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Power generation modeling for a wearable thermoelectric energy harvester with practical limitations

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HIGHLIGHTS

- Explored the effect of practical issues in body heat thermoelectric energy harvester.
- Suggested optimal/practical geometries for the heat sink and thermoelectric module.
- Considered the effect of a boost converter's voltage dependent efficiency.
- Estimated power output of 0.48 mW within a wearable area.

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ABSTRACT

Recent studies on improving the thermoelectric figure of merit (*ZT*) have advanced research into self-powered, wearable technologies using thermoelectric generators. However, previous design approaches do not consider structurally practical heat sink and module geometries, the use of a boost converter, or the size constraint of the generator due to aesthetic appeal, all of which lower the overall power output. Additionally, the reduced efficiency in using a boost converter changes the electrical and thermal load matching conditions for maximum power. In this study, the limitations of practicality were considered for a wearable thermoelectric generator that utilizes a state-of-the-art boost converter and an optimized heat sink. Heat sink fin geometries and thermoelectric module geometries were explored to maximize the power output within a 42.0 cm^2 area and a 1.0 cm total height, in order to justify the wearability of the energy harvester. With optimized values of fin and module heights, the system was designed to produce 0.48 mW of electrical power at a boosted output voltage of 3.0 V, enough to power a small heart-rate monitor.

1. Introduction

Thermoelectric energy harvesters have the potential to free people from frequent charging and battery replacement of portable devices through their incorporation into wearable device applications. Thermoelectric generators convert waste heat from the human body into electrical energy without being interrupted via the Seebeck effect, which produces an electrical potential proportional to a temperature difference [1]. Unfortunately, the application of thermoelectric devices is often not practical or feasible due to their low voltage and power production, as well as their limited heat dissipation capability. The performance of thermoelectric devices depends on three material properties: thermal conductivity, the Seebeck coefficient, and electrical resistivity. Many research efforts focus on improving these properties through nano-structuring or band gap engineering [2,3]. However, system level optimization has not yet been explored as extensively as the material properties and many practical issues have been overlooked.

Three main aspects have been ignored in designing an energy harvesting system with thermoelectric generators: limited heat dissipation from the cold side of the module, low system output voltage, and the limited practical size of the system. Another general practice in designing a thermoelectric power generator, which should be avoided, is the use of the traditional method for evaluating the maximum power generation, as it assumes an infinite amount of heat dissipation from the cold side. This implies that the cold side temperature is equal to the temperature of the ambient air around it [4,5], which leads to an overestimation of power production. In reality, a finite thermal resistance exists between the thermoelectric module and the ambient, causing the actual

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temperature drop to be much larger than the value predicted by the traditional approach. Moreover, internal heat generation by Joule heating and the Peltier effect, which cause further change in temperature difference across thermoelectric materials, is often neglected in the load matching condition when utilizing the traditional approach [6]. In using energy conservation equations, the module's cold side thermal resistance and internal heat generations must be taken into account [7]:

$$Q_H = K(T_H - T_C) + SIT_H - \frac{1}{2}I^2R = \frac{T_{BODY} - T_H}{\psi_H} \tag{1}$$

$$Q_C = K(T_H - T_C) + SIT_C + \frac{1}{2}I^2R = \frac{T_C - T_\infty}{\psi_C} \tag{2}$$

where K is the thermal conductance of the module, T_H is the temperature of the module's hot side, T_C is the temperature of the module's cold side, S is the Seebeck coefficient of the module, I is the module's input current, R is the electrical resistivity of the module, T_{BODY} is the internal temperature of the human body, T_∞ is the ambient temperature, ψ_H is the thermal resistance of the wearer's skin, and ψ_C is the thermal resistance of the heat sink. Furthermore, K, S, and R may be described with the following equations:

$$S = N(\alpha_p - \alpha_n) \tag{3}$$

$$R = \frac{4N^2\rho L + 8N^2R_C}{A_S FF} \tag{4}$$

$$K = \frac{A_S k FF}{L} \tag{5}$$

where N is the number of leg pairs in the generator, α_p and α_n are the Seebeck coefficients of the p-type and n-type legs respectively, ρ is the electrical resistance of the thermoelectric material, L is the leg length, R_C is the electrical contact resistance between each leg, A_S is the surface area of the generator, k is the thermal conductivity of the thermoelectric material, and FF is the fill factor, which may be described with the following:

$$FF = \frac{2NA_C}{A_S} \tag{6}$$

where A_C is the cross-sectional area of a thermoelectric leg. With these equations, an appropriate model for a thermoelectric power generator can be created.

