The Optimum Leg Length of a Micro-Thermoelectric Generator Modules

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Abstract

Micro-thermoelectric generators (µTEGs) are emerging as promising power sources for low-energy devices, including Internet of Things (IoT) nodes, medical implants, and wearable electronics. Their compactness, reliability, and maintenance-free operation make them highly attractive, since µTEGs exploit solid-state thermoelectric conversion without moving parts and directly harvest waste heat. This study develops a comprehensive modeling framework to analyze the impact of critical design parameters on µTEG performance. Particular emphasis is placed on leg length, as scaling thermoelectric legs to the microscale reduces thermal resistance and enhances power density. Simulation results demonstrate that reducing leg length initially improves both output power and efficiency, though performance declines when parasitic effects dominate at excessively small scales. Additional parameters, including hot-side temperature, leg cross-sectional area, and ceramic plate thickness, are also systematically investigated. The hot-side temperature strongly governs output voltage and conversion efficiency, while leg area influences the trade off between electrical resistance and heat conduction. Similarly, ceramic plate thickness affects thermal spreading resistance, which significantly alters overall device efficiency. These findings provide useful design guidelines for optimizing µTEG structures. By tailoring microscale geometries and carefully managing coupled thermal–electrical pathways, compact and efficient µTEGs can be realized for future self-powered energy application.

Submitted: 15-JAN-2025

Accepted: 25-JUN-2025

Published:

DOI:

Highlights:

- Optimal leg length identified to maximize µTEG power output and efficiency.
- Microscale dimensions significantly enhance µTEG performance and material utilization.
- Optimized temperature differences, leg area, and ceramic plate thickness improves heat transfer and reduces thermal resistance.

1. Introduction

The pressing need for sustainable development and climate change mitigation, as emphasized by the Kyoto Protocol, mandates reducing global dependence on fossil fuels. This imperative has accelerated research into alternative renewable energy sources such as wind, hydropower, and solar energy, which have become focal points across diverse scientific disciplines. Among these alternatives, thermoelectric energy holds distinct advantages including compactness, light weight, and cost-effective fabrication. These attributes render thermoelectric modules highly versatile, supporting a broad spectrum of applications from autonomous microsystems and waste heat recovery in high-performance processors to wearable electronics and implantable medical devices (Yang, Y. et al., 2007; Solbrekken, G. et al., 2004; Leonov, V. et al., 2009; Yang, S. et al., 2010; Nakpathomkun, N. et al., 2010).

A thermoelectric generator (TEG) is a solid-state device that converts heat directly into electricity by exploiting temperature gradients across electrically connected thermocouples arranged in series and thermally in parallel, sandwiched between electrically insulating layers (Goldsmid, H. J., 2009). By harnessing waste heat, TEGs improve system efficiency and reduce thermal losses, enabling low-energy electronics to be powered sustainably by local temperature differences. While traditional larger modules are effective in many applications, emerging demands for energy-efficient, miniaturized systems—particularly in the Internet of Things (IoT)—have driven interest toward micro-thermoelectric generators (μTEGs). These devices, with thicknesses of just a few tens of microns, can operate under small temperature gradients and provide distributed renewable energy sources capable of sustainably charging batteries in low-power systems consuming less than 100 μW (Bell, L. E., 2008; Schwyter, E. et al., 2008; Al-Fuqaha, A. et al., 2015; Micro Energy Harvesting, 2015).

Batteries remain the default power source for many such devices, but they introduce challenges related to limited lifespans and frequent replacements, which impede miniaturization and long-term deployment of wireless sensor nodes. Micro thermoelectric generators offer a promising alternative by continuously scavenging thermal energy whenever a temperature difference exists across the device, thus providing reliable, maintenance-free power sources for small-scale electronics (Lim, W. Y. B. et al., 2020; Rowe, D. M., 2010; Ren, W. et al., 2021; Tarancón, A., 2019).

