

Simulation-Guided Optimization of Stair-Shaped Wearable Thermoelectric Generators Using COMSOL Multiphysics®

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Abstract

Wearable thermoelectric generators (WTEGs) are promising for self-powered electronics, but their performance is strongly limited by thermal management. This study presents a COMSOL Multiphysics®-guided optimization of a stair-shaped WTEG. Simulations showed that Cu-foil electrodes in the first-generation device created a parasitic thermal bridge, reducing the temperature difference across the thermoelectric legs. Replacing the Cu foil and Kapton substrate with Cu-wire electrodes and aerogel increased the open-circuit voltage from 1.1 to 4.0 mV and output power from 0.5 to 2.6 μ W. Further optimization of electrode placement increased the power to 2.8 μ W. A Z-shaped electrode reduced internal resistance from 0.65 to 0.60 Ω while maintaining the thermal gradient, achieving 4.21 mV and 2.99 μ W. The results demonstrate that balancing thermal-gradient preservation and electrical contact resistance is essential for high-performance WTEGs.

Keywords: Wearable thermoelectric generator, COMSOL Multiphysics®, electrothermal coupling, stair-shaped architecture, device optimization, flexible electronics.

Introduction

The rapid growth of wearable electronics, health-monitoring sensors, and Internet-of-Things (IoT) devices has increased demand for lightweight, autonomous power sources[1]. Conventional batteries are constrained by finite lifetimes, periodic charging, added mass, and environmental concerns. Energy-harvesting technologies therefore provide an attractive alternative, particularly for low-power wearable systems. Among these technologies, wearable thermoelectric generators (WTEGs) are promising because they directly convert body heat into electricity without moving parts, chemical reactions, or external mechanical excitation[2,3].

A thermoelectric generator develops a voltage through the Seebeck effect when a temperature difference is maintained across a thermoelectric material. In wearable applications, this temperature difference is established between the warm skin surface and the cooler ambient environment. Practical WTEGs, however, face an important architectural trade-off. High conformability requires the device to be thin and flexible, but reducing thickness generally shortens the effective heat-transfer path and decreases the temperature difference across the thermoelectric (TE) legs[4]. Thus, improved flexibility can come at the expense of voltage and output power.

This trade-off is a central challenge in wearable thermoelectric design. Vertical pi-type devices can sustain relatively large temperature

differences but are generally bulky and mechanically rigid[5,6]. Lateral pi-type devices offer improved flexibility, although the achievable thermal gradient is often limited[7,8]. More recently, Y-shaped architectures have been developed to guide heat more effectively, but these designs typically require additional heat-guiding structures, such as metallic columns, which increase mass and can reduce wearability[9].

Here, COMSOL Multiphysics® is used to analyze, redesign, and optimize a stair-shaped WTEG architecture that decouples overall device thickness from the effective heat-transfer path[10] (Fig. 1(a)).

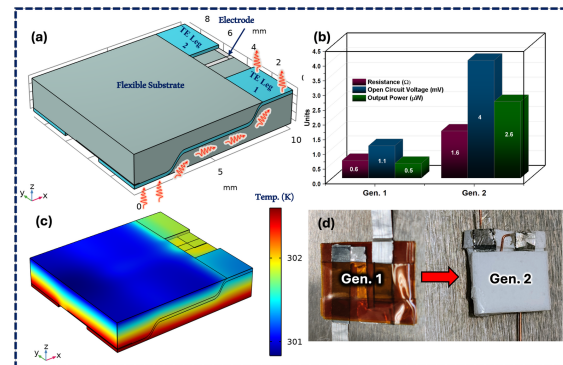


Figure 1. (a) Schematic of heat transfer in the stair-shaped WTEG. (b) Comparison of the output performance of Gen. 1 and Gen. 2 devices. COMSOL Multiphysics® visualizations of heat transport in (c) Gen. 1 and (d) Gen. 2 WTEGs.

