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Design and Research of Thermoelectric Energy Harvesting Methods for Instantaneous Use

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Abstract

In today's consumer-oriented market, researchers are attempting to harness energy from ambient sources for sustainable energy generation leading to reduction of dependency on conventional energy sources. Energy harvesting methods offers enormous opportunities to derive energy from our natural surroundings to directly operate self-powered devices or storing it for later use. Generating energy from our nearby environment seems to be a promising solution to address the growing concerns of powering small devices and sensors. Energy harvesters are similar to transducers, designed to extract energy from sources available in environment and convert it into useable electrical energy. This research aims to show the practical implementation of Triboelectric and Thermoelectric energy harvesting using hardware prototypes and set-up. A useable amount of energy is extracted from an energy harvester and results are validated using a hardware model for real-time application. In addition, the study focuses on analyzing the working principles, design considerations, and performance characteristics of both triboelectric and thermoelectric energy harvesting systems under different operating conditions. The proposed experimental setup evaluates the efficiency, output voltage, and power generation capability of the developed prototypes, highlighting their suitability for low-power electronic applications. Emphasis is placed on demonstrating the reliability and feasibility of these energy harvesting techniques for powering sensors, wearable electronics, and Internet of Things (IoT) devices. The results obtained from the experimental investigation indicate that ambient energy harvesting can serve as a viable supplementary power source, contributing to sustainable and eco-friendly energy solutions. This work further provides insights into the potential integration of hybrid energy harvesting systems to enhance overall energy output and ensure continuous power availability for autonomous and self-powered systems.

Keywords: Thermoelectric generator, peltier module, TEG modules, thermal conductivity, peltier cells.

INTRODUCTION

Generation of electrical energy from heat stores huge potential due to the availability of heat energy in various forms like waste heat from engines, domestic applications and industrial operations. Largest source of heat energy is abundant amount of sunlight falling on earth surface. This makes thermal energy conversion practices a favorable area of research and exploration. The phenomenon of thermal to electric energy conversion here rests on the Seebeck effect. The Seebeck effect was discovered by Thomas Johann Seebeck who reported