Over the past two decades, the evolution of μTEGs has been driven by advances in Micro-Electro-Mechanical Systems (MEMS) technology, which has enabled rapid improvements in design and fabrication. Various materials and fabrication methods have been explored to optimize performance (Zhang, Q., 2022; Li, G. et al., 2018; Shin, K. et al., 2015; Bottner, H. et al., 2004; Uda, K. et al., 2014; Beretta, D. et al., 2018). For example, Snyder et al. (2003) demonstrated low-cost μTEG fabrication by combining standard lithography with electrochemical deposition to create vertical generators achieving power densities of 40 $\mu W/cm^2$. Roth et al. (2014) introduced a novel method using dual photoresists, where SU-8 molds were electrochemically deposited with thermoelectric legs, laminated with patterned dry films, and integrated via flip-chip techniques, yielding a normalized power output of 1 $\mu W/cm^2 °C^2$. Zhang et al. (2016) further advanced fabrication by integrating 127 thermoelectric leg pairs through microfabrication and electrochemical deposition, achieving a normalized power density of 3.34 $\mu W/cm^2 °C^2$. Corbett et al. (2021) focused on improving contact resistance, a critical limiting factor, though their device was not characterized as a power generator.

Despite these advances, key challenges persist. Even with the development of high ZT materials, the normalized power density of μTEGs remains modest. To enhance performance, it is crucial to optimize both electrical contact resistance and packing density (the number of thermoelectric legs per device area). Additionally, the efficiency of thermal coupling between the device and the heat source is often overlooked; poor thermal contact reduces the effective temperature gradient and diminishes output power. Another significant but underexplored design parameter is the thermoelectric leg length, which directly influences total power output and conversion efficiency.

In light of these challenges, the present study aims to systematically investigate the optimal leg length for micro-thermoelectric generator modules. Furthermore, it analyzes other critical parameters impacting device performance, including thermal coupling effects, with the goal of maximizing power output and overall efficiency. By addressing these design factors, this work seeks to advance the practical application of μTEGs as efficient, reliable energy harvesters for low-power electronics and IoT devices.

2. Modeling of Micro-Thermoelectric Generator Module

In this section, a detailed modeling framework is developed to investigate the performance of micro-thermoelectric generator (μTEG) with a focus on optimizing leg length and other critical parameters. The model incorporates the thermoelectric principles governing energy conversion, including Seebeck effect, electrical and thermal conductivity, and heat transfer dynamics as temperature independent. This assumption is true in the case of using effective material properties as discussed and addressed by Elarusi, A, et al., 2016 and Weera, S, et al., 2020 where this model was validated along with experimental data by Lee H, 2017. By calculating the interplay of these factors, the aim is to determine the optimal configurations that maximize power output and efficiency under varying operating conditions. Additionally, the model considers material properties, thermal and electrical contact resistances, and the geometric structure of the μTEG to provide a comprehensive analysis of its performance.

As seen in Fig. 1 for a unicouple micro-thermoelectric generator, the equations for the steady-state heat balance can be given as follows.

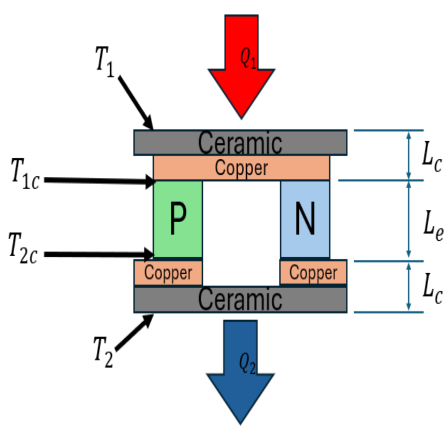

Fig. 1: One couple of μTEG.

$$\dot{Q}_1=\frac{A_e k_c}{L_c}(T_1-T_{1c}) \quad (1)$$

$$\dot{Q}_1=\alpha I T_{1c}-\frac{1}{2} I^2 R_e-\frac{A_e k_e}{L_e}(T_{2c}-T_{1c}) \quad (2)$$

$$\dot{Q}_2=\alpha I T_{2c}+\frac{1}{2} I^2 R_e-\frac{A_e k_e}{L_e}(T_{2c}-T_{1c}) \quad (3)$$

$$\dot{Q}_2=\frac{A_e k_c}{L_c}(T_{2c}-T_2) \quad (4)$$

$$I=\frac{\alpha(T_{1c}-T_{2c})}{R_L+R_e} \quad (5)$$

The above Eqs. can be solved for T_{1c} and T_{2c} as a function of seven parameters as

$$T_{1c}= T_{1c}(R_L,T_1,A_e,l_o,l_c,\rho_c,k_c) \quad (6)$$

$$T_{2c}= T_{2c}(R_L,T_1,A_e,l_o,l_c,\rho_c,k_c) \quad (7)$$

where

$$R_L=R_e=\frac{\rho_e\times L_e}{A_e}+\frac{\rho_c}{A_e}$$

$$k_e=k_n+k_p$$

Hence, Eq. 6 and Eq. 7 can be solved by using a mathematical program, which results with the power output and the efficiency for μTEG.

3. Results and Discussions

The results of this study provide valuable insights into the performance optimization of micro-thermoelectric generator (μTEG). Key findings include the influence of leg length on power output and efficiency, as well as the impact of thermal coupling and material properties on device performance. These findings are analyzed in detail to identify trends and establish relationships between critical parameters. Furthermore, comparisons with existing studies highlight the advancements achieved in this work and underscore its potential implications for enhancing μTEG module designs in real-world applications. After an extensive search for commercially available micro-thermoelectric generator modules, one suitable module was identified: MGM250-17-10-16. The specifications, properties, and dimensions of this module have been thoroughly reviewed and are summarized in Table 1. However, the μTEG is less than 1 mm but this module was selected based on its compatibility with the objectives of this study and its relevance to the performance optimization analysis. Its detailed characteristics provide a solid foundation for modeling and validation, ensuring accurate and meaningful results.

Table 1. The specifications of µTEG (MGM250-17-10-16).

Description	Value
Seebeck coefficient	$\propto_n$=(0.001530736×T^2-1.08058874×T-28.338095) ×10^{-6} V/℃ $\propto_p$ =(-0.003638095×T^2+2.74380952×T-296.214286) ×10^{-6} V/℃
Thermal Conductivity	k_n=(0.0000334545×T^2-0.023350303×T+5.606333) W/m℃ k_p=(0.0000361558×T^2-0.026351342×T+6.22162) W/m℃
Electrical Conductivity	σ_p=(0.015601732×T^2-15.708052×T+4466.38095) ×10^2 S/m σ_n=(0.01057143×T^2-10.16048×T+3113.71429) ×10^2 S/m
Leg Lenth	L_e=2 mm
Ceramic thickness	L_c=0.6 mm
Hot side temperature	T_1=250 ºC
Cold side temperature	T_2=30 ºC
Power output	W=0.42 W
Electrical Resistance	R_e=1 Ω
Number of thermocouples	n=17

Based on the specifications and utilizing the introduced model, the results were predicted and analyzed. As illustrated in Fig. 2, the relationship between power output and leg length was plotted.

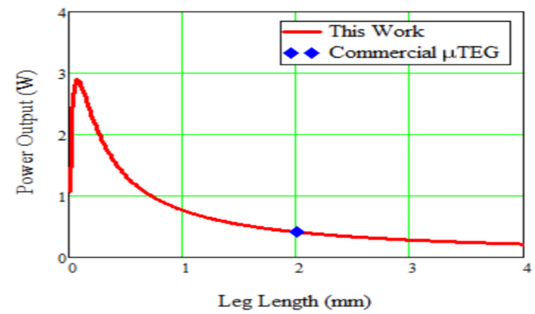

Fig. 2: Predicted and commercial power output versus leg length.

The results demonstrate that the model effectively validates the performance of the commercial thermoelectric module at the specified leg lengths. Notably, the analysis reveals a significant increase in power output as the leg length is reduced, particularly in the micro-scale range where the leg length is less than 1 mm. This indicates that minimizing the leg length has a profound impact on enhancing power output, especially when approaching optimal dimensions. By reducing the leg length to its optimum value, it is possible to achieve higher power output while simultaneously benefiting from a reduction in both module size and material usage. This optimization not only improves the performance of the thermoelectric module but also contributes to more sustainable material utilization, making it especially suitable for applications requiring compact and high-performance designs. The plot clearly highlights the existence of an optimum leg length at which maximum power output can be achieved. This finding provides valuable insights that can significantly enhance the design and development of micro-thermoelectric modules, offering improved performance and better resource management. Although the MGM250-17-10-16 module has a 2 mm leg length, it is among the smallest commercially available µTEGs and is categorized as "micro" due to its compact size. The model's agreement with this module validates its predictive accuracy. However, as shown in Fig. 2 and 8, the optimal leg length for maximum power output typically lies below 1 mm, under idealized conditions. This highlights opportunities for performance improvement through further leg length reduction, provided fabrication constraints are addressed.

One of the critical parameters influencing thermoelectric module performance is the electrical resistance, which is plotted against leg length in Fig. 3. The results confirm that the electrical resistance values obtained through the model align well with the commercial module's specifications, validating the model's accuracy. Furthermore, the analysis reveals a clear trend: electrical resistance increases with increasing leg length.

This relationship indicates that reducing the leg length leads to a corresponding decrease in electrical resistance. Such a reduction is beneficial for improving the overall performance of the thermoelectric module, as lower electrical resistance directly enhances power output. This is particularly advantageous in optimizing the design of micro-thermoelectric modules, where smaller leg lengths can achieve both reduced resistance and higher efficiency. In conclusion, the findings emphasize the importance of leg length as a key design parameter. By carefully minimizing leg length to its optimal value, it is possible to achieve a dual benefit of reduced electrical resistance and enhanced power output, ultimately leading to more efficient and compact thermoelectric systems.

On the other hand, the parameters T_{1c} and T_{2c}, which are defined and illustrated in Figure 1, are further analyzed and plotted as a function of leg length in Fig. 4. These temperatures exhibit a trend where they either increase or decrease until they stabilize at the junction temperature values T_1 and T_2, respectively.

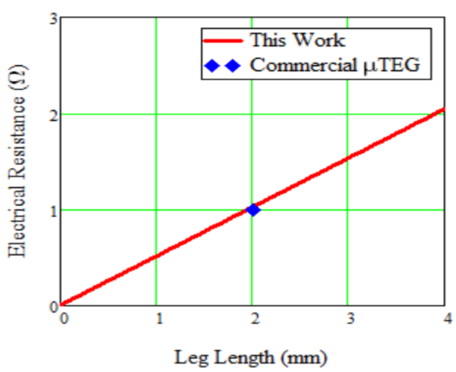

Fig. 3: Predicted and commercial electrical resistance versus leg length.

Notably, for leg lengths of 1 mm and above, there is minimal variation in T_{1c} and T_{2c}, indicating that thermal behavior becomes largely independent of further increases in leg length beyond this point. This observation supports the conclusion that microscale dimensions are optimal for leg length when aiming to achieve maximum power output. By maintaining leg length in the micro range, the thermoelectric generator's performance can be enhanced. The temperature difference between T_{1c} and T_{2c} reflects the impact of thermal coupling inefficiencies, which reduces the effective temperature gradient and, consequently, the power output. Improved coupling is observed as leg length decreases, with T_{1c} and T_{2c} approaching the boundary temperatures. These inefficiencies can be mitigated by reducing ceramic thickness, improving thermal interface materials, and optimizing bonding layers and contact conditions to minimize interfacial thermal resistance.

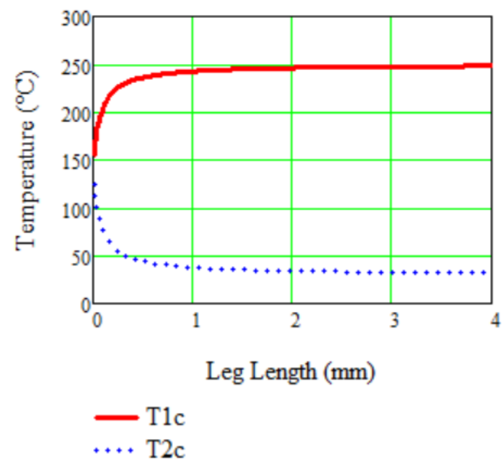

Fig. 4: Temperatures T_{1c} and T_{2c} versus leg length.

In Fig. 5, the relationship between efficiency and leg length is illustrated. The plot reveals that efficiency shows minimal variation for leg lengths exceeding 1 mm. This observation aligns with the conclusion that reducing the leg length to the microscale provides significant advantages for micro-thermoelectric generator (μTEG). Specifically, maintaining a microscale leg length not only enhances efficiency but also contributes to achieving higher power output. The results underscore the importance of optimizing leg dimensions within the micro range to maximize the performance of μTEG s, as further increases in leg length yield negligible improvements in efficiency while potentially increasing material usage and thermal resistance. The term "optimal leg length" in this study refers to the length that maximizes power output. As demonstrated in Fig. 2 to Fig. 5, reducing leg length into the microscale range minimizes electrical resistance and significantly enhances power output. Although microscale leg lengths introduce fabrication challenges, existing MEMS techniques—such as photolithography, electrochemical deposition, and flip-chip bonding—have demonstrated reliable fabrication of sub-100 μm legs, making the proposed dimensions feasible.

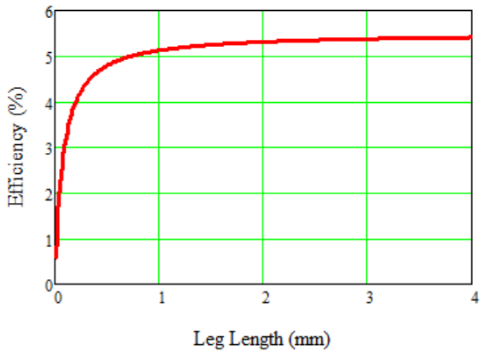

Fig. 5: Efficiency versus leg length.

It is particularly interesting to observe the effect of varying the hot-side temperature on the optimal leg length, as illustrated in Fig. 6. The results indicate that, despite changes in the hot-side temperature, all temperatures follow a similar trend, with the optimum leg length corresponding to maximum power output. This consistent behavior highlights the robustness of the relationship between leg length and power output under different thermal conditions. Moreover, the significant enhancement of power output at the microscale is especially noticeable, further emphasizing the benefits of adopting smaller leg dimensions for micro-thermoelectric generator (μTEG). In addition to power output, Fig. 7 provides a comparison of efficiency across different hot-side temperatures as a function of leg length. The trends reveal how efficiency varies with leg length for each temperature, offering deeper insights into the interplay between thermal gradients and device geometry. These findings reinforce the importance of optimizing leg length, particularly at the microscale, to achieve both high efficiency and maximum power output across a range of operating conditions.

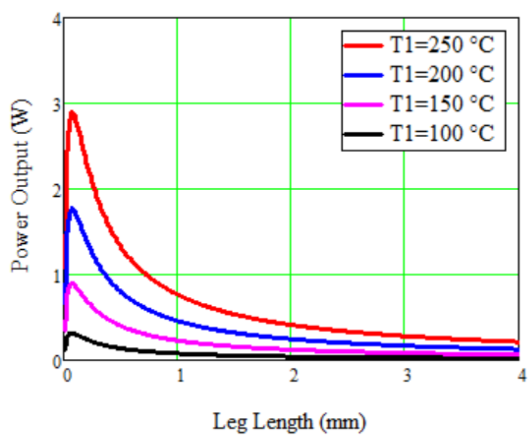

Fig. 6: Power output for different temperatures versus leg length.

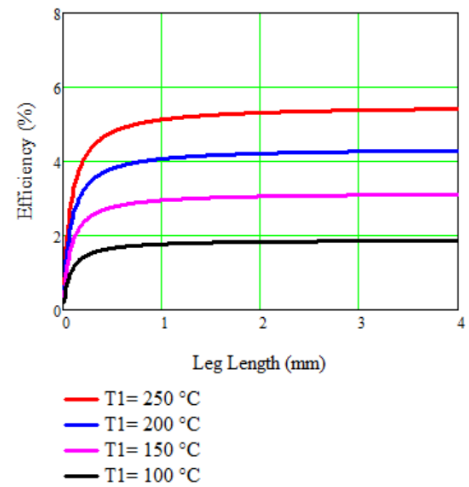

Fig. 7: Efficiency for different temperatures versus leg length.

One of the most closely related parameters to leg length is the leg cross-sectional area. The relationship between power output, leg area, and leg length is plotted in Fig. 8. The results clearly show that as the leg area increases, the power output also increases, demonstrating the significant influence of leg area on thermoelectric performance. However, despite this increase in power output with larger leg areas, the optimal leg length consistently remains within the microscale range. This finding underscores the importance of maintaining a balance between leg length and leg area to maximize performance. While increasing the leg area enhances the electrical and thermal pathways, the optimal power output is still achieved when the leg length is kept small. This highlights the microscale as the most effective range for leg length, enabling the highest power output while minimizing thermal resistance. These insights are crucial for designing an efficient micro-thermoelectric generator (μTEG) with optimized geometric parameters. On the other hand, Fig. 9 illustrates the relationship between efficiency and leg length for various leg areas. Interestingly, the plot reveals that changes in leg area have no discernible effect on efficiency, regardless of the variations in leg area values. Even when a higher range of leg area values is tested, the efficiency remains virtually unchanged. This finding is intriguing as it suggests that, unlike power output, the efficiency of micro-thermoelectric generator (μTEG) is largely insensitive to variations in leg area. This behavior highlights the distinct roles played by geometric parameters in influencing different performance metrics of μTEG. While leg area significantly impacts power output, its effect on efficiency appears negligible, underscoring the importance of optimizing other parameters, such as leg length to achieve improvements in efficiency. These results provide valuable insights for designing μTEG s with a balanced approach to maximizing both power output and efficiency. The differing trends in Fig. 8 and Fig. 9 can be explained by the distinct dependencies of power and efficiency. Increasing leg area improves electrical and thermal pathways, enhancing power output. However, efficiency remains nearly constant because both electrical output and heat input increase proportionally. This reflects a geometric effect on power, while efficiency is primarily governed by material properties and temperature gradient. The figure of merit, which defines efficiency potential, is independent of leg area, explaining this decoupling.

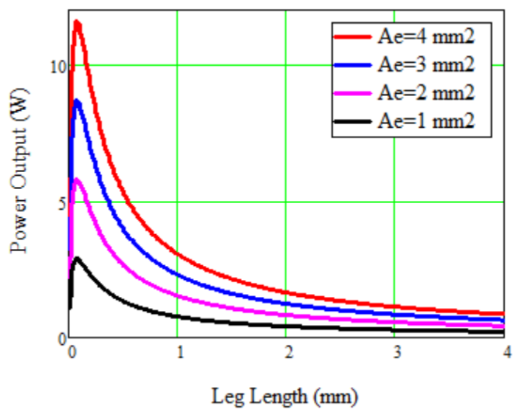

Fig. 8: Power output for different leg areas versus leg length.

One of the most critical parameters influencing the performance of micro-thermoelectric generator (μTEG) is the thickness of the ceramic plate (L_c). The effect of this parameter is investigated and plotted for various values, showing the relationship between power output and leg length (refer to Fig. 10). The results indicate that the ceramic plate thickness has a noticeable impact, particularly at smaller values, where a distinct optimal leg length emerges for achieving maximum power output.

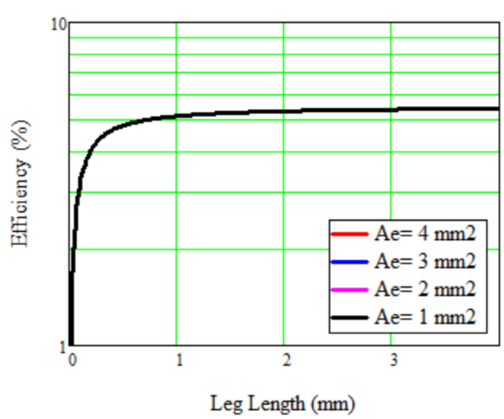

Fig. 9: Efficiency for different leg areas versus leg length.

To further analyze this behavior, the plot is regenerated specifically for microscale values of ceramic plate thickness (refer to Fig. 10). The refined analysis reveals that reducing the thickness of the ceramic plate leads to a significant increase in power output. This enhancement becomes especially evident at microscale leg lengths, where the interplay between geometric parameters has the most pronounced effect. Conversely, at larger leg lengths, the influence of ceramic plate thickness on power output becomes negligible, indicating that L_c primarily affects the performance at smaller scales. These findings underscore the importance of minimizing L_c in TEG designs to maximize power output, particularly when operating at microscale dimensions. By reducing thermal resistance and enhancing heat transfer efficiency at the junctions, thinner ceramic plates contribute to improved energy conversion. As a result, the thickness of the ceramic plate emerges as a key design parameter, particularly in optimizing TEG performance at the microscale. On the other hand, the efficiency of micro-thermoelectric generators (μTEG) for different values of ceramic plate thickness, including microscale dimensions, is plotted as a function of leg length in Fig. 11. The results reveal that while efficiency remains relatively consistent for larger ceramic plate thicknesses, noticeable changes begin to emerge when smaller, microscale thickness values are considered. These changes in efficiency at reduced ceramic plate thickness highlight the critical role of L_c in optimizing thermal and electrical performance. At smaller thicknesses, the reduced thermal resistance enhances the heat flow across the device, potentially improving the energy conversion process and resulting in higher efficiencies. This behavior is particularly important for microscale designs, where geometric parameters exert a more significant influence on performance.

These findings emphasize the importance of carefully selecting the ceramic plate thickness to achieve an optimal balance between efficiency and other performance metrics, particularly for μTEG applications operating at microscale dimensions. Fig. 10 and Fig. 11 provide valuable insights into how L_c can be adjusted to further refine the design and enhance the overall efficiency of μTEG modules.

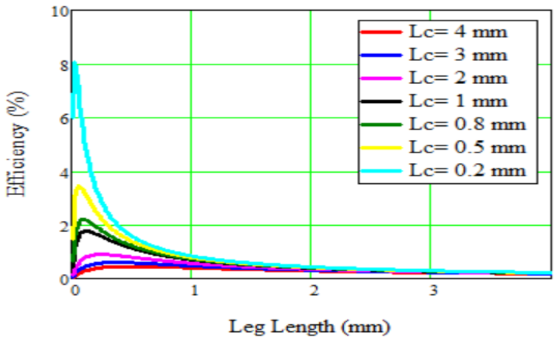

Fig. 10: Power output for different ceramic plate thickness versus leg length.

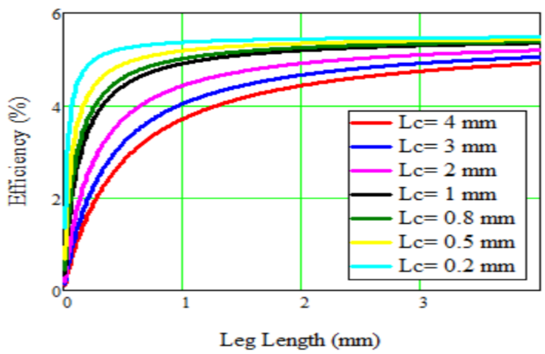

Fig. 11: Efficiency for different ceramic plate thickness versus leg length.

While Fig. 10 and Fig. 11 indicate that reducing L_c enhances performance by lowering thermal resistance, it is important to note that there exists an optimum ceramic thickness beyond which further reduction yields limited gains and may compromise mechanical integrity. Very thin plates (e.g., < 0.2 mm) risk cracking or warping during fabrication and use. Thus, optimizing L_c involves balancing thermal performance with structural durability. This work emphasizes absolute power output under realistic geometric and thermal conditions. By incorporating thermal/electrical contact effects and identifying optimal leg dimensions, the model provides practical guidance for μTEG design in low-gradient environments.

4. Conclusion

This study provides comprehensive insights into the optimization of micro-thermoelectric generators by examining critical design parameters, including leg length. The findings demonstrate that reducing leg length to microscale dimensions significantly enhances both power output and efficiency, establishing it as a key factor in μTEG performance. Additionally, optimizing temperature differences, leg area, and ceramic plate thickness further improves energy conversion by minimizing thermal resistance and maximizing heat transfer efficiency. The results also highlight the robustness of the proposed modeling framework in predicting performance trends and identifying optimal configurations for various operating conditions. These outcomes offer practical guidance for the design of μTEGs, paving the way for their integration into compact, low-power, and sustainable systems. By addressing key challenges in μTEG development, this work contributes to advancing thermoelectric technology, facilitating its application in diverse fields such as IoT, medical implants, and renewable energy systems.

Nomenclature

A Cross-sectional area (m^2)
W Width (m)
H Height (m)
L Length (m)
I Electric current (A)
k Thermal conductivity (W/m °C)
n Number of thermocouples
T Temperature (°C)
Q Heat transfer rate (W)
R Thermal resistance (Ω)

Greek symbols
α Seebeck coefficient (V/℃)
ρ Electrical resistivity (Ωm)

Subscripts
1 Hot
2 Cold
c Ceramic substrate material
L Load resistance
e Thermoelement

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Conflict of Interest: Authors have no conflict of interest.