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Wearable thermoelectric generator for harvesting heat on the curved human wrist

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HIGHLIGHTS

- A numerical model to study the performance of wearable TEG on curved surface is developed.
- Radii of curvature of the curved surface have great effects on the heat distribution in the TEG.
- The TIL with thin thickness and high thermal conductivity is beneficial to enhance the voltage generation.

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ABSTRACT

Wearable electronics and sensors for health monitoring are becoming increasingly popular as their functionality continues to grow. Wearable thermoelectric generators (TEGs) are attracting interest due to their ability to self-power these electronic devices or sensors by harvesting human body heat. For wearable TEGs, a flexible thermal interface layer (TIL) is used underneath the TEG for wearing on the human body. The large thermal resistance induced at the interface between the skin and the TEG currently limits improvements in the performance of wearable TEGs and needs to be evaluated. This paper develops a numerical model to investigate the performance of wearable TEGs on the curved human wrist. The TEG and bottom TIL are meshed using rectangular grids and the body-fitted coordinate (BFC) transformation, respectively. Using the finite volume method (FVM), the proposed model is calculated, and the temperature and voltage distributions in the TEG and bottom TIL are analyzed. The effects of the radii of curvature of the curved surface, the material properties, and the thicknesses of the TIL are investigated both numerically and experimentally. The results obtained in this research can be utilized for optimal structural designs for wearable TEGs and for material selection of the TIL to enhance the power generation for self-powered electronics.

1. Introduction

With the advancement of microelectromechanical systems (MEMS), miniaturized flexible electronics and sensors can be worn on the human body and used for health or environmental monitoring. The power supply demands of these miniaturized devices are typically in the range of microwatts to milliwatts [1]. Wearable thermoelectric generators (TEGs) have been shown to be a promising strategy for powering these devices, as they can convert human body heat into electricity [2,3]. The wearable TEGs that have been developed usually feature the advantages of small compact size and light weight, while the low efficiency and low power density limit TEGs' application when the functionality of the devices is expanded. To enhance the performance of TEGs, considerable researches have been carried out in the development of new thermoelectric materials with a high figure of merit (*ZT*) [4,5], novel fabrication processes [6,7], optimal structural designs [8–10], and so on.

Wearable TEGs are designed to be worn on the human body, e.g., the forehead, chest, forearm, wrist, legs, etc. For these TEGs, rigid thermoelectric legs are usually designed on a flexible substrate [11,12]. The selection of material for the substrate is critical as it affects the performance of the TEG, because it will introduce a large thermal resistance at the interface between the skin and TEG and in turn lower the voltage and power generation. Sakamoto et al. [13] presented an experimental method to evaluate thermal resistance at the interface layer when the TEG was on a flat surface. The thermal interface substrate with a thinner layer and higher thermal conductivity could enhance the performance of the TEG. When the TEG is worn on skin that is curved,

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Nomenclature

Roman

W	width of thermoelectric leg (mm)
H	height of thermoelectric leg (mm)
L_1	distance between N- and P- type thermoelectric legs in one unit (mm)
L_2	half-distance between N- and P- type thermoelectric legs in adjacent unit (mm)
T	temperature (K)
V	voltage (V)
k	thermal conductivity (W/m·K)
h	convection coefficient (W/m²·K)
J	Jacobian factor
m, n, l	the coefficient in body fitted coordinates (BFC) transformation

Greek

α	Seebeck coefficient (VK^{-1})
γ	electrical conductivity (Sm^{-1})
ξ, η	axes in BFC
δ	thickness of the TIL (mm)

Subscripts

e, w, n, s	control interfaces
C, E, W, N, S	control volumes
OC	open circuit

the flexible substrate, e.g., the thermal interface layer (TIL), is bent and deformed. The effects of bending around the curved surface and of the deformed TIL on the heat flowing through the TEG for heat harvesting needs to be investigated and become one goal of this research.

