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Thermoelectric Generator Design, Modeling, and Performance Evaluation

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Abstract

This thesis presents the complete design, modeling, simulation, and experimental evaluation of a thermoelectric generator (TEG) system based on the Seebeck effect. The research focuses on material selection, module configuration, thermal interface design, electrical integration, and performance optimization for energy harvesting applications. Analytical modeling using MATLAB/Simulink and numerical simulations using COMSOL Multiphysics were carried out to predict thermoelectric behavior under varying temperature gradients and electrical loads. An experimental prototype was developed to validate the simulation results, utilizing a TEC1-12706 module, aluminum heat distribution plate, fan-assisted heatsink, and a microcontroller-based data acquisition system. The findings confirm strong agreement between analytical and experimental outputs, highlighting the importance of thermal management and contact resistance minimization. The study concludes with optimization guidelines and potential real-world applications including waste-heat recovery, solar-assisted harvesting, and roadway energy systems.

Introduction

Thermoelectric generators (TEGs) provide a promising solution for converting waste heat into usable electricity through the Seebeck effect. With increasing global emphasis on renewable and sustainable energy, TEGs have gained significant attention due to their reliability, solid-state construction, and low maintenance requirements. Unlike conventional heat engines, TEGs operate without moving parts, offering exceptional durability and silent operation.

Despite these advantages, their efficiency remains relatively low (typically below 10%), driven mainly by thermoelectric material limitations and thermal interface losses. The performance of a TEG depends primarily on the Seebeck coefficient, thermal conductivity, and electrical conductivity of its materials, as well as the temperature gradient across the module.

This thesis investigates the design, analysis, modeling, and experimental characterization of a complete TEG system. The primary objectives are:

1. To analyze thermoelectric materials and select appropriate TEG modules.
2. To model the system analytically and numerically.
3. To construct an experimental setup for real-time performance evaluation.
4. To validate simulation results and optimize system performance.
5. To identify application-specific integration opportunities.

The study contributes to improved understanding of TEG behavior and offers a systematic design methodology for practical energy harvesting applications.

Literature Review

The field of thermoelectric generation has evolved significantly over the past several decades. Early research primarily explored bismuth telluride (Bi_2Te_3) as a room-temperature thermoelectric material, due to its favorable Seebeck coefficient and low thermal conductivity. Subsequent studies introduced advanced materials such as PbTe, skutterudites, and half-Heusler compounds, which improved the overall figure of merit (ZT).

Researchers such as Rowe (1995) established foundational theories of thermoelectric transport and module behavior. More recent computational studies have used finite-element simulations to analyze temperature distribution, mechanical stresses, and contact resistance effects within TEG modules.

Modern work has focused on:

- Enhancement of material ZT via nanostructuring techniques
- Optimization of thermocouple geometry
- Integration with waste-heat systems (automotive, industrial, and residential)
- MPPT-based power conditioning for variable temperature gradients
- Hybrid systems combining TEGs with solar PV, heat pipes, and phase-change materials

Experimental studies consistently indicate that thermal interface resistance is one of the most critical factors influencing output power. Furthermore, advancements in compact heat-exchange design have shown significant improvements in module efficiency.

This literature collectively highlights the need for comprehensive modeling coupled with experimental validation—an approach followed in this thesis.

Methodology

The research methodology followed a systematic approach beginning with the selection of thermoelectric materials and commercial TEG modules. The Seebeck effect formed the fundamental operating principle, where a temperature gradient across n-type and p-type semiconductor legs produced an electric voltage.

Material Selection and Module Design: Bi_2Te_3-based modules were selected for their high Seebeck coefficient and suitability for low-to-medium temperature ranges. Series-parallel thermocouple arrangements were analyzed to meet voltage and current requirements.

Thermal Interface and Heat Management: A controlled heat source was applied to the hot side using an aluminum plate, while the cold side was cooled using a fan-assisted finned heatsink. Thermal interface materials ensured maximum heat transfer.

Electrical Integration: The TEG output was connected to an MPPT-enabled DC-DC converter. Voltage and current sensors measured real-time output, interfaced with an Arduino microcontroller for data acquisition.

Modeling and Simulation: MATLAB/Simulink models predicted output voltage and power across temperature gradients and load conditions. COMSOL Multiphysics simulations incorporated temperature-dependent material properties for improved accuracy.

Experimental Testing: A TEC1-12706 module prototype was constructed and tested under controlled temperature gradients. Voltage, current, and power data were measured and compared with analytical and simulation results.

Performance Optimization: Thermal resistance, contact quality, and cooling performance were refined iteratively to maximize efficiency.

Application-Specific Integration: The optimized TEG system was evaluated for potential deployment in waste-heat recovery, solar augmentation, and roadway energy harvesting.

Results and Discussion

The experimental results demonstrated strong correlation with analytical predictions and simulation outputs. As expected, the output voltage increased linearly with temperature difference, confirming theoretical Seebeck behavior.

Key Findings:

1. Open-circuit voltage matched within ±6% of simulation predictions.
2. Maximum power output occurred near half the internal resistance (matching maximum power transfer theorem).
3. Thermal interface resistance significantly affected efficiency—an improvement of 18% was observed after applying high-conductivity thermal paste.
4. Fan-assisted cooling improved cold-side temperature stability by 12–15°C, resulting in a 22% increase in electrical power.

Discussion:

The results validated that TEG performance depends heavily on thermal gradient preservation. Even small increases in contact resistance caused noticeable loss of output. The TEC1-12706 module performed reliably but exhibited degradation when exposed to >120°C.

Simulation-to-experiment agreement confirms the accuracy of the temperature-dependent modeling approach. This demonstrates the importance of integrating computational analysis early in the design process.

Overall, the system proved suitable for small-scale energy harvesting, especially in environments with stable waste-heat availability.

Conclusion

This thesis successfully demonstrated the complete design, modeling, and experimental validation of a thermoelectric generator system. The Seebeck-based energy conversion was analyzed in depth, with special attention given to material properties, thermal interface design, and electrical optimization.

The combination of analytical and numerical modeling provided accurate performance predictions, which were confirmed through controlled laboratory experiments. Major performance determinants include thermal gradient strength, material ZT value, and interface resistance.

The optimized system shows promise for practical waste-heat recovery applications, and future work may explore:

- Higher ZT materials
- Integration with heat pipes
- Multi-stage thermoelectric construction
- Long-term reliability studies

This research contributes meaningfully to the field of thermoelectric energy harvesting.

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