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Performance optimization of thermoelectric generators designed by multi-objective genetic algorithm

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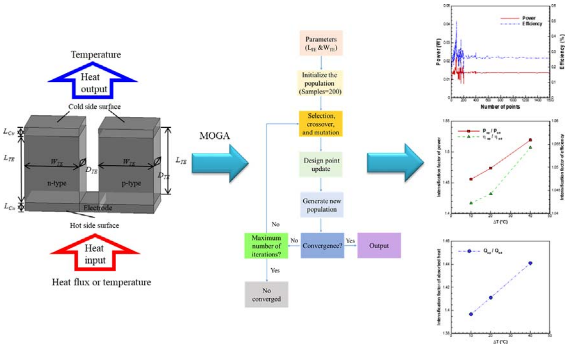
HIGHLIGHTS

- Output power and efficiency of a TEG system using waste heat from heat pipes are studied.
- Geometry of TEG elements is optimized using a multi-objective genetic algorithm (MOGA).
- The output power the TEG with optimization can be increased by about 51.9%.
- The output power can be further enhanced by up to 4.40% when impedance matching is used.
- The maximized output power and efficiency are much higher than those reported in other studies.

GRAPHICAL ABSTRACT



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ABSTRACT

The purpose of this study is to investigate the output power and efficiency of a TEG system using waste heat from heat pipes, and then optimize its performance. The TEG material is $Bi_{0.4}Sb_{1.6}Te_3$ and its figure-of-merit (ZT) is 1.18 at room temperature. The predictions indicate that a longer length of the elements has greater power output and efficiency based on a fixed heat flux on the hot side surface, whereas a shorter length has greater output power based on a fixed temperature difference. The geometry of the TEG is designed through a multi-objective genetic algorithm (MOGA) to maximize its efficiency. When the temperature difference is fixed at 40 °C, the output power and efficiency of the TEG with optimization is increased by about 51.9% and 5.4%, compared to the TEG without optimization. Once the impedance matching, namely, the internal resistance is equal to the external load resistance, is used, the output power can be further enhanced by about 3.85–4.40%. When the heat flux is fixed at 20,000 Wm^{-2} along with the temperature difference of 40 °C, the output power and efficiency of a pair of elements can be increased to 7.99 mW and 9.52%, respectively. These results are much higher than those reported in other studies. Accordingly, it is concluded that the MOGA is a powerful tool to design the geometry of a TEG for maximizing its performance and real applications in industry.

1. Introduction

Issues related to the environment and energy use are some of the biggest challenges in the 21st century. One of the promising technologies to diminish energy use is to capture and recover waste heat for producing energy. When fossil fuels (natural gas, oil, coal, etc.) are

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Nomenclature

A	surface area (mm^2)
D	depth (mm)
$\overrightarrow{E}$	electric field intensity vector ($V\ m^{-1}$)
I	electric current (A)
$\overrightarrow{J}$	electric current density vector ($A\ m^{-2}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
L	length (mm)
P	output power of TEG (W)
P_{op}	optimum output power of TEG (W)
Q	heat transfer rate (W)
q	heat flux ($W\ m^{-2}$)
$\dot{q}$	heat generation per unit volume ($W\ m^{-3}$)
$\overrightarrow{q}$	heat flux vector ($W\ m^{-2}$)
R	electric resistance (Ω)
R_e	external load resistance (Ω)
S	Seebeck coefficient ($V\ K^{-1}$)
ST	Stability percentage (%)
T	temperature (°C)
V	voltage (V)
W	width (mm)

Greek letters

η	efficiency (%)
ρ_e	electrical resistivity (Ω m)
φ	electric scalar potential (V)

Subscripts

c	cold side of TE element
Cu	copper
h	hot side of TE element
im	impedance matching
n	n-type TE element
op	optimum
ori	original
p	p-type TE element
TE	thermoelectric element

consumed by humans through combustion, only one third is used effectively, and two thirds is wasted, mostly in the form of waste heat [1,2]. Therefore, technology for recovering this waste heat is a very promising energy saving method to provide a more efficient usage of fuel [3]. It was reported that the low-temperature waste heat with temperature lower than 230 °C constituted around 60% of the total rejected energy from the industrial sector [4]. In this aspect, thermoelectric generators (TEGs) can be used to harvest this low-grade waste heat for power generation [5], where waste heat is directly converted to electricity through the Seebeck effect. It has been known that TEGs have the merits of being entirely solid-state and environmentally friendly, and are extremely reliable, simple, compact, safe, and without vibrating parts, and this noise generation is also reduced [6,7].