The performance of TEGs worn on the human body has been studied by numerical modeling and experimental tests. Leonov [14] developed a model to study the effects of localized properties of the body (like skin temperature and heat flow) on the thermal properties of the TEG. The curved shape of the skin and its effects were not included. The results showed that the radiator on the cold-side of the TEG can reduce the thermal resistance at that part of the human body and, in turn, this generates greater power. Suarez et al. [15] presented a quasi-three-dimensional (3D) model to study the design criteria for rigid and flexible TEGs for wearable applications on the human body. For wearable TEGs, they identified the significance of thermal conductivity over Seebeck coefficient and electrical resistivity of the thermoelectric material in enhancing voltage and power generation. The thermal conductivity of the filler material in the TEG has also been demonstrated as a critical parameter to affect performance. For wearable TEGs, polydimethylsiloxane (PDMS) has been utilized as a flexible insulating and supporting material for the encapsulation of rigid thermoelectric legs [16–18]. The effects of PDMS filler in the TEG on a flat surface have been studied via the development of a numerical model [19], and results showed that the PDMS can improve the flexibility of the TEG without sacrificing power generation. However, the model developed previously does not consider the effects of a curved surface and the TIL, which often occur in wearable applications. Here, we propose a numerical model that aims to investigate the performance of a wearable TEG on curved skin surface. The influence of the deformation of the TIL induced on heat flow, temperature and voltage distributions in the TEG will be analyzed.

In this paper, we present a numerical model to investigate the performance of a wearable TEG on a curved surface. The physical domains of the rigid thermoelectric legs and deformed TIL are meshed using rectangular grids and body-fitted coordinate (BFC) transformations, respectively. Then, this model is solved through the finite volume

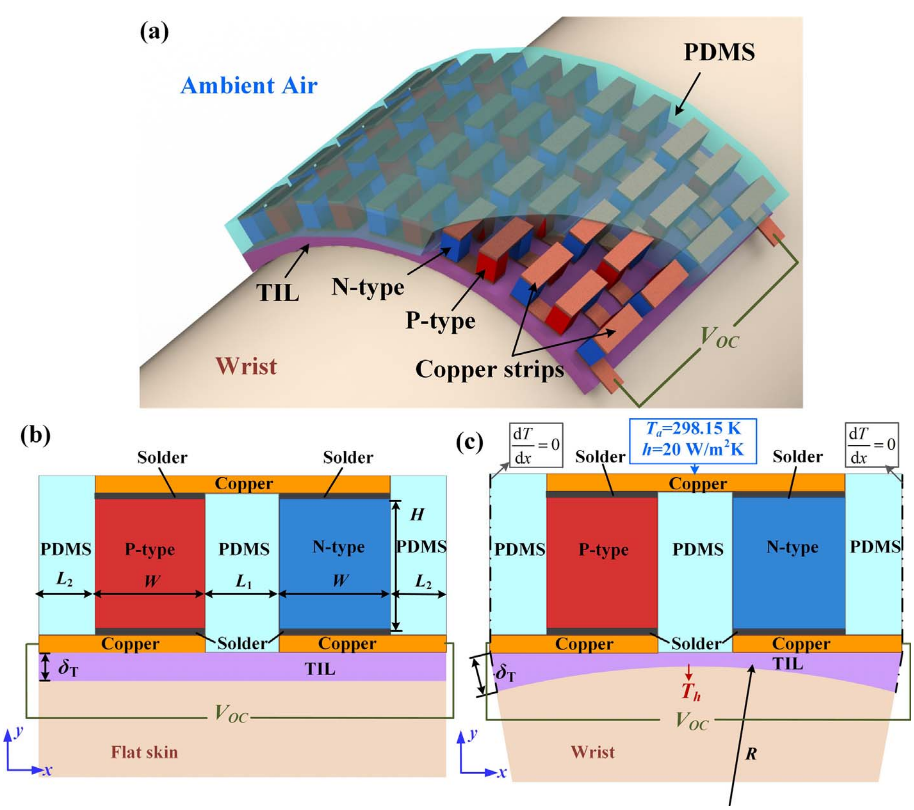

Fig. 1. Structural design of a wearable TEG on the wrist (a); cross-sectional view of the TEG on skin that is a flat surface (b), and skin that is a curved surface (c).