Theory and Experimental Setting

The electrical output of a thermoelectric generator is primarily governed by the temperature difference across the active TE legs and the total internal electrical resistance. The open-circuit voltage is expressed as

$$V_{OC} = S_{eff} \Delta T \quad (1)$$

where S_{eff} is the effective Seebeck coefficient and ΔT is the temperature difference across the thermoelectric path[11]. Under matched-load conditions, the maximum output power is

$$P_{max} = \frac{V_{OC}^2}{4R_{int}} = \frac{(S_{eff} \Delta T)^2}{4R_{int}} \quad (2)$$

These relations highlight the coupled nature of the design problem. High performance requires a large ΔT while maintaining a low internal resistance R_{int} [12]. Minimizing resistance alone is insufficient if the temperature difference across the TE legs is compromised.

Governing Equations and Numerical Model

A coupled thermal-electrical model was implemented in COMSOL Multiphysics®. The thermal model solves steady-state heat conduction through the TE legs, electrodes, and substrate:

$$\nabla \cdot (k \nabla T) = 0 \quad (3)$$

$$q = -k \nabla T \quad (4)$$

For each material region, k is the thermal conductivity, T is temperature, and q is heat flux. A simplified one-dimensional estimate of parasitic heat leakage through a component is

$$\dot{Q} = \frac{kA}{L} (T_h - T_c) \quad (5)$$

where A is the heat-conduction area, L is the conduction length, and T_h and T_c are the hot- and cold-side temperatures, respectively. This relation explains why a Cu-foil electrode can act as a strong parasitic thermal bridge: copper has high thermal conductivity, and the foil geometry provides a relatively large conduction area. Replacing the foil with a wire reduces A and therefore suppresses undesirable heat leakage. The electrical resistance of a TE leg is

$$R_{TE} = \frac{\rho_{TE} L_{TE}}{A_{TE}} \quad (6)$$

$$A_{TE} = W_{TE} D_{TE} \quad (7)$$

The total internal resistance is the sum of the TE-leg resistance, electrode resistance, and contact resistance:

$$R_{int} = R_{TE} + R_{elec} + R_{cont} \quad (8)$$

The COMSOL analysis was organized in two stages. First, architectural simulations compared heat-flow

behavior for four electrode/substrate combinations: Cu foil/Kapton, Cu wire/Kapton, Cu foil/aerogel, and Cu wire/aerogel. Second, parametric sweeps were performed over the TE-leg dimensions, particularly L_{TE} and D_{TE} , to quantify their effects on internal resistance, temperature difference, and output power. The optimization objective was to maximize

$$P_{max}(\mathbf{x}) = \frac{[S_{eff} \Delta T(\mathbf{x})]^2}{4R_{int}(\mathbf{x})} \quad (9)$$

with the design vector $\mathbf{x} = [\kappa_{sub}, A_{elec}, L_{TE}, D_{TE}]$. Practical constraints were also considered qualitatively, including flexibility, manufacturability, handling difficulty, and stable electrical contact.

Preliminary Results

In our previous work[10], the first-generation stair-shaped WTEG used Cu-foil electrodes and a Kapton substrate. The Cu foil provided low electrical resistance and minimal contact resistance, as verified experimentally using the linear four-probe method. Nevertheless, the first-generation device produced a relatively low open-circuit voltage and output power, indicating that the dominant loss mechanism was thermal rather than electrical. We therefore used COMSOL Multiphysics® to evaluate the effects of electrode form (foil or wire) and substrate thermal conductivity (Kapton: $0.14 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$; aerogel: $0.04 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$) on heat transfer from the hot to the cold side of the stair-shaped WTEG. The computed temperature and heat-flux fields showed that the Cu-foil electrode acted as an unintended thermal bridge (Fig. 1(c)), transferring heat from the hot region toward the cold region and reducing the effective temperature difference across the TE legs. Thus, although Cu foil was electrically advantageous, it was thermally detrimental.

This finding changed the design strategy. Rather than minimizing internal resistance in isolation, the device had to be optimized as a coupled thermal-electrical system. The second-generation design therefore replaced the Cu foil with Cu wire and the Kapton substrate with aerogel (Fig. 1(d)). Experiments validated the simulation-guided redesign. The first-generation device had an internal resistance of approximately 0.6Ω but produced only about 1.1 mV and $0.5 \mu\text{W}$ at a hot-side temperature of approximately 302 K . The second-generation device had a higher internal resistance of approximately 1.6Ω , yet the improved temperature difference increased the open-circuit voltage to about 4.0 mV and the output power to approximately $2.6 \mu\text{W}$. Figure 1(b) compares the output performance of the two generations. These results show that the optimum design is not necessarily the

one with the lowest electrical resistance, but the one that best balances temperature-difference preservation and electrical losses.

