	input thermal power (W)	R_i	internal resistance (Ω)
P_c	power dissipated by convection	s	ratio of R_L to R_i
T	temperature (K)	φ	electric scalar potential (V)
T_{hs}	temperature of the heat sink (K)	ε	dielectric permittivity (F/m)
T_a	ambient temperature (K)	Z	figure of merit (K^{-1})
T_H	hot-side temperature (K)	α	Seebeck coefficient (V/K)
T_C	cold-side temperature (K)	λ	thermal conductivity (W/m/K)
T_M	model temperature (K)	σ	electrical conductivity (S/m)
A	superficial area of the heat sink (m^2)	λ_t	total thermal conductivity of TE legs (W m^{-1} K^{-1})
A_N	cross-sectional area of *N*-type TE legs (m^2)	σ_P	electrical resistivity of *P*-type TE legs (S/m)
A_P	cross-sectional area of *P*-type TE legs (m^2)	σ_N	electrical resistivity of *N*-type TE legs (S/m)
$\vec{q}$	heat flux vector (W/m^2)	$[\alpha]$	Seebeck coefficient matrix (V/K)
$\dot{q}$	heat generation rate per unit volume (W/m^3)	$[\lambda]$	thermal conductivity matrix (W m^{-1} K^{-1})
$\vec{J}$	electric current density vector (A/m^2)	$[\sigma]$	electrical conductivity matrix (S/m)
$\vec{D}$	electric flux density vector (C/m^2)	n	couple number
$\vec{E}$	electric field intensity vector (V/m)	l	height of TE legs (m)

power by calculation methods. Montecucco and Knox [16] calculated the thermal and electrical dynamics of TEG system to study transients and steady-state operation of real TE systems. Xiao et al. [17] established a solar TEG model which contains multi-stage TE pairs to optimize the output performance. Liao et al. [18] used two simulation models to calculate the thermal temperature and power generation of a thermoelectric-solar hybrid energy system exposed to dynamic transient sources. Wu et al. [19] adopted the finite method to discuss the thermodynamics and thermal stress performance of the thermoelectric module. Chen et al. [20] adopted a real-sized finite element module to study the behavior of solar TEGs employing thermal concentration. Su et al. [21] calculated the solar full spectrum system with a hybrid device model consisting of a dye-sensitized solar cell and a thermoelectric generator. Kossyvakis et al. [22] analyzed the commercially available thermoelectric module by computational and experimental methods to combine both experimental and computational data. And, most recently, He et al. [23] analyzed and discussed the impact of non-uniform heat flux on the thermoelectric generators by computational and experimental methods.

Although much work has been done to study the TEG by computational methods, most calculations are based on the invariable geometry and amount of TE pairs. And, literatures discussing the relationship between the performance of TEGs and the amount of TE pairs under the constant thermal input power are scarce. In this paper, a real-sized three-dimensional finite element model of the TEG is established. The TEG is composed of a TEM and a heat sink. Both the geometry and amount of TE pairs are programmable and alterable. The thermal input power is set as a constant and the load resistance is matched. The height, cross-sectional area, and amount of TE pairs are set as variables respectively. The average temperature difference across the TEM, the hot-side temperature distribution, and the output performance of the TEG are calculated and discussed.

2. Mathematical model

2.1. Governing equations of thermoelectricity

For a thermoelectric analysis, the equation of heat flow can be expressed as [24]

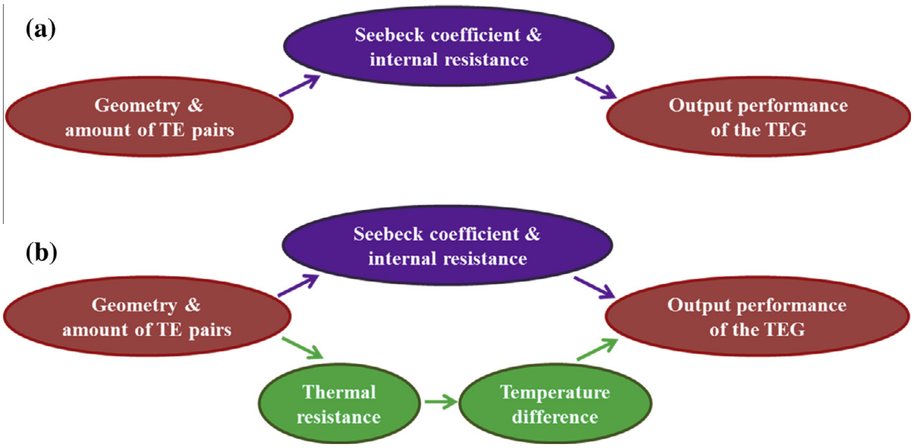

Fig. 1. The relationship between the output performance of the TEG and the geometry and amount of TE pairs. (a) Under a constant temperature difference; (b) under a constant thermal input power.