Recent research provides three possible pathways to improve the performance of thermoelectric systems: (1) material preparation, (2) operation control, and (3) device design. The primary direction of material preparation is to produce TEGs with a high value of figure-of-merit (ZT). For example, Zhang et al. [8] fabricated a TEG using high-efficiency nanostructured thermoelectric materials. Their TEG system produced a high-power density of 2.1 W/cm^2 along with 5.3% efficiency. Dharmaiah et al. [9] optimized the effects of powder size and oxygen content on the thermoelectric properties of sintered bodies. As a consequence, the Seebeck coefficient was increased by 52%, whereas the thermal conductivity was decreased by 36%. The highest ZT value was 1.23 at 350 K for 32–75 μm powder size samples. With regard to operation control, Meng et al. [10] studied the dynamic output power and conversion efficiency of a TEG, which were caused by variations of the hot end temperature, cold end temperature and load current. They illustrated that the output power from the TEG and heat amount adsorbed from the ambient depended on the hot end temperature and the cold end temperature, and the response of the output power was almost synchronous when load current was varied. Snarskii et al. [11] proposed a rotating thermoelectric device operating in a periodic steady state, and their results showed that the cooling regime in the sinusoidal mode had a better performance. The results of Chen et al. [12,13] indicated that oscillating the temperatures of the hot-side and/or cold-side surfaces using sinusoidal functions and increasing the phase angle was able to effectively improve the performance of TEGs where the mean efficiency could be enhanced by up to 8% when compared with the temperature without oscillation, and the maximum mean efficiency was 8.45%.

As far as TEG system design is concerned, Niu et al. [14] found that in systems with similar volumes of semiconductor materials, varying the shape from normal cuboid (constant cross-sectional area) to hexahedrons (variable cross-sectional area) could increase the power output significantly. Zhang et al. [15] proposed a method for finding the appropriate length ratio of a segmented TEG to increase the output power and thermoelectric conversion efficiency, and found the optimal length ratios corresponding to the output power and thermoelectric conversion efficiency were different. Chen et al. [16] analyzed the performance of a TEG system using the Taguchi method, and revealed that the influences of geometrical factors on the power and efficiency were ranked as heat sink length > fin height > fin thickness > heat sink width. Some relevant studies concerning the design of TEG system such as TEG geometry or lengths of the TE elements, heat exchanger, and segmented TEG are summarized in Table 1 [6,14–20].

In terms of waste heat recovery technologies, the heat pipe is one of the best heat exchangers to achieve the recovery, with the following advantage: no moving parts, compact structure, high effectiveness, no cross contamination, and small pressure drop, along with being lightweight, economical, and reliable [21]. Lately, some studies about TEG combined with heat pipes have been reported. Remeli et al. [22] used a combination of heat pipes and TEGs in a waste heat recovery system to recover waste heat. Their theoretical model predicted a 2 kW test rig could recover 1.345 kW thermal power. In another experimental study [21], a TEG was sandwiched between two heat pipes. They reported that the highest heat exchanger effectiveness of 41% was achieved where the system could recover around 1079 W of heat and produce around 7 W of electric power. He et al. [23] presented an experimental and analytical study on an integrated solar heat-pipe/thermoelectric

Table 1
Improvement methods for thermoelectric generators system.

Material	Improvement methods	Maximum power (mW)	Maximum efficiency (%)	Ref.
Bi_2Te_3	Element geometry	300	4.15	[6]
Bi_2Te_3	Element geometry	77	4.3	[14]
LiNiO, $BiSbTeC_{60}$	Segmented TEG	9.5	4.25	[15]
Bi_2Te_3	Taguchi method	4138	5.46	[16]
Bi_2Te_3, Sb_2Te_3	Length of the thermoelements	21	4.3	[17]
Bi_2Te_3	Element geometry	5.2	0.57	[18]
$Bi_2Te_{2.7}Se_{0.3}$, $Bi_{0.5}Sb_{1.5}Te_3$	Element geometry and heat conductive layer	0.01224	–	[19]
Bi_2Te_3	Heat exchangers	0.285	–	[20]