Energy Conversion and Management 87 (2014) 566–575

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Geometric effect on cooling power and performance of an integrated thermoelectric generation-cooling system

Wei-Hsin Chen [a,*], Chien-Chang Wang [b], Chen-I Hung [b]

[a] Department of Aeronautics and Astronautics, National Cheng Kung University, Tainan 701, Taiwan, ROC
[b] Department of Mechanical Engineering, National Cheng Kung University, Tainan 701, Taiwan, ROC

ARTICLE INFO

Article history:
Received 25 May 2014
Accepted 17 July 2014
Available online 8 August 2014

Keywords:
Thermoelectric generation and cooling
Integrated thermoelectric system
Geometric design
Contact resistance
Heat convection
Finite element scheme

ABSTRACT

Geometric design of an integrated thermoelectric generation-cooling system is performed numerically using a finite element method. In the system, a thermoelectric cooler (TEC) is powered directly by a thermoelectric generator (TEG). Two different boundary conditions in association with the effects of contact resistance and heat convection on system performance are taken into account. The results suggest that the characteristics of system performance under varying TEG length are significantly different from those under altering TEC length. When the TEG length is changed, the entire behavior of system performance depends highly on the boundary conditions. On the other hand, the maximum distributions of cooling power and coefficient of performance (COP) are exhibited when the TEC length is altered, whether the hot surface of TEG is given by a fixed temperature or heat transfer rate. The system performance will be reduced once the contact resistance and heat convection are considered. When the lengths of TEG and TEC vary, the maximum reduction percentages of system performance are 12.45% and 18.67%, respectively. The numerical predictions have provided a useful insight into the design of integrated TEG–TEC systems.

1. Introduction

In recent years, the problems of global warming and air pollution have greatly stimulated the development of green energy technologies. In these technologies, thermoelectric devices are receiving a great deal of attention duo to their numerous attractive merits. For example, they are compact and environmentally friendly, and can be operated easily with long life and low maintenance cost [1,2]. According to thermoelectric effects, thermoelectric devices have two different operating modes. One is the generation mode using thermoelectric generators (TEGs) to directly convert thermal energy into electrical energy [3]. The energy source of TEGs can come from waste heat which is extensively available in industry [4,5]. The other is the cooling mode whereby thermoelectric coolers (TECs) can cause a temperature difference for cooling applications by inputting electrical energy [6]. The development of TEG and TEC has been considered as a low-carbon and green energy technology, and they have been successfully applied in military, aerospace, and industry [7].

In general, TEGs and TECs are individually utilized for practical applications, such as waste heat recovery [8,9] and ceiling cooling system [10]. Recently, an integrated TEG–TEC system has been proposed by Chen et al. [11]. In their integrated system, TECs were driven by TEGs so that no additional electrical power source was required for the TECs. They provided the optimal number ratios between the TEGs and the TECs under various operating conditions through an analytical analysis. Later, several studies also investigated the integrated systems. For example, Khattab and Shenawy [12] constructed an experimental system and successfully used solar TEGs to drive a TEC all year round. Meng et al. [13] used an analytical method to analyze the performance of a thermoelectric heat pump driven by a TEG. They found that the heat source temperature of the TEG had a greater effect on heating load than on the coefficient of performance (COP). On the contrary, the heat sink temperature of the thermoelectric heat pump had a more significant effect on the COP than on the heating load. Meng et al. [14] also adopted another analytical method to investigate the influence of physical dimensions of thermoelectric elements on the performance of an integrated TEG–TEC system. Their results indicated that performance improvements could be achieved by optimizing the physical dimensions of thermoelectric elements.

Geometric design is a crucial issue in optimizing performance of a thermoelectric system. For a given thermoelectric module, the geometrical optimization of the thermoelectric element is a feasible way to maximize its performance or efficiency [15]. Regarding

* Corresponding author. Tel.: +886 6 2004456; fax: +886 6 2389940.
E-mail address: weihsinchen@gmail.com (W.-H. Chen).

http://dx.doi.org/10.1016/j.enconman.2014.07.054
0196-8904/

Nomenclature

A	area (mm^2)
A_c	cross-sectional area of the collector (mm^2)
C_g	concentration ratio of solar thermoelectric generator
COP	coefficient of performance of the integrated system
$\underset{\sim}{D}$	depth of thermoelectric element (mm)
$\underset{\sim}{E}$	electric field intensity vector ($V\,m^{-1}$)
h	convection heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
I	electric current (A)
$\underset{\sim}{I^L}$	electric current load vector (A)
$\underset{\sim}{J}$	electric current density vector ($A\,m^{-2}$)
K^{TT}	thermal stiffness matrix
$K^{\varphi T}$	Seebeck stiffness matrix
$K^{\varphi\varphi}$	electric stiffness matrix
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	length of thermoelectric element (mm)
N	element shape function
q''	heat flux ($W\,m^{-2}$)
q_s	solar irradiance ($W\,m^{-2}$)
Q	heat transfer rate (W)
Q_{in}	input energy of solar thermoelectric generator (W)
Q_{TE}	input energy per thermoelectric couple (W)
Q^L	thermal load vector (W)
R	electrical resistance (Ω)
T	temperature (°C)
T_e	vector of nodal temperatures (°C)
T_∞	environment temperature (°C)
W	width of thermoelectric element (mm)

Greek letters

α	Seebeck coefficient ($V\,K^{-1}$)
η_a	absorptivity of the collector coating
η_{opt}	optical efficiency of the Fresnel lens
ρ	electrical resistivity (Ω m)
ρ_{con}	electrical contact resistivity ($\Omega\,m^{-2}$)
ϕ	electric scalar potential (V)
φ_e	vector of nodal electric potentials (V)

Subscripts

C	thermoelectric cooler
$conv$	heat convection between the thermoelectric elements and the environment
G	thermoelectric generator
H	hot side
L	cold side
n	N-type thermoelectric element
p	P-type thermoelectric element

the generation mode, Jang et al. [16] analyzed the geometric effect of thermoelectric elements on micro-TEG performance by means of a finite element method. Their results showed that there was an optimal length of thermoelectric elements to achieve the highest power. Additionally, a higher efficiency could be obtained with a greater length of thermoelectric element. For the cooling mode, Lee and Kim [17] used a numerical method to investigate the cooling performance of a micro-TEC. They reported that the cooling rate increased and the maximum COP decreased when the thickness of the thermoelectric element decreased.

As far as the practical thermoelectric system is concerned, in fact, there exists an undesired effect of electrical contact resistance contributed from both interfaces and interconnects [18]. Min and Rowe [19] reported that the effect of contact resistance on the COP of a TEC became significant when the length of thermoelectric element was relatively short. Another unfavorable effect regarding geometry is heat loss to the environment from TEG surfaces. The effect of heat loss from thermoelectric elements to the ambient environment on TEG performance has been explored in recent research. For instance, a TEG system combined with parallel-plate heat exchangers was constructed by Niu et al. [20] where a hot fluid and a cold fluid passed through the hot side and the cold side of the TEG, respectively. Their experimental results indicated that heat loss from the TEG to the environment increased markedly when the inlet fluid temperature at the hot side was lifted. The theoretical analysis of Xiao et al. [21] revealed that the existence of heat loss caused a large exergy loss in a TEG system and this effect should be taken into account in the analysis. However, the geometric design of the thermoelectric system was not considered in their study.

From the review of the above literature, it is evident that specifying optimal geometric design parameters may be a promising method of improving or maximizing the performance of thermoelectric systems. However, to the authors' knowledge, very little research has been performed on the geometric design of thermoelectric systems under the effects of heat loss and electrical contact resistance, especially in an integrated TEG–TEC system. In order to provide a useful insight into the importance of geometric design for improving the performance of an integrated TEG–TEC system, a numerical method is developed to model an integrated system and predict the performance of the system. The effects of heat loss and electrical contact resistance on the performance are taken into account. The effects of two different boundary conditions due to altered operating conditions are also considered.

2. Methodology

2.1. Physical model and assumptions

A schematic of the integrated system for study is shown in Fig. 1a where a TEC and a TEG are included in the system. In the system, the TEG absorbs heat $Q_{H,G}$ from the heat source at the hot side and liberates heat $Q_{L,G}$ to the heat sink at the cold side, thereby generating electric current through the Seebeck effect [22]. Then, the current is directly used to power the TEC, which absorbs heat $Q_{L,C}$ from the refrigerated object at the cold side and dissipates heat $Q_{H,C}$ to the heat sink at the hot side based on the Peltier effect [23]. In order to investigate the influence of heat loss on the performance of the integrated system, a heat convection process between the thermoelectric elements and its environment is taken into account. The radiation heat transfer is relatively small at low-temperature conditions [21], so it is neglected in this study. In Fig. 1a, $Q_{conv,G}$ and $Q_{conv,C}$ denote the convective heat flow rates along the lateral surfaces of the TEG and the TEC, respectively. For the sake of simplicity, the following assumptions are adopted.

(a) The integrated system is in steady-state.
(b) An identical model is used for the TEC and the TEG; therefore, they have the same configurations and material properties, except for the Seebeck coefficients which are positive and negative in the p-type and n-type elements, respectively.
(c) Material properties of the thermoelectric elements are temperature-dependent.
(d) The thermoelectric elements are connected electrically in series and thermally in parallel.