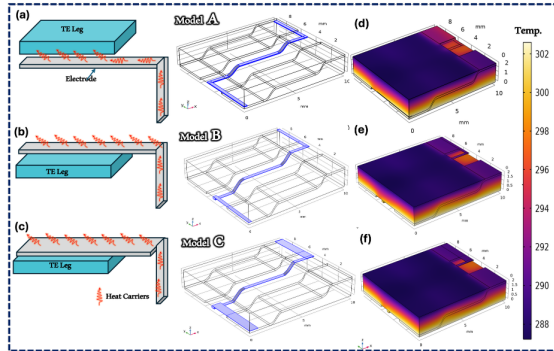


Figure 2. (a-c) Schematics of heat transfer between the electrode and TE leg for Models A-C. (d-f) COMSOL Multiphysics® visualizations of heat transport for Models A-C, respectively.

Enhancement of Output Power through Electrode Position and Geometry Optimization

The Gen. 2 WTEG achieved an output power of 2.6 μW under an applied temperature difference of approximately 12 K. Further improvement was investigated through systematic optimization of the electrode position and geometry.

In both Gen. 1 and Gen. 2 devices, the contact electrode was located between the flexible substrate and the active TE material (Fig. 2(a)). Although this configuration provides strong mechanical adhesion and resistance to detachment, it also directs heat into the subsequent TE leg rather than allowing it to dissipate to the surroundings. Relocating the electrode from beneath to above the TE leg was therefore expected to promote direct heat dissipation from the electrode to the ambient environment, reduce heat transfer into the adjacent leg, and increase the effective temperature difference and output power (Fig. 2(b)).

Electrode geometry also governs both electrical resistance and thermal transport along the hot-to-cold axis. Wider electrodes can reduce electrical/contact resistance, whereas narrower sections restrict conductive heat flow. Decoupling these competing effects is therefore essential. To address both requirements, we propose a Z-shaped contact electrode with wide regions at each end connected by a narrow central passage (Fig. 2(c)). The wide end regions increase the contact area between the electrode and TE leg, whereas the narrow central passage reduces the cross-sectional area available for heat conduction. This geometry is intended to preserve good electrical connection while limiting parasitic heat transfer from the hot to the cold side.

The hypothesis was evaluated using a multiphysics model in COMSOL Multiphysics®, with identical boundary conditions applied to all simulated configurations to ensure a consistent comparison.

Simulation Results and Discussion

Finite element analysis (FEA) was performed for three device configurations:

Model A: The previously reported stair-shaped WTEG with the electrode positioned beneath the TE material.

Model B: A stair-shaped WTEG with the electrode positioned above the TE material.

Model C: A stair-shaped WTEG with a modified Z-shaped electrode positioned above the TE material.

For all simulations, the hot-side temperature was set to 302 K and the ambient temperature to 288 K. Heat exchange between the cold surface and the surrounding air was represented by a fixed heat-transfer coefficient of $70 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$. The maximum output power, P_{max} , was evaluated using the matched-load relation given above. In the electrothermal finite element model, the bulk electrical resistivities of the TE legs and Cu electrode were assigned as material properties.

Effect of Electrode Position (Model A vs. Model B)

Relocating the contact electrode from beneath the active TE material (Model A) to above it (Model B) substantially changed heat transfer from the hot end of leg 1 to the cold end of the subsequent leg. With the electrode beneath the TE leg, the cold end of leg 2 was approximately 5 K warmer than that of leg 1, indicating efficient heat transfer from the electrode into leg 2 (Fig. 2(d)). When the electrode was moved above leg 2, the thermal pattern changed markedly: leg 2 and its electrode reached temperatures comparable to those of leg 1 (Fig. 2(e)). This behavior arises from two related effects. First, the top-mounted electrode is directly exposed to convective heat transfer, which enhances heat dissipation to the surroundings and keeps its temperature closer to ambient. Second, this exposure suppresses heat transfer from the electrode into leg 2. Because electrode repositioning does not change the contact area, the overall internal resistance remains unchanged between Models A and B. The enhanced cold-side heat dissipation, however, increases the effective temperature difference and therefore the open-circuit voltage and output power. Under an applied temperature difference of approximately 12 K, Model B produces 4.2 mV open-circuit voltage and 2.8 μW output power (Fig. 3(a)).