Recently, several researchers have realized the importance of thermal load matching to maximize the temperature difference across the module and increase the power and voltage output. Therefore, they have suggested a new power optimization strategy: matching the thermal resistances [8]:

$$\psi_{TEM} = (\psi_H + \psi_C)\sqrt{1 + ZT} \tag{7}$$

where ψ_{TEM} is the thermal resistance of the thermoelectric module and ZT is the dimensionless thermoelectric figure of merit, which is given by the following:

$$ZT = \frac{(\alpha_p - \alpha_n)^2}{k\rho}T \tag{8}$$

where T is the temperature at which the figure of merit is being evaluated. Using this method, the maximum power can be produced when a thermoelectric power generator is designed to satisfy Eq. (7), assuming the electrical load matching condition is $R_L/R = \sqrt{1 + ZT}$, where R_L is the electrical load resistance and R is the module electrical resistance [1].

A more general approach to evaluate the power output for a thermoelectric generator is suggested by Youn et al. and McCarty and Piper [9,10]:

$$V_{OC} = S\Delta T_{OC} \tag{9}$$

$$V_{OUT} = \frac{V_{OC}}{2} \tag{10}$$

$$I_{SC} = S\frac{T_H - T_C}{R} \tag{11}$$

$$P_{MAX} = \frac{V_{OC}I_{SC}}{4} \tag{12}$$

where V_{OC} is the module's open circuit voltage, V_{OUT} is the output voltage of the module, I_{SC} is the short circuit current of the module, P_{MAX} is the maximum power output of the module for a given heat sink performance, and ΔT_{OC} is the open circuit temperature difference across the module. One should note that the temperature difference in Eq. (11) is different from that of Eq. (9) due to additional heat generation inside the module by Joule heating and the Peltier effect. Also, the power output is independent of the number of leg pairs, due to the assumption of negligible electrical contact resistance; however, the number of leg pairs will change the output voltage and current ranges of the system. While the temperature difference under the open circuit can be derived by a simple thermal circuit analogy, due to no internal heat generation by electrical current flow, the temperature difference under the short circuit should be calculated by solving Eqs. (1) and (2). In using Eqs. (9)–(12), it is assumed that the electrical load resistance ratio is such that the maximum power conditions are present [10], which differs from the traditional load matching condition. As demonstrated by Gomez et al. [7], when internal heat generation caused by Joule heating and the Peltier effect is taken into account, the maximum power output does not necessarily occur when the load resistance is matched with internal resistance [10]. However, Youn et al. has shown that the current and voltage curve of a thermoelectric power generator is straight, regardless of the thermal load being matched or not [9]. Therefore, the maximum power can be easily evaluated without numerically solving the energy conservation equations: the maximum power output happens when the voltage output is close to half the open circuit voltage (Eq. (10)) and the maximum power output is the product of the short circuit current and the open circuit voltage divided by four (Eq. (12)). However, these optimum conditions have two main limitations in wearable thermoelectric power generation design. Firstly, in order to maintain aesthetic appeal, wearable thermoelectric generators are limited in physical space, which makes it difficult to ensure thermal load matching. Secondly, the voltage output must be boosted to gain useful power out of the generator, which causes further reduction in the power output. Since the boost converter efficiency depends on its input voltage, the power output from a thermoelectric energy harvester is no longer independent of the voltage value. Therefore, the recent maximum power output conditions (Eqs. (7) and (12)) are no longer mathematically valid. For these reasons, new optimal module geometry and electrical load matching conditions must be suggested for the wearable energy harvester design.

In previous efforts, wearable thermoelectric generators have often been made far bulkier than desired and produce only a small amount of power. An earlier study shows that a thermoelectric device almost 3 cm tall could only produce 20–30 μW/cm^2 [11,12]. Suarez et al. used a 3D model to design and test a custom module, which was able to produce 120 μW [13]. More recently, a flexible thermoelectric generator with 100 leg pairs has been able to generate 4.18 nW and 160 mV with a temperature difference of 15 K across the module [14]. In investigating flexible thermoelectric generators, extensive research in organic semiconductor material for flexible thermoelectrics has been conducted by Chen et al. [15]. Such research can be used to enhance the output power of a thermoelectric power generation system by creating better contact