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Design of heat sink for improving the performance of thermoelectric generator using two-stage optimization

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ABSTRACT

Thermoelectric (TE) devices can provide clean energy conversion and are environmentally friendly; however, little research has been published on the optimal design of air-cooling systems for thermoelectric generators (TEGs). The present study investigates the performance of a TEG combined with an air-cooling system designed using two-stage optimization. An analytical method is used to model the heat transfer of the heat sink and a numerical method with a finite element scheme is employed to predict the performance of the TEG. In the first-stage optimization, the optimal fin spacing for a given heat sink geometry is obtained in accordance with the analytical method. In the second-stage optimization, called compromise programming, decreasing the length of the heat sink by increasing its frontal area ($W_{HS}H_f$) is the recommended design approach. Using the obtained compromise point, though the heat sink efficiency is reduced by 20.93% compared to that without the optimal design, the TEG output power density is increased by 88.70%. It is thus recommended for the design of the heat sink. Moreover, the TEG power density can be further improved by scaling-down the TEG when the heat sink length is below 14.5 mm.

1. Introduction

Over the last several decades, there has been a dramatic progress in the development of green energy technology which can reduce greenhouse gas emissions and fossil fuel usage. Thermoelectric (TE) devices, which consist of p-type and n-type semiconductors, can be considered as a useful tool to practice the green energy technology. TE devices can be divided into two types, namely thermoelectric coolers (TECs) [1–4] and thermoelectric generators (TEGs) [5–8]. TECs convert electricity into thermal energy for cooling via the Peltier effect, whereas, TEGs convert thermal energy, say, waste heat, into electrical power via the Seebeck effect.

Unlike convectional heat engines or compression refrigerators, TE devices are solid-state; they contain neither moving parts nor refrigerants [9]. Therefore, the whole system can be simplified and operated over an extended period of time without maintenance [10]. TE devices can produce energy without using fossil fuel and can thus reduce greenhouse gas emissions. However, the energy conversion efficiency of TE devices is lower than those of convectional heat engines or refrigerators [11]. The efficiency of TEGs and the coefficient of performance (COP) of TECs are functions of not only the figure of merit (ZT) but also the temperature difference across the devices [12]. ZT is the performance index of a thermoelectric material. Its value is relatively low (about 1.0) for the best existing commercial TE cooling modules whereas that for conventional air-conditioning system is about 4.0 [13]. Consequently, a strategy for improving the performance of TE devices is needed.

In reviewing past research concerning thermal design of TEGs, a number of studies have been reported. For example, Esarte et al. [14] employed a theoretical method to analyze the influence of the design parameters of heat exchangers on the power supplied by a TEG. The theoretical results well matched the experimental values for low flow rates but not for high flow rates. Chen et al. [15] found that heat transfer irreversibility affected the performance of TEG and thus had to be considered in analysis. A TEG system combined with the heat exchangers at both the hot and cold side was numerically modeled by Astrain et al. [16]. Their results showed that when the thermal resistances of heat exchangers on both sides of the TEG were decreased by 10%, the TEG output power was increased by 8%.

Recently, waste heat has been recovered for further usage. Waste heat can be used for space and water heating [17,18],