Effect of Electrode Geometry (Model C)

After optimizing thermal transport through electrode repositioning, further improvement required

reducing electrical resistance without disturbing the enhanced temperature profile. Based on the preliminary observation that a larger electrode area lowers electrical resistance, we hypothesized that selectively widening only the electrode ends, rather than the entire electrode, could reduce resistance while preserving the optimized thermal behavior. Under identical boundary conditions, the simulated temperature distributions of leg 2 and its electrode in Model C closely matched those in Model B, indicating that the Z-shaped modification had negligible influence on the optimized thermal transport (Fig. 2(f)). At the same time, the modified electrode path reduced the computed internal resistance from $0.65\ \Omega$ in Models A and B to $0.60\ \Omega$ in Model C. Because contact resistance, R_{cont} , was set to zero in all simulations, any additional practical reduction associated with an increased contact area was not included in the model. By combining the optimized thermal behavior with lower electrical resistance, Model C (fig. 3 (c)) achieved the best overall performance, with an open-circuit voltage of $4.21\ \text{mV}$ and an output power of $2.99\ \mu\text{W}$. Figure 3(b,d) compares the simulated output characteristics of the stair-shaped WTEG configurations.

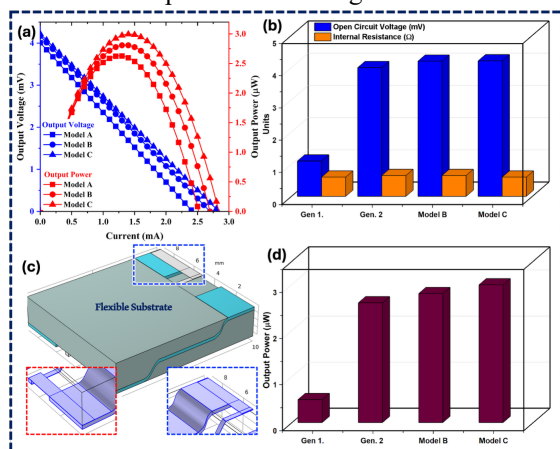


Figure 3. (a) Voltage and power versus applied current for Models A-C. Comparison of (b) open-circuit voltage and internal resistance and (c) schematic representation of Model C (d) output power for Gen. 1, Gen. 2 (Model A), Model B, and Model C.

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These results demonstrate that the best design is not defined by minimum electrical resistance or maximum thermal resistance alone. Instead, performance is determined by the balance between the two. The stair-shaped WTEG is therefore a thermally guided architecture, and COMSOL Multiphysics® provides a quantitative framework for progressing from an initial concept to a validated and optimized design.

Conclusion

This study demonstrates that maximizing the performance of a stair-shaped WTEG requires treating the device as a coupled thermal-electrical system rather than optimizing electrical resistance in isolation. Simulations and experiments showed that electrode materials and geometries with the lowest electrical resistance are not necessarily optimal because they can create parasitic thermal bridges that reduce the temperature difference driving thermoelectric conversion. Replacing Cu-foil electrodes with Cu wire and the Kapton substrate with aerogel substantially increased output power by preserving this temperature difference, despite an increase in internal resistance. Further gains were obtained by relocating the electrode above the TE leg to enhance heat dissipation at the cold junction and by introducing a Z-shaped electrode that combines wide end regions with a narrow heat-restricting passage. The optimized Model C achieved $2.99\ \mu\text{W}$, nearly six times the output power of the original first-generation device. More broadly, the results establish a simulation-guided design framework in which COMSOL Multiphysics® supports iterative structural refinement of stair-shaped and other geometrically complex WTEG architectures. Future work should experimentally validate the Z-shaped electrode, evaluate long-term mechanical durability under repeated bending, and scale the architecture to multi-leg arrays for practical wearable power applications.

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