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Design and performance of compact thermoelectric generators based on the extended three-dimensional thermal contact interface

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ABSTRACT

The thermal contact can influence the output performance of thermoelectric generators. However, in some applications, the heat source cannot afford an enough heating area for thermal contact. Therefore, compact thermoelectric generators based on optimized thermal contact interface should be designed and developed. In this paper, three-dimensional thermal extensional structures are designed, simulated, implemented and tested to optimize the thermal contact interface of compact thermoelectric generators. The result indicates that the compact thermoelectric generators based on three-dimensional thermal extensional structures can reduce the requirement of thermal contact area and make the heat flow directionally transferred to thermoelectric modules along the three-dimensional structure. In only 3600 mm^2 thermal contact area, the compact thermoelectric generators based on the three-dimensional structure can generate 5.58 V and 829 mW within 900 s.

1. Introduction

Thermoelectric generators (TEGs) can convert heat energy into electric energy. They are solid-state energy converters that have no mechanical moving parts and hence are silent, reliable, and environmentally friendly [1]. Based on these advantages, TEGs are usually used as the energy supply of low-power systems for remote sensing, control, safety surveillance and metering [2]. And, it also can be used in applications ranging from the harvesting of waste heat [3] to conversion of solar heat energy into electricity [4].

Recently, as the demand for environment protection and sustainable development is soaring, remarkable advances have been achieved in thermoelectric (TE) materials [5], TE power management systems [6] and TE applications [7]. Especially in TE applications, much work has been done to study the latent and possible applications [8]. Bonin et al. [9] designed and tested a small TEG for environmental monitoring devices. Liu et al. [3] designed and fabricated a completed TEG system to recover waste heat from automotive exhaust. He et al. [10] developed a solar heat pipe TEG unit which can generate power by using solar heat. And, Yu et al. [11] presented a wearable micro TEG to harvest human heat energy.

Generally speaking, the TEG is mainly composed of thermoelectric modules (TEMs) which contain a hot side and a cold side to establish a temperature difference across thermoelectric materials [12]. The maximum output power of the TEM can be calculated as Eq. (1) [13].

$$P_{max} = \frac{(n\alpha\Delta T)^2}{4R_{in}} \tag{1}$$

The parameter P_{max} is the maximum output power of TEM, n is amount of TE pairs, α is Seebeck coefficient, ΔT is temperature difference, and R_{in} is internal resistance of TEM. As shown in Eq. (1), excellent maximum output power requires outstanding temperature difference.

If the TEM and the heat source are given, the temperature difference will mainly depend on two key factors. One is the cooling method; and the other one is thermal contact condition between TEMs and heat sources [14]. The cooling method determines the cold-side temperature. The thermal contact condition, between TEMs and heat sources, determines the hot-side temperature [15]. Generally speaking, air convention, water cooling, and phase change energy storage are commonly used cooling methods. For

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Nomenclature

Q	heat (J)
Q_c	convective heat loss (W)
C	thermal capacity (J/K)
c	specific thermal capacity (J kg^{-1} K^{-1})
λ	thermal conductivity (W m^{-1} K^{-1})
T	temperature (K)
T_s	heat source temperature (K)
T_a	ambient temperature (K)
T_{ave}	average temperature (K)
t_s	surface temperature (K)
t_f	fluid temperature (K)
E	radiation loss (W/m^2)
A_c	cross-sectional area (m^2)
A	convective area (m^2)
R_{HS}	thermal resistance of heat sinks (K/W)
R_{TEM}	thermal resistance of TEMs (K/W)
P_{max}	maximum power of the TEM (W)
$P_{max\text{-}TEG}$	maximum power of the TEG (W)
V_o	open-circuit voltage (V)
R_{in}	internal resistance of the TEM (Ω)
R_{tin}	total internal resistance of the TEG (Ω)
n	number of TE pairs
α	Seebeck coefficient (V/K)
m	mass (kg)
d	length (m)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
R_{Ah}, R_{Bh}, R_{Ch}	thermal resistance of horizontal part (K/W)
R_{Av}, R_{Bv}, R_{Cv}	thermal resistance of vertical part (K/W)
R_{At},R_{Bt}, R_{Ct}	total thermal resistance of TEG based on 3D structure (K/W)
ε	emissivity
σ	Stenfan–Boltzmann constant (W m^{-2} K^{-4})

example, Wang et al. [16] designed and fabricated a TEG which is cooled by air-cooling system; Yadav et al. [17] investigated various TEG configurations to generate power at micro scales under water cooling condition; and, we previously reported a novel self-powered wireless temperature sensor based on TEG which adopted phase changing material as the cooling material [18]. The corresponding cold-side temperature of above applications is restricted around room temperature, water temperature, and phase changing temperature. In these applications, since the cold-side temperatures are restricted, the output performance of TEMs will be directly influenced by the thermal contact condition between heat sources and TEMs.