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Nomenclature

A_c	Cross-sectional area (mm^2)
A	Surface area (mm^2)
C_p	Specific heat at constant pressure (kJ kg^{-1} K^{-1})
D_{TE}	Depth of TE element (mm)
D_g	Fin-to-fin spacing (mm)
$\vec{E}$	Electric field intensity vector (V m^{-1})
f	Distance function in the compromise programming
G	Ratio of the cross-sectional area to length of TE element (mm)
H_f	Fin height (mm)
$\bar{h}$	Average heat transfer coefficient of the fins (W m^{-2} K^{-1})
h	Heat transfer coefficient (W m^{-2} K^{-1})
I	Electric current (A)
$\vec{J}$	Electric current density vector (A m^{-2})
k	Thermal conductivity (W m^{-1} K^{-1})
L	Length (mm)
N_f	Number of fins
N_{TE}	Number of TEG couple
P	Output power of TEG (mW)
P''	Output power density of TEG, $\equiv P/A_{c,\mathrm{TE}}$ (mW mm^{-2})
P_f	Fin perimeter (mm)
Δp	Pressure drop across the heat sink (N m^{-2})
Pr	Prandtl number, $\equiv \nu/\alpha$
$\dot{q}$	Heat generation per unit volume (W m^{-3})
$\vec{q}$	Heat flux vector (W m^{-2})
Q	Heat transfer rate (W)
Q_l	Heat transfer rate for the boundary layer flow limit (W)
Q_s	Heat transfer rate for the fully developed flow limit (W)
R	Electric resistance (Ω)
S	Seebeck coefficient (V K^{-1})
T	Absolute temperature (K)
T_w	Surface temperature of the fins (K)
T_∞	Fluid inlet temperature (K)
t_f	Fin thickness (mm)
V	Total volume of heat sink (mm^3)
W	Width (mm)
X	Geometry parameter of the heat sink (mm)
(x,y)	Real point in the compromise programming
(x^*,y^*)	Ideal point in the compromise programming
ZT	Dimensionless TE figure of merit

Greek letters

α	Fluid thermal diffusivity (m^2 s^{-1})
φ	Electric scalar potential (V)
η	Efficiency (%)
μ	Fluid viscosity (N s m^{-2})
ν	Fluid kinematic viscosity (m^2 s^{-1})
ρ	Fluid density (kg m^{-3})
ρ_e	Electrical resistivity (Ω m)

Subscripts

B	Heat sink base
base	Base case
c	Cold side of TE element
eff	Effective
F	Fluid
f	Fin
HS	Heat sink
h	Hot side of TE element
L	External load
loss	Heat loss from the side surfaces of the TE element
max	Maximum
n	n-type for TE element
opt	Optimum
p	p-type for TE element
TE	Thermoelectric element
t	Total heat sink heat transfer area

improving energy recovery efficiency and system efficiency [19,20], and enhancing chemical reactions [21,22]. Moreover, several studies [23,24] have shown the promising potential of using TEGs for waste heat recovery. Meng et al. [25] proposed a TEG model with multi-irreversibilities; they suggested that the results could be regarded as the feasibility reference using the waste heat for power generation. Because there is almost no cost for obtaining waste heat, the low efficiency problem of TE devices is not a critical issue [24].

Some studies have optimized the geometric design of TE devices. A numerical optimization of a TEC was presented by Xuan [26]. The results indicated that the construction cost of a TEC was closely related to the cooling power density, whereas the running cost was inversely proportional to COP. Kubo et al. [27] altered the size of incisions along the lateral faces of a TE device; they found that the relationship between the TE performance and the incision size depended on the cold side temperature. Yilbas and Sahin [28] introduced two parameters, the slenderness ratio and the external load parameter, to analyze the TEG efficiency; their results showed that the higher efficiency could be obtained for almost all the external load parameters considered when the slenderness ratio was less than 1. Jang et al. [29] optimized the design of micro-TEGs using finite element analysis. High efficiency was obtained when the length of the thermoelements was large. In addition, the power generated declined with the cross-sectional area of the thermoelements, whereas efficiency showed the opposite trend.

A review of the literature shows that the design of the geometry plays an important role in optimizing the performance of TEGs. However, few studies have reported on the optimization of geometry design of TEGs incorporated with air-cooling system. An air-cooling system combined with a heat sink is commonly used for dissipating the heat produced by electronic devices due to its low unit price, low weight, and high reliability [30]. Accordingly, the objective of the present study is to investigate the characteristics of TEGs with an air-cooling design where a finite element method is used to predict the performance of the TEGs. The effects of the heat sink geometry and TEG dimensions on performance are taken into account. To improve the performance of the TEGs, two-stage optimization is carried out. Specifically, an analytical method is used to model the air-cooling system, followed by employing a method of compromise programming to seek the optimal performance of TEGs.

2. Mathematical formulation and modeling

Numerical simulations are adopted to predict the performance of TEGs. The physical and numerical models are described below.

2.1. Assumptions

To simplify the TEG system, the following assumptions are made: