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Thermo Electric Trace, Power at Pace: Optimization of Power Output in Seebeck Mode Peltier Modules through Enhanced Thermal Paste and Heat Sink Design

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Abstract
The increasing demand for efficient waste-heat recovery systems highlights the need for optimized thermoelectric generators (TEGs). This study investigates the enhancement of power output in Peltier modules operating in Seebeck mode by focusing on the synergy between thermal interface materials and heat sink configurations. Using a mixed method convergent parallel design, the research simultaneously gathered quantitative experimental data and qualitative observational data to provide a holistic understanding of thermal management efficiency. In the quantitative research, an experimental approach was used to measure voltage, current, and wattage outputs across three different thermal paste formulations and heat sink.

Parallel qualitative observations during the "Cooling Efficiency" and "Stability" tests provided context for these numerical drops, identifying thermal saturation and "pump-out" as primary limiting factors. The merging of data confirmed that peak efficiency is not reached through maximum cooling or maximum material application, but through an optimal thermal "middle ground." These findings provide a scalable framework for improving waste-heat recovery systems in small-scale green technology. Observations of the "Cooling Efficiency Test" revealed that the removal of cooling agents led to a voltage drop to 0.15V, confirming that the system's "Power at Pace" is dependent on maintaining a sharp thermal gradient rather than just cooling. The data suggests that excessive paste acts as a thermal insulator (pump-out effect), while the heat sink's capacity limits long-term peak performance. The study concludes that an optimized "middle-ground" approach in material application is superior for small-scale thermoelectric energy harvesting.

Keywords: Seebeck Effect, Mixed Method Research, Convergent Parallel Design, Thermal Management, Peltier Module, Energy Harvesting

Introduction

In the modern industrial era, energy efficiency has emerged as a cornerstone of sustainable development, driven by escalating global demand and the urgent need to meet climate goals. While industrial processes and electronic devices generate vast amounts of "low-grade" waste heat, this energy is frequently discarded, contributing to global energy intensity challenges. To address this, Thermoelectric (TE) materials have gained prominence for their ability to facilitate the direct conversion of thermal gradients into electrical energy. Operating on the Seebeck Effect a principle first observed in 1821 where a temperature differential across semiconductors generates a voltage these solid-state devices function without moving parts or chemical emissions. By capturing heat that would otherwise be lost to the environment, thermoelectric generators (TEGs), including repurposed Peltier modules, bridge the gap between thermal management and sustainable electronic design, offering a reliable "green" power source for both decentralized grids and wearable technology.

The theoretical framework of this study is anchored in the synergy between Thermodynamics and Energy Efficiency Theory, emphasizing that energy flow from hot to cold can be harvested rather than ignored. By addressing the traditional trade-off between electrical conductivity and the Seebeck coefficient through innovative molecular engineering, it is possible to transform simple heat sources, such as candles or industrial exhaust, into functional power. This research demonstrates thatthermoelectric generation is not merely a laboratory concept but a practical application of Sustainable Energy Theory, providing low-impact, carbon-neutral solutions. Ultimately, by utilizing readily available materials to convert temperature differences into usable electricity, this study highlights a scalable pathway toward reducing resource waste and promoting environmental responsibility in both industrial and educational contexts.

Research Design

This study will utilize quantitative research it is a variety of statistical tests and instruments Siripipatthanakul et, al (2023). A systematic method for investigating phenomena by collecting and analyzing numerical data, using statistical analysis to find patterns, test theories, and make predictions that can often be generalized to larger populations, focusing on objective measurements rather than subjective meanings. It answers "What are the effects of?" and "is there a correlation between?" questions through structured tools like surveys and experiments. It is a type of research that has numerical data collection and uses a variety of scientific methods. Statistical Data found in Quantitative Research is an experiment that requires mathematical computation.

The Research Design for this study employs a Convergent Parallel Mixed Methods approach, characterized by the simultaneous collection and analysis of quantitative and qualitative data to provide a comprehensive evaluation of Peltier module optimization. These two independent data streams are integrated during the interpretation phase, where they are compared and contrasted to see if the physical observations (qualitative) support or explain the power efficiency trends (quantitative).

Data Gathering

Experimental research is a scientific method of conducting research in which one or more independent variables are altered and applied to one or more dependent variables in order to determine their influence on Zubair (2022). It is an attempt by the researcher to maintain control over all factors that may affect the result of an experiment. In doing this, the researcher attempts to determine or predict what may occur. The experimental design is described in statistics as the design of an information.

In order to achieve the goal of this research the student researchers will go through a step-by-step process in order to gather and collect data that this study will need. Experiment and testing will act as a tool to collect, measure and analyze data. According to Wang & Bai (2022) to experimentation is the test in compatibility in both research and practice of broadening sustainability experiments.

Step 1: Purchase the Materials and Equipment Needed

The Student Researchers will gather the things needed in order to perform the experiment. These materials are, Peltier (TECI-12706), Heat Sink, Motor (3 voltz) Mini Light, Thermal Paste, Candle snd Ice.

Step 2: Prepare the Materials to be used

This step is vital because preparing things will help the process be more controllable. The Student Researchers will clean and check the materials to be used to avoid having any problem during the experiment.

Step 3: Testing of the Experiment

The student researchers will systematically test tto determine if the experiment is effective in creating a Thermoelectric Generator. This step requires crucial and careful observatio, measurements and analysis to know what is the result of the experiment.

Step 5: Interpret the Collected Data

The student researchers will use descriptive analysis such as tables and numerical data to organize the data that are collected in the experiment. The student will also analyze and interpret the data from the experiment using quantitative methods.

Step 6: Validate the Experiment Tests Used

The student researchers will present the results to an expert or a designated teacher to verify it's validity and reliability of the experimental test taken. This step will ensure that the methods are right and appropriate for the study and will lead to accurate and credible results.

Population and Sampling

This sampling method significantly increases the accuracy and reliability of the experimental results. By testing the Thermoelectric Generator on specific, non-randomized test sheds or comparison structures, you can observe how the material reacts to various factos. This provides a more connected understanding of the products effectiveness as the research document the material's performance in the exact context where it is meant to do its purpose.

Finally, quasi-experimental sampling is the most appropriate choice for a structural invention due to the logistical constraints of construction research. Quasi-experimental designs allow the researcher to leverage naturally occurring groups or specific job sites, providing a pragmatic framework that maintains high external validity. This ensures that the data gathered isn't just a result of a sterile lab environment, but a reflection of how the invention performs under the chaotic, multi-variable stresses of an actual construction project.

Data Analysis

The student researchers will apply and utilize quantitative data analysis methods to evaluate the effectiveness of the thermoelectric generator. It will begin by conducting a series of controlled experiments to measure different of the developed coating. Data will be collected on various parameters. These measurements will be recorded systematically, and the researchers will use statistical methods to analyze the data collected or gathered.

After all testing was completed, the collected data were carefully organized, recorded, and analyzed. Descriptive statistics were used to summarize measurements such as averages and observed values Siedlecki (2020). Graphs and tables were created to make the results clearer and easier to interpret. The analysis focused on determining which mixture offered the highest level of strength, durability, and environmental benefit while remaining practical for potential users. Because conclusions were based strictly on numerical results rather than personal opinions, the study ensured that its findings were reliable, evidence-based, and meaningful.

Materials

In this study, the selection of materials plays an important role in making a Thermoelectric Generator. The materials were chosen to ensure efficiency. The materials used in the study are;

Picture of Material	Description
	It fills the microscopic air gaps between the peltier and the heat sink to ensure maximum heat transfer.
	Sits on the heat side to draw heat no directly from the peltier so it doesn't overheat.
	It serves as the engine because it converts heat flow into electrical energy.
	The load of the generator because it proves that the generator is working by spinning.
	The heat source for the hot side.
	The cooling agent for the cold side.

Results and Discussion

This chapter details the findings of the experimental study entitled "Thermoelectric Trace, Power at Pace." The primary focus is the analysis of how the integration of enhanced thermal paste and optimized heat sink designs influences the electrical production of Peltier modules operating in Seebeck mode. By examining the relationship between temperature management and energy harvest, this section interprets the data to determine which configurations most effectively maximize power output.

Table 1: Open-Circuit Voltage Test

Trial	Time Spent	Average Voltage	Rank
1	1:00 minute	1.70v	5
2	2:00 minutes	2.25v	4
3	3:00 minutes	2.88v	1
4	4:00 minutes	2.81v	2
5	5:00 minutes	2.58v	3

Table 01 displays the results of the open-circuit voltage test, which measured the electrical output of the module over five minutes. The data shows a steady increase in voltage during the first three minutes, starting at 1.70V and reaching a peak of 2.88V. This peak, which earned the Rank 1 spot, indicates that the system reached its most efficient state at the three-minute mark, where the temperature difference between the sides of the module was at its greatest.

This initial rise highlights how well the enhanced thermal paste and heat sink work together. As the heat sink began to dissipate heat and the paste ensured a solid connection, the "Power at Pace" goal was achieved. The significant jump from 1.70V in the first minute to nearly 2.9V in the third suggests that the materials used were highly effective at quickly establishing a strong thermal flow.

However, after the three-minute peak, the voltage began to decrease slightly. In Trial 4 (4:00 minutes), the output dipped to 2.81V, and by Trial 5 (5:00 minutes), it fell further to 2.58V. This decline suggests that the heat sink eventually reached a limit where it could no longer keep the cold side cool enough. As the temperature difference narrowed, the electrical output naturally followed suit.

Overall, the interpretation of this data shows that while the design is excellent at for generating a high burst of power quickly, it faces challenges in maintaining that peak indefinitely.

Table 2: Load Test

Load Type	Voltage	Observed Result
No Load	6.77v	This represents the maximum potential of the system when no energy is being consumed, showing a high base voltage from the thermal generator. It serves as the baseline for the module's efficiency before any external resistance is added.
One LED Light	4.25v	The voltage drops as the LED draws power, indicating that the system is successfully converting heat into usable electricity for a low-power device. This shows the module can easily sustain small electronics while maintaining a stable output.
Mini Motor Fan	2.58v	The significant drop to 2.58V occurs because the motor requires higher current and creates more "pull" on the system's energy. This demonstrates that while the module can power mechanical movement, the heavier load puts a greater strain on the maintained thermal energy.

Table 02 demonstrates how the thermoelectric system performs when different types of electrical "work" are added to it. The initial high reading of 6.77V shows the system's full potential when it is not being used, proving that the thermal paste and heat sink are creating a strong energy source. This baseline confirms that the module is efficiently converting heat into a significant amount of stored electrical pressure before any device draws from it.

As loads are connected, such as the LED light or the mini motor, the voltage decreases because these devices consume the available energy to function. The drop to 4.25V for the LED indicates that while the system is providing power, it still maintains a stable and healthy output for low-energy electronics. This shows that the "Power at Pace" design is well-suited for common, small-scale applications.

Finally, the further drop to 2.58V when powering the mini motor reveals the limits of the current setup. Because a motor requires more physical force and current to spin, it puts a much heavier strain on the thermal gradient than a simple light. This transition proves the module is capable of powering real-world mechanical movement, even though heavier loads naturally reduce the remaining voltage more significantly.

Table 3: Thermal Paste Effectiveness Test

Test Scenario	Max Voltage Achieved
25% Paste	2.34v
50% Paste	7.70v
75% Paste	2.59v
100% Paste	3.01v

Table 03 provides the data table illustrates the relationship between the percentage of thermal paste applied and the resulting Max Voltage Achieved during a performance test. The scenarios range from a minimal application of 25% to a full application of 100%. At the lower end of the scale, the 25% paste application yielded a voltage of 2.34V, which serves as the baseline for this specific data set.

The most striking observation in the data is the performance of the 50% Paste scenario. At this level, the maximum voltage achieved spikes significantly to 7.70V. This represents the peak value in the table, more than tripling the output of the 25% scenario. This suggests that, within the context of this specific test, a moderate amount of thermal paste provides the most efficient thermal conductivity or stability required to reach higher voltage thresholds.

Interestingly, as the amount of paste increases beyond the 50% mark, there is a sharp decline in performance. When the paste application is increased to 75%, the maximum voltage achieved drops precipitously to 2.59V. This indicates that "more" is not necessarily "better" in this experiment. An overabundance of paste may be creating a thermal barrier or causing "pump-out," which negatively impacts the system's ability to maintain high voltage levels.

The final scenario, 100% Paste application, shows a slight recovery compared to the 75% mark, reaching 3.01V. While this is higher than both the 25% and 75% scenarios, it still falls drastically short of the 7.70V achieved at the 50% level. This reinforces the conclusion that the relationship between paste volume and voltage output is non-linear, following a bell-curve trend rather than a steady increase.

Table 4: Cooling Efficiency

Test Scenario	Max Voltage	Rank
With Ice	1.60v	2
Without Ice	2.80v	3
Ice Removed	0.15v	1

The Cooling Efficiency Test evaluated the performance of a system across three distinct scenarios by measuring the maximum voltage output. Lower voltage readings in this context typically indicate higher cooling efficiency or a reduction in thermal-induced resistance. According to the results, the "Ice Removed" scenario achieved the highest efficiency, ranking 1st with a significantly low maximum voltage of 0.15V. This suggests that the residual thermal state after the ice treatment provided the most stable or efficient environment for the system to operate.

In contrast, the "Without Ice" scenario performed the poorest, ranking 3rd with the highest recorded voltage of 2.80V. This clearly demonstrates that a lack of cooling intervention leads to higher voltage requirements, likely due to increased heat levels affecting the system's electrical properties. The "With Ice" scenario served as a middle ground, ranking 2nd with a voltage of 1.60V. While this was a marked improvement over the scenario without ice, it did not reach the peak efficiency seen in the post-ice removal phase. Overall, the data confirms that the application and subsequent removal of a cooling agent (ice) creates the most favorable conditions for minimizing voltage.

Table 5: Stability Test

Trial	Time Stamp	Max Voltage Achieved
1	1:00 minute	3.36v
2	2:00 minutes	3.10v
3	3:00 minutes	2.67v
4	4:00 minutes	2.46v
5	5:00 minutes	2.60v

Table 05. showes the Stability Test was conducted across five sequential trials to evaluate the consistency of the system's electrical output over a five-minute duration. By recording the Max Voltage Achieved at one-minute intervals, the test provides a clear overview of how the system’s performance fluctuates or stabilizes over time.

During the initial phase of the test, the system recorded its highest output in Trial 1 with a maximum voltage of 3.36V at the one-minute mark. Following this peak, there was a steady decline in voltage through Trial 2 (3.10V) and Trial 3 (2.67V). This downward trend suggests a period of initial stabilization where the system sheds excess energy or settles into a consistent operating state.

By Trial 4, the voltage reached its lowest point of the study, measuring 2.46V at the four-minute timestamp. This specific data point represents the minimum threshold for the system during the test period. The consistent drop from the first to the fourth minute indicates a high degree of predictability in the system's initial discharge or cooling curve.

Interestingly, the final measurement in Trial 5 showed a slight increase in voltage to 2.60V at the five-minute mark. While this is a minor uptick compared to the previous trial, it remains significantly lower than the starting voltage. This variation at the end of the test might indicate a secondary stabilization phase or a minor fluctuation in the internal environment of the device.

In summary, the data from Table 05 illustrates a system that begins with a high energy output and gradually tapers toward a more stable, lower voltage range. The transition from 3.36V to a steady range around 2.46V–2.60V confirms that the system undergoes a measurable adjustment period before reaching a state of relative equilibrium.

Conclusion

Based on the results, the researchers conclude that Peltier modules are a reliable way to turn wasted heat into usable power as long as the heat and cold are managed correctly. The project proved that the Seebeck effect works best when there is a large temperature gap between the two sides of the module. A key lesson from the experiment is that "more is not always better" specifically with thermal paste, where a medium amount worked much better than a thick layer. This shows that careful assembly is just as important as the parts themselves.

In the end, the prototype successfully showed that heat from a simple source, like a candle, can be captured and turned into clean electricity. This supports the idea of sustainable energy because it uses heat that would otherwise be wasted. Since the generator has no moving parts, it is a durable and quiet way to produce energy. This design is a practical solution for small needs, such as emergency lights or charging small devices in places where there is no regular electricity.

Recommendations

To make this generator even better, several steps are recommended for future projects. First, instead of using ice which eventually melts, researchers should try liquid cooling systems to keep the cold side at a constant temperature for a longer time. Using different metals for the heat sinks, like copper, might also help move heat faster than the aluminum used in this study. Future researchers could also enhance the statistics using improved instruments to reveals the needed data more accurately. Finally, future versions could use multiple Peltier modules connected together to create enough power to charge modern smartphones or larger batteries, making the device even more useful for the community.

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