Until now, there are many methods to improve the thermal contact condition between heat sources and TEMs. Karri et al. [19] employed thermal grease in a TE exhaust energy conversion system to enhance the thermal conductivity between the TEM and exhaust heat exchanger. Özdemir et al. [20] adopted thermal grease to ensure the thermal conductivity between the TEM and the solar collector tube. Liu et al. [21] studied the influence of heat exchangers to improve the thermal exchange performance between heat sources and TEMs in automotive application. Barma et al. [22] adopted a heat exchanger to enhance the heat exchange between the TEM and the heat source. Champier et al. [23] discussed the influence of pressure on the thermal contact resistance between the TEG and heat source. Kinsella et al. [24] adopted a pressure on TEGs to get a good thermal contact between TEMs and the heat source. For these above applications, TEMs are directly placed onto the heating plane because there is no limit to the heating plane area. However, for small applications, the size of heat sources is always limited, and the area of heating plane is restricted [25]. In this case, the heating plane may not afford an enough area to cover all TEMs. Therefore, the heat source cannot contact with every TEM efficiently. To break the restriction on heating area, a feasible method is to extend the heating plane, which can make TEM contact with the heat source completely.

In this study, three-dimensional (3D) thermal extensional structures are designed and fabricated to optimize the thermal interface between TEGs and a small heating plane. The 3D structure contains a thermal contact segment and a thermal extensional segment. The thermal contact segment supplies a small thermal contact interface which reduces the requirement of thermal contact area. And the thermal extensional segment can extend the heating plane from a two-dimensional (2D) plane into 3D space, which makes all TEMs contact with the heat source completely. Dynamic simulations are simulated to evaluate the thermal transfer property of these 3D structures. Generating performances of the TEG based on these 3D thermal extensional structures are obtained through experimental methods. Different cooling methods are adopted and discussed.

2. Design of 3D thermal extensional structures

The TEM adopted in this paper is TEC-12704 whose size is 40 mm × 40 mm × 3.3 mm ($L \times W \times H$). Therefore, the initial area of thermal contact interface is 6400 mm^2 (40 mm × 40 mm × 4) when four TEMs are directly placed onto the heating plane as the conventional method. Obviously, if four TEMs are placed as the conventional method, the performance of TEGs is the highest because there is no additional thermal resistance caused by additional thermal transfer part. However, in some applications, the heating plane cannot supply enough area to place all TEMs on it. To solve this problem, thermal extensional structures must be introduced to extend the thermal contact interface although additional thermal resistance will decrease the performance of TEGs. Undoubtedly, the feasibility is more important than the high performance.

Based on the above consideration, a 3D thermal extensional structure (type A) is designed to extend the thermal contact interface from the 2D plane into 3D space. As shown in Fig. 1a, this structure contains a horizontal part and a vertical part. The base surface of the horizontal part is the thermal contact segment which makes thermal energy transfer into the 3D structure. To compare the thermal contact area with the initial area, the thermal contact area was calculated. The area of thermal contact segment is 2720 mm^2 ($L \times W$ = 80 mm × 34 mm) which is only 42.5% of the initial area. The vertical part is the thermal extensional segment which extends the thermal contact surface from the 2D plane into the 3D space. TEMs can be arranged on both sides of the thermal extensional segment. The height of the vertical part is 50 mm. The thickness of all parts is 2 mm. The area of thermal contact interface extends from 2720 mm^2 into 8000 mm^2 (50 mm × 80 mm × 2).

The thermal resistance model of type A structure can be described as Fig. 2a. T_s and T_a are the heat source temperature and ambient temperature respectively. The thermal resistance of type A structure is: