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A Comprehensive Study on Cooling Enhancement of Thermoelectric Modules Using Advanced Thermal and Structural Optimization Techniques: Components Using COMSOL

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Abstract: This work studies techniques to increase the cooling efficiency of thermoelectric coolers by boosting the Peltier effect while lowering parasitic heat transfer processes such as Fourier heat conduction and Joule heating. Two complementary strategies were examined: system-level heat management and geometric alteration of thermoelectric components. An experimental study was conducted on a 54 W bismuth telluride–based thermoelectric cooler, and numerical simulations were performed using COMSOL Multiphysics to examine the influence of thermoelement geometry. The thermal management study examined the effects of input voltage, air velocity, heat sink design, and the integration of phase change material. OM35 phase change material was inserted into square, rectangular, and circular aluminum heat sink pockets. Results showed that higher input voltage raised both hot- and cold-side temperatures, whereas increasing air velocity lowered them. Among the designs, the square PCM-filled heat sink provided the most effective heat extraction, dramatically reducing the cold-side temperature compared with designs without PCM. The numerical study examined different shapes of thermoelements, including cylindrical, cuboidal, pin-type, trapezoidal, and octahedral frustums. Certain shapes provided greater cooling performance and lower thermal stress. Pulse current operation further enhanced cooling, with greater pulse ratios giving lower temperatures.

Keywords: Thermoelectric Cooler (TEC); Peltier Effect; Thermal Management; Global Warming; Phase Change Material (PCM); Ozone Depletion Potential; Cooling Technology.

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1. Introduction

The global concern surrounding environmental degradation has grown significantly over the past few decades, largely due to the expanding use of conventional refrigerants and the increasing demand for cooling technologies. Early awareness of the harmful impacts of refrigerants emerged in the late 1970s, when international bodies began recognizing the danger posed by ozone-depleting chemicals. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), widely used in traditional cooling systems, were found to release chlorine atoms into the upper atmosphere, which catalyze the breakdown of ozone molecules.

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Their ozone-depletion potential (ODP) values reflect this threat, with CFCs having the highest environmental impact. Hydrofluorocarbons (HFCs), although less damaging to the ozone layer, contribute significantly to global warming due to their high global warming potential (GWP). As cooling and air-conditioning devices continue to proliferate—primarily to support human comfort, their combined environmental footprint has become unavoidable. Recent global agreements, including the 2016 Paris Agreement, highlight the urgent need to reduce greenhouse gas emissions.

According to the International Institute of Refrigeration, modern cooling systems account for a substantial share of global electricity usage and carbon emissions. Furthermore, climate assessments reveal a concerning rise in global temperatures, with recent years the hottest on record. These alarming trends emphasize the need for environmentally responsible cooling technologies that do not rely on harmful refrigerants or heavy electrical loads. Conventional vapor compression refrigeration (VCR) systems, although widely adopted, depend heavily on grid electricity or diesel generators. Their operation is tied to fossil fuel consumption and, consequently, substantial CO_2 emissions. Alternatives such as vapor absorption systems are less environmentally harmful but involve bulky equipment and complex maintenance. Renewable energy systems, despite their advantages, face limitations due to inconsistent availability.

These challenges highlight the need for a clean, compact, and energy-efficient cooling method that can operate reliably under diverse conditions. In this context, thermoelectric cooling technology emerges as a promising solution [9]. Thermoelectric devices utilize the movement of charge carriers to convert electrical energy directly into a temperature difference, eliminating the need for refrigerants. As solid-state devices with no moving parts, thermoelectric coolers (TECs) are highly reliable, compact, and inherently eco-friendly. Operating on direct current (DC), they are compatible with renewable and off-grid energy sources. Their clean operation, zero emissions, quiet functioning, and minimal maintenance requirements make them strong candidates for meeting global sustainability goals, particularly those related to affordable clean energy and climate action.

The working principle of thermoelectrics relies primarily on the Seebeck and Peltier effects. In the Seebeck effect, a voltage is generated by a temperature difference across two junctions. In contrast, in the Peltier effect, heat is absorbed or released when current flows through a junction of two different materials. These two principles establish a strong coupling between thermal and electrical behavior. In TECs, semiconductor materials such as bismuth telluride (Bi_2Te_3), lead telluride (PbTe), and silicon-germanium alloys are commonly used, each exhibiting peak performance within specific temperature ranges. Thermoelectrics can be broadly classified by application: devices that convert heat into electricity are termed thermoelectric generators (TEGs), whereas those that create a cooling effect via the Peltier effect are called thermoelectric coolers (TECs). TECs consist of a series of p-type and n-type semiconductor legs sandwiched between ceramic plates and connected via metallic interconnects.

These legs are arranged electrically in series and thermally in parallel. While TECs offer many advantages, their performance is often constrained by thermal stress, heat leakage, and material limitations [10]. A major factor determining TEC efficiency is the Seebeck coefficient, electrical conductivity, and thermal conductivity. High ZT values generally correspond to better performance; however, improving one property often negatively affects another, making material optimization challenging. Although significant progress has been achieved through nanostructuring and advanced material engineering, practical improvements must also focus on non-material approaches, including geometry optimization, thermal management, and structural design. To improve TEC performance, several thermal management strategies are employed. Air cooling, liquid cooling, heat pipes, and phase change materials (PCMs) are among the most common techniques.

PCMs are particularly advantageous because they can store large amounts of thermal energy through latent heat, reducing temperature fluctuations and improving stability. Despite their advantages, PCM-based systems must consider low thermal conductivity and potential leakage issues. Heat pipes offer another effective solution, enabling rapid, reliable heat transport via phase-change cycles within sealed tubes. In addition to thermal management, optimizing the geometry of TEC legs is crucial for reducing thermal stress and improving heat flow distribution. Studies show that leg length, cross-sectional area, and leg shape strongly influence stress generation and device reliability. Introducing pore structures within the legs is another promising method for altering material properties without altering the intrinsic semiconductor characteristics. These pores can reduce thermal conductivity, lower material usage, and improve cooling performance under the same operating conditions. Pulse-current operation offers another opportunity to enhance cooling capacity [11].

By delivering electrical power in controlled pulses rather than continuous flow, it is possible to achieve lower cold-side temperatures and reduce Joule heating. The effectiveness of pulse current depends on factors such as pulse ratio, pulse width, and leg geometry. This approach is gaining attention for applications that demand rapid or extreme cooling, such as electronics cooling, battery thermal management, and biomedical refrigeration. Given the rising demand for sustainable cooling technologies and the limitations of conventional refrigeration systems, research on TECs has become increasingly important. Improving their thermal management, reducing thermal stress, lowering material consumption, and enhancing the overall coefficient of performance (COP) are key research priorities. As TEC technology progresses, its advantages of compactness, reliability, quiet operation, and environmental friendliness continue to widen its applicability across fields such as aerospace, communication

equipment, medical devices, building cooling, and portable systems [15]. This study investigates strategies to enhance the cooling performance of thermoelectric coolers (TECs) by improving the Peltier effect and minimizing parasitic heat transfer mechanisms within the device. Two major approaches—thermal management at the system level and geometric modification of thermoelement legs—were explored to suppress Fourier heat conduction and Joule heating, both of which limit the overall efficiency of TECs. The thermal management aspect was examined experimentally using a 54 W Bismuth Telluride-based TEC, while the influence of thermoelement geometry was analyzed using numerical simulations conducted in COMSOL Multiphysics (version 6.1a) [12].

The thermal performance study evaluated the effects of input voltage, air velocity across the hot side, heat sink configuration, and the incorporation of phase change material (PCM). OM35 PCM was tested in three aluminum heat sink designs: square, rectangular, and circular pockets. Results showed that increasing the TEC's input voltage elevated both hot- and cold-side temperatures, whereas higher air velocity reduced them. Among the heat sink configurations, the square pocket filled with PCM exhibited the highest heat extraction capability, achieving cold- and hot-side temperatures of 27°C and 58.7°C, respectively, compared to 34°C and 68.3°C under similar conditions without PCM. Although PCM effectively reduced cold-side temperature, it also increased thermal stress due to the larger temperature difference across the TEC. In the second phase, the study examined how altering thermoelement geometry affects thermal stress and cooling efficiency. Several shapes—including cylindrical, cuboidal, pin-type, trapezoidal, and octahedral frustums—were evaluated.

Geometries such as the cylinder, cuboid, pin-2, and trapezoid-2 demonstrated improved thermal performance and lower cold-side temperatures compared to the other designs. Pulse-current operation was then applied to the best-performing shapes to optimize cooling further [14]. The influence of pulse width, duty ratio, heat transfer coefficient, and cooling load was assessed. Higher pulse ratios produced lower cold-side temperatures, with the pin geometry reaching a minimum temperature of 276 K. In contrast, pulse width had minimal impact on temperature variation. The final part of the work introduced porosity into the thermoelement legs as an additional optimization method. Various pore configurations were examined to determine their impact on temperature reduction and material savings. Incorporating pores reduced the cold-side temperature by 4–9 K under identical operating conditions. A minimum temperature of 264 K was achieved with horizontal pore orientation, which was also the most effective arrangement. Furthermore, the presence of pores enabled a reduction in thermoelement length, thereby decreasing material consumption while maintaining the desired performance [13].

2. Literature Review

Thermoelectric cooling technology has received sustained research attention due to its potential to provide compact, reliable, and environmentally benign cooling solutions. Early foundational studies established the theoretical basis for thermoelectric cooling through the Seebeck, Peltier, and Thomson effects, highlighting the coupled electrical and thermal transport mechanisms that govern device performance. These studies also identified the thermoelectric figure of merit (ZT) as the key indicator of material efficiency, motivating extensive research into material development and performance enhancement [1]. Bismuth telluride–based alloys have remained the most widely used thermoelectric materials for near-room-temperature applications due to their relatively high ZT values and stable performance. Numerous investigations have focused on improving material properties through alloying, doping, and nano-structuring. While these approaches have achieved measurable gains in efficiency, they often involve complex fabrication techniques and increased material costs, limiting large-scale commercial adoption.

As a result, researchers have increasingly shifted attention toward system-level and structural optimization strategies that can enhance performance without altering intrinsic material properties [2]. Thermal management has been widely recognized as a critical factor in the performance of thermoelectric coolers (TECs). Inefficient heat rejection at the hot side leads to excessive Joule heating and reduced temperature difference across the device. Studies on air-cooled and liquid-cooled heat sinks demonstrate that enhanced convection significantly improves cooling capacity, although liquid cooling introduces additional system complexity. Phase change materials (PCMs) have emerged as an attractive alternative due to their ability to absorb large amounts of heat at nearly constant temperature. Previous research shows that PCM-assisted heat sinks can effectively delay temperature rise and stabilize TEC operation, particularly under transient or pulsed loading conditions [3].

In parallel, geometric optimization of thermoelectric legs has been explored to suppress parasitic heat conduction and reduce thermal stress. Conventional TECs typically employ cuboidal legs; however, numerical and experimental studies have shown that tapered, pin-type, and trapezoidal geometries can more favorably redistribute heat flow and stress. These asymmetric designs alter the cross-sectional area ratio between the hot and cold sides, thereby influencing both electrical resistance and heat transfer. Such geometric tailoring has been shown to improve cooling performance while simultaneously enhancing mechanical reliability. Pulse current operation represents another important advancement in TEC performance enhancement. Unlike steady DC operation, pulsed current driving exploits transient thermal behavior to increase instantaneous Peltier cooling while limiting average Joule heating. Prior investigations report that higher duty ratios and optimized pulse frequencies can significantly reduce cold-side temperature, particularly when combined with optimized leg geometries.

However, the effectiveness of pulse operation is strongly dependent on thermal boundary conditions and device configuration [4]. More recently, the introduction of porosity into thermoelectric legs has attracted attention as a promising approach to reduce thermal conductivity and material use. Porous structures disrupt heat-conduction pathways while maintaining sufficient electrical conductivity, thereby improving cooling efficiency. Finite element–based multiphysics simulations have played a crucial role in evaluating such designs, enabling detailed analysis of temperature fields, stress distribution, and thermo-mechanical coupling. Despite these advances, comprehensive studies that combine thermal management, geometric optimization, pulse-current operation, and porosity effects within a single framework remain limited [5].

3. Computational Study on Thermal Performance and Stress Behavior of Tecs with Different Leg Geometries

3.1. Need for Thermal Stress Analysis in Thermoelectric Coolers

Thermoelectric coolers (TECs) operate by directly converting electrical energy into a temperature gradient through the Peltier effect. Among the various thermoelectric materials available, bismuth telluride (Bi_2Te_3) remains the most widely used due to its high figure of merit and suitability for near-room-temperature applications. However, this material is inherently brittle, making it susceptible to mechanical and thermal stress. A typical TEC unit consists of p-type and n-type semiconductor legs placed between two ceramic plates and joined using metallic electrodes. Depending on the structural arrangement, TECs may be symmetric or asymmetric—each configuration influencing thermal stress distribution differently [6]. Continuous advances in thermoelectric research focus primarily on improving energy conversion efficiency, optimizing heat flow, and enhancing cooling performance.

Despite this, the mechanical reliability of thermoelectric legs has received comparatively limited attention. When TECs operate under varying current inputs, cooling loads, and environmental conditions, substantial stresses develop at the hot and cold junctions due to mismatches in thermal expansion between Bi_2Te_3 and metallic interconnects. Excessive thermal stress can lead to micro-crack formation, delamination, and eventual device failure [7]. Therefore, evaluating thermal-stress behavior is essential when exploring modified leg geometries. Computational tools such as COMSOL Multiphysics provide an effective platform for analyzing stress distributions while simultaneously modeling heat transfer. By studying symmetric and asymmetric leg configurations, it is possible to identify shapes that minimize local stress concentrations, reduce temperature build-up, and enhance overall thermal performance [8].

3.2. Geometry Details and Material Parameters

The diagram shows how a thermoelectric module is configured between two ceramic substrates, one hot and one cold, with copper electrodes and P-type and N-type legs. There are two alternative types of leg shapes shown: (a) a rectangular symmetric leg shape and (b) a trapezoidal asymmetric leg shape. These shapes are meant to change how heat flows and how well the device works electrically. Figure 1 shows the thermoelectric module design, comparing rectangular and trapezoidal leg shapes to examine how leg shape affects the device's thermal and electrical behavior.

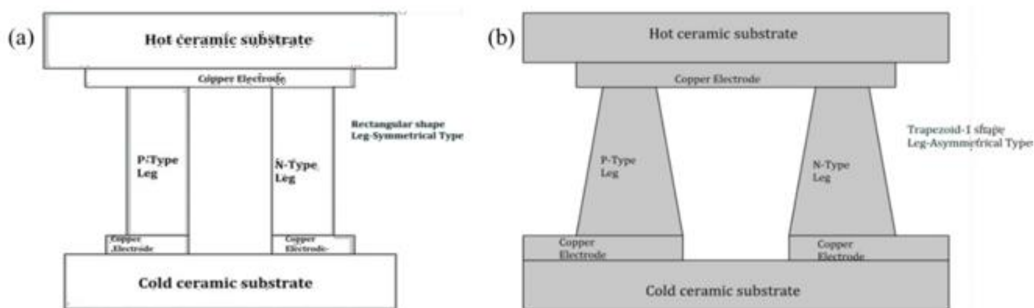

Figure 1: Structural design of a thermoelectric module with different leg geometries (a) & (b)

The study investigates seven thermoelectric leg geometries, including conventional symmetric shapes—cylinder and cuboid—and five asymmetric variations: pin-1, pin-2, trapezoid-1, trapezoid-2, and octahedral frustum. All geometries maintain a constant leg height of 2 mm with a cold-side area of 1 mm × 1 mm, ensuring a uniform basis for comparison. Figure 2 in the uploaded document displays these geometrical variations. All legs use Bi_2Te_3 as the thermoelectric material, while copper layers serve as the electrical conductors. In symmetric shapes such as cylinders and cuboids, both the cold and hot sides have the same surface area. However, asymmetric designs differ in area distribution:

- **Pin-1 and Trapezoid-1:** Cold side area > hot side area.
- **Pin-2 and Trapezoid-2:** Cold side area < hot side area.
- **Octahedral Frustum:** Equal surfaces but tapering edges increase electrical resistance.

The mechanical and thermal properties of Bi_2Te_3 and copper—including modulus of elasticity, density, heat capacity, thermal expansion coefficient, and Poisson's ratio—govern stress behavior. While electrical and thermal transport properties vary with temperature, mechanical constants are taken from reported literature.

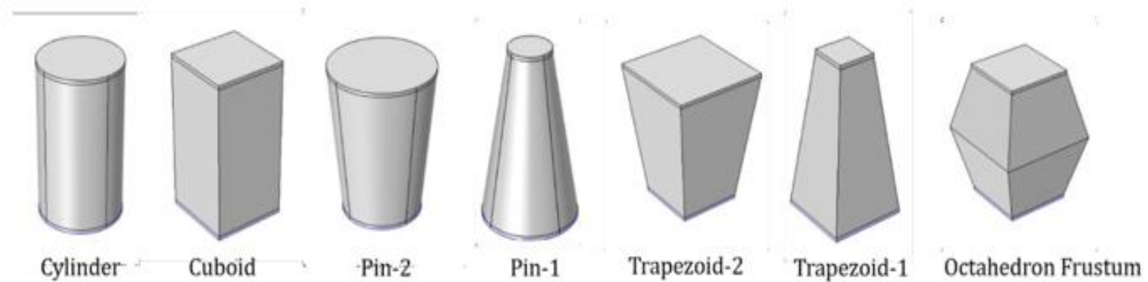

Figure 2: Various geometric configurations of thermoelectric legs considered for analysis

The software library in COMSOL inherently accounts for temperature-dependent thermal conductivity, heat capacity, and electrical conductivity, enabling accurate thermo-elastic coupling.

4. Numerical Modeling Approach

4.1. Boundary Conditions and Assumptions

The computational analysis applies several simplifying assumptions to ensure stable and solvable numerical conditions:

- A steady-state three-dimensional heat conduction model is used.
- The hot-side temperature is fixed at 300 K for all simulations.
- No heat loss is assumed from lateral surfaces, implying adiabatic side boundaries.
- Thermal and electrical contact resistances are neglected.
- Cooling load (Qc) is uniformly applied to the cold-side boundary.

These assumptions do not significantly alter the models' physical behavior but help maintain computational feasibility.

4.2. Model Validation

Validation was performed by comparing the simulated von Mises stress at the cold side of a reference geometry with results available in previous literature. The comparison shows good agreement, with an RMS error of approximately 0.74 and a deviation of 3.72%, confirming the reliability of the adopted simulation methodology.

5. Results and Discussion

5.1. Temperature Fields for All Geometries

Temperature distributions for all leg shapes are illustrated in the referenced Figure 3. Regardless of shape, the hot side remains fixed at 300 K, while variations appear predominantly at the cold side. Geometries with larger cold-side contact areas, such as pin-1 and trapezoid-1, exhibit lower temperature drops because they spread the incoming cooling load over a larger region. Conversely, shapes with narrow cold-side areas (pin-2 and trapezoid-2) show steeper gradients and enhanced cooling.

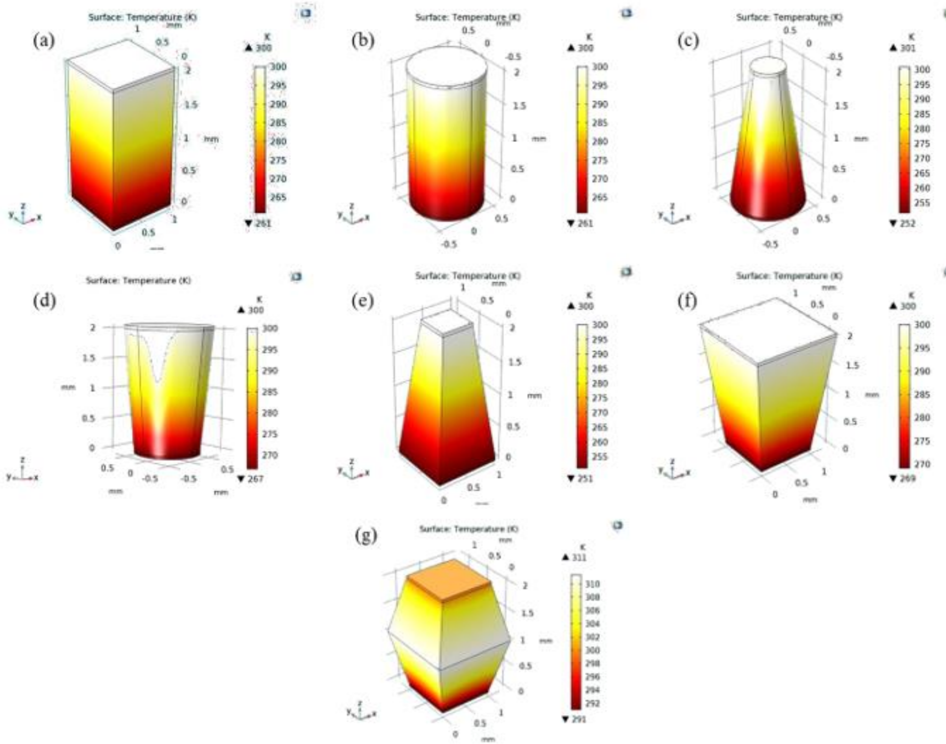

Figure 3: Temperature distribution analysis for various thermoelectric leg shapes obtained from simulation (a) to (g)

5.2. Effect of Cooling Load and Current on Cold-Side Temperature (Tc)

The cold-side temperature response to varying cooling loads (0.005–0.55 W) is presented in the dataset for Figure 4. As expected, increasing Qc results in a higher Tc across all geometries because the legs must absorb more heat from the cold junction. Among all shapes, pin-1 and trapezoid-1 achieve the lowest Tc at small loads (243 K at Qc = 0.005 W), due to their larger cold-side areas, which facilitate effective heat removal. In contrast, the octahedral frustum exhibits the highest Tc at low loads due to its higher electrical resistance and reduced heat-carrying capacity. When analyzing the effect of current (1–1.5 A) under a fixed cooling load (Qc = 0.03 W), a decrease in Tc is observed with increasing current for all geometries except pin-1 and trapezoid-1. The increasing current amplifies Peltier cooling, thus reducing Tc.

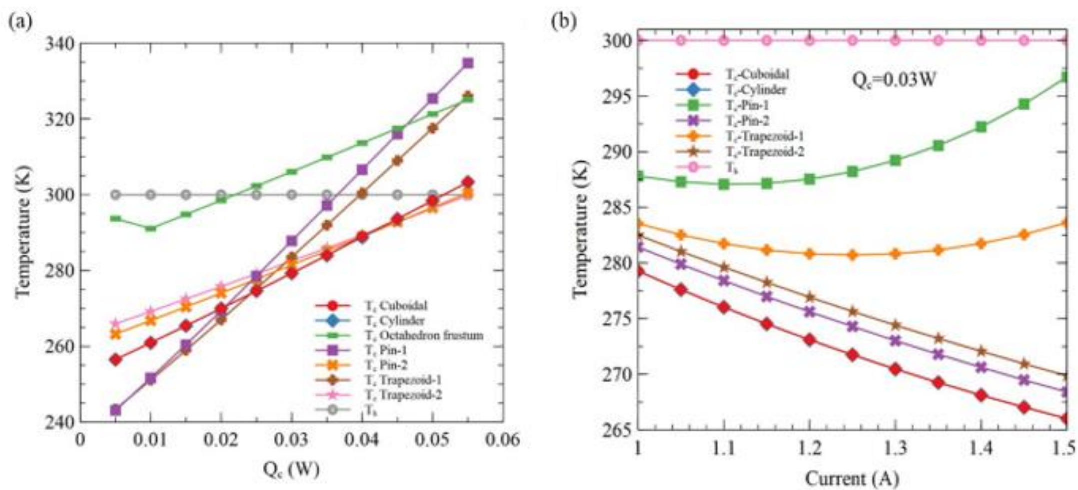

Figure 4: Temperature performance analysis of various thermoelectric leg shapes under varying heat load and current (a) & (b)

However, for pin-1 and trapezoid-1, excessive current causes the hot side to overheat due to their small hot-side area, which restricts heat rejection to the environment. Consequently, Tc rises after 1.2 A for these geometries.

5.3. Influence of Hot-Side Heat Transfer Coefficient (h)

Figure 5 illustrates how the hot-side heat transfer coefficient influences Tc when Qc is held constant at 0.03 W. Increasing the heat transfer coefficient improves hot-side heat dissipation, thereby reducing cold-side temperatures. Among the shapes, the cylinder and pin-2 consistently achieve the lowest Tc values at high heat-transfer coefficients (279 K and 281 K at 2×10^4 W/m²K). Pin-1 displays the largest Tc range (298–292 K), again due to its limited heat-rejection capability arising from a smaller hot-side area.

5.4. Cooling Load Effects on Cold-Side and Hot-Side Thermal Stresses

The von Mises stress variations associated with cooling loads are shown in Figure 5. In all geometries, cold-side stress increases significantly at higher cooling loads because larger temperature differences elevate thermo-elastic strain. At small Qc values, the stress remains comparatively low.

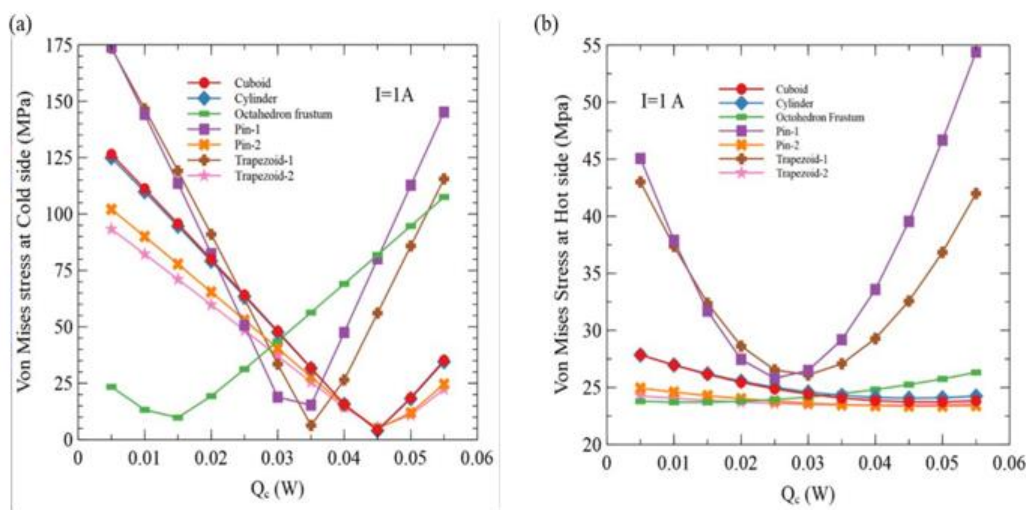

Figure 5: Effect of heat input on von Mises stress for various thermoelectric leg shapes (a) & (b)

For hot-side stresses, symmetric geometries (cuboid, cylinder) and shapes with larger hot-side areas (pin-2, trapezoid-2) show the lowest stress levels. In contrast, pin-1 and trapezoid-1 demonstrate maximum hot-side stress levels of 54 MPa and 42 MPa, respectively, at 0.055 W—due to restricted heat dissipation and sharper temperature gradients.

5.5. Current-Induced Thermal Stress Behavior

Highlights current-driven stress variations. As the current increases, hot-side von Mises stresses rise for all geometries, as higher electrical input enhances Joule heating and temperature gradients. Trapezoid-2 shows the lowest hot-side stress (2.3×10^7 Pa), while pin-1 experiences the highest stress (2.65×10^7 Pa at 1 A). The results of the present study reinforce the understanding that thermoelectric cooler performance is governed not only by material properties but also by thermal management strategy and structural design. The experimental investigation demonstrates that integrating phase change materials into heat sinks significantly enhances heat absorption at the hot side, thereby reducing temperature feedback to the cold junction. This improvement directly translates into higher cooling effectiveness, particularly during high-load or transient operating conditions. The numerical analysis further reveals that asymmetric leg geometries offer clear advantages over conventional shapes. By increasing the hot-side surface area relative to the cold side, these geometries facilitate more efficient heat rejection while maintaining strong Peltier cooling at the cold junction.

At the same time, stress concentrations are reduced due to smoother temperature gradients, improving mechanical reliability. These findings highlight the importance of considering thermo-mechanical coupling during TEC design rather than focusing solely on thermal performance. Pulse current operation emerges as a complementary enhancement technique. The results indicate that pulse ratio plays a more significant role than pulse width in achieving lower cold-side temperatures. This observation suggests that controlling current intensity and off-time is more critical than pulse duration for practical TEC applications. When

combined with optimized geometries and effective thermal management, pulse operation enables substantial cooling enhancement without excessive electrical input. The introduction of porosity within thermoelectric legs provides an additional layer of optimization. Properly oriented pores reduce Fourier heat conduction while allowing material reduction and compact device design. From an engineering perspective, this approach offers a practical pathway to improve performance while reducing material costs, a key barrier to widespread adoption of TEC.

6. Conclusion

This work presents a comprehensive investigation into improving the cooling efficiency and mechanical reliability of thermoelectric coolers by combining experimental thermal management strategies with detailed computational analysis of modified leg geometries. The results clearly demonstrate that the performance of TECs is strongly influenced by internal parasitic effects—namely, Fourier heat conduction and Joule heating—which ultimately limit the achievable temperature difference across the device. Through systematic experimentation with heat sinks integrated with phase change materials and extensive simulation of various leg geometries under steady and pulsed current conditions, this study identifies several effective pathways to overcome these limitations. The thermal management experiments showed that using a heat sink filled with PCM significantly enhances heat absorption and delays the onset of temperature rise. Among the tested designs, the square heat sink with complete PCM filling achieved the lowest cold-side temperature, thanks to its larger heat-dissipation area and higher thermal storage capacity. Increased air velocity also contributed to lower cold-side temperatures by strengthening forced convection and reducing conductive heat return to the cold junction. These findings confirm that optimized heat sink design and PCM selection are decisive in mitigating Joule and Fourier heat effects. The computational study on thermoelectric leg geometries further revealed that non-uniform cross-sectional shapes outperform conventional cylindrical and cuboidal legs.

Geometries such as pin and trapezoidal legs—with a larger hot-side area relative to the cold side—exhibited superior cooling behavior and more favorable stress distribution. Pulse-current operation also improved cooling for these shapes, as higher pulse ratios enhanced Peltier heat absorption without significantly increasing average Joule heating. The influence of pulse width was minimal, indicating that pulse intensity, rather than duration, is more critical for achieving lower cold-side temperatures. The introduction of porosity into TEC legs provided another effective means of suppressing Fourier heat conduction. Horizontal pores, in particular, produced the lowest cold-side temperatures while enabling a reduction in leg length without compromising performance. This not only reduces thermal leakage but also lowers semiconductor material usage, improving the economic viability of TEC manufacturing. Overall, the study confirms that a combination of optimized thermal management and intelligent geometric redesign can substantially enhance TEC performance. The use of PCM-filled heat sinks, asymmetric leg shapes, pulse-current operation, and strategically placed pores collectively offer a practical route to achieving higher cooling capability with reduced thermal stress. These outcomes strengthen TECs' potential to meet modern cooling demands, offering a reliable, compact, and environmentally friendly alternative to conventional refrigeration systems.

6.1. Scope of the Present Study

The scope of this manuscript is to improve the cooling efficiency and structural reliability of thermoelectric coolers through a combined experimental and computational approach. Specifically, the study addresses the following aspects:

- Experimental evaluation of thermal management strategies using heat sinks integrated with phase change materials under varying electrical and airflow conditions.
- Multiphysics finite element modeling of thermoelectric coolers to analyze temperature distribution and thermo-mechanical stress behavior.
- Comparative assessment of symmetric and asymmetric thermoelectric leg geometries with respect to cooling performance and stress reduction.
- Investigation of pulse current operation and its influence on cold-side temperature under optimized geometric configurations.
- Evaluation of porous thermoelectric leg designs for reducing thermal conduction and material consumption.

The work focuses on steady-state and controlled transient conditions relevant to practical TEC operation. Large-scale system integration, long-term degradation modeling, and economic analysis are beyond the immediate scope but are recognized as important considerations for future studies.

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Data Availability Statement: The datasets generated and analyzed during this study are based on simulation outputs obtained from COMSOL Multiphysics for evaluating cooling enhancement and structural optimization of thermoelectric modules. The relevant data supporting the conclusions of this research are available from the corresponding author upon reasonable request.

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Conflicts of Interest Statement: The authors confirm that there are no known competing financial or personal interests that could have influenced the research outcomes. All referenced materials have been properly acknowledged.

Ethics and Consent Statement: This research is purely simulation-based and does not involve human participants, animals, or sensitive personal data. Therefore, formal ethical approval and participant consent were not required.

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