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Power output and efficiency of a thermoelectric generator under temperature control

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ABSTRACT

Operation control is an effective way to improve the output power of thermoelectric generators (TEGs). The present study is intended to numerically investigate the power output and efficiency of a TEG and find the operating conditions for maximizing its performance. The temperature distributions at the hot side and cold side surfaces of the TEG are approximated by sinusoidal functions. The influences of the temperature amplitudes at the hot side surface and the cold side surface, the phase angle, and the figure-of-merit (ZT) on the performance of the TEG are analyzed. The predictions indicate that the mean output power and efficiency of the TEG are significantly enhanced by the temperature oscillation, whereas the mean absorbed heat by the TEG is slightly influenced. An increase in the temperature amplitude of the hot side surface and the phase angle can effectively improve the performance. For the phase angle of 0°, a smaller temperature amplitude at the cold side surface renders the better performance compared to that with a larger amplitude. When the ZT value increases from 0.736 to 1.8, the mean efficiency at the phase angle of 180° is amplified by a factor of 1.72, and the maximum mean efficiency is 8.45%. In summary, a larger temperature amplitude at the hot side surface with the phase angle of 180° is a feasible operation for maximizing the performance.

1. Introduction

Combustion of fuels is currently the most important route to gain heat and power. The efficiency of combustion in power plants is around 35% [1] and is lower than 30% in the internal combustion engines of vehicles [2]. This implies, in turn, that over 65% of energy in fuels is released into the environment in the form of waste heat. In industry, waste heat in flue gases has been widely recovered to preheat air to intensify combustion efficiency. Nevertheless, much low-temperature or low-grade waste heat is not recovered yet. In this aspect, the organic Rankine cycle (ORC) [3] and thermoelectric (TE) generation [4] are considered as the promising technologies to harvest low-temperature waste heat for power generation.

The thermoelectric generator (TEG) is a device which can directly convert heat into electricity through the Seebeck effect [5]. Unlike ORC which is a stationary facility in nature, TEGs are characterized by their small sizes and easy installation into certain facilities. For this reason, TEGs can be employed not only in military, aerospace, industrial, and scientific work, but also in people's life [4,6,7]. Navarro-Peris et al. [8] utilized compressor heat loss as the heat source of TEGs to evaluate the possibilities of increasing efficiency in refrigeration and heat pump systems based on compression cycles. Yu et al. [9] developed a numerical model using vehicle exhaust waste heat as the heat source of a TEG. Hashim et al. [10] presented a model for the geometry optimization of TEGs in a hybrid photovoltaic-thermoelectric (PV/TE) system where an increase in both the overall power output and conversion efficiency might be achieved by incorporating a TEG to harvest waste heat from photovoltaic cells. Zhu et al. [11] designed and fabricated a thin-film solar TEG which could use solar energy as a power supply for wireless sensors and microscale devices. Georgopoulou et al. [12] presented a mathematical model to describe the dynamic behavior of marine thermoelectric components where two marine applications, including a marine scavenge air cooler with TEGs and an auxiliary engine exhaust gas duct with TEGs, were described.

TEGs have the merits of zero emissions, high reliability, no moving part, small size, light weight, and no working fluid [13]. However, the conversion efficiency of TEGs is low, thereby limiting

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Nomenclature

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

Greek letters

β	amplitude (K)
η	efficiency (%)
ω	phase angle (°)
λ	period (min)
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
n	n-type TE element
p	p-type TE element
TE	thermoelectric element

their applications [14]. Increasing the figure-of-merit of materials (i.e., ZT) is an effective way to improve the efficiency of TEGs [15], that is, the higher the ZT of a TEG, the higher is its efficiency, as shown in Table 1 [16–26]. Alternatively, a lot of studies have been carried out to enhance the performance of TEGs by optimizing the TE system. This can be achieved through the design or adjustment of heat exchanger [27], heat sink surface area and cold-side heat transfer capacity [28], TEG geometry [29], number of elements in TEG [30], external load resistance [16,31], and the combinations of materials [17]. For instance, Niu et al. [29] found that, for the nearly same volume of semiconductor materials, changing the shape of elements from normal cuboid (constant cross-sectional area) to hexahedrons (variable cross-sectional area) was able to significantly facilitate the power output of a TEG. Dunham et al. [17] used a variety of combinations of thermal conductivity, electrical conductivity, and Seebeck coefficient with the same ZT for the power density optimization of micro TEGs, and discovered that increasing Seebeck coefficient followed by decreasing thermal conductivity for short leg lengths and increasing electrical conductivity for long leg lengths yielded the best result.

The control of operating conditions such as waste heat temperature [28], convection for cooling [32,33], temperature difference between the hot-side and cold-side surfaces [34], and the temperature at the cold side [35] can also promote the performance of TEGs. Recently, a few studies have been performed on the improvement of TEG performance via oscillating the TEG surfaces' or environmental temperatures. Attia et al. [27] experimentally explored the power output of TEGs in a dynamic temperature environment where the effects of heat exchanger size, heat exchanger insulation, period of environmental temperature oscillation, and radiative heat transfer on the power output of TEGs were examined. They reported that, when the oscillation period was larger to a certain extent, heat exchangers had sufficient time to come into thermal equilibrium with the environment, resulting in a small temperature difference across the thermoelectric plate and thereby power output. Moreover, the power generation increased with increasing heat exchanger size, and the insulation of a heat exchange was conducive to power generation. Bomberge et al. [36] developed a model to predict the power generation of a TEG in a temporally-varying temperature environment which simulated the situation of using the sun and night sky as the heat source and sink in a desert valley. Their scaling study on the device size concluded that there existed an optimal size for maximizing power density, and the power generation in a temporally-varying temperature environment was a reliable power source for remote power applications. The experimental and theoretical analysis of Yan and Malen [18] showed that the use of a periodic heat source could improve the conversion efficiency of a TEG when compared to that with a constant heat source, as a consequence of larger time average of the square of temperature difference between the both

Table 1
Maximum efficiency of TEG at various operating conditions and using different materials.

Material	ZT (at 298 K)	ΔT	$\eta_{\max}$	Reference
Bi_2Te_3	0.69	137	5.46	[16]
Bi_2Te_3	0.6	100	1	[17]
Bi_2Te_3	1	100	8.64	[18]
Bi_2Te_3, Sb_2Te_3	–	15	4.3	[19]
Bi_2Te_3	0.69	–	4.89	[20]
Bi_2Te_3, Sb_2Te_3	–	200	7.4	[21]
$(BiSb)_2Te_3$, Bi_2Te_3	–	240	8.18	[22]
Bi_2Te_3	1	270	9.3	[23]
Nanostructured bulk half-Heusler alloys	1	500	5.3	[24]
Bi_2Te_3	–	85	2.3	[25]
Bi_2Te_3	0.64	145	5.45	[26]
Bi_2Te_3	0.736	125	4.90	This study
$Bi_2(Te,Se)_3$	1	125	6.04	This study
$(Bi,Sb)_2Te_3$	1.4	125	7.40	This study
Bi_2Te_3 super-lattices	1.8	125	8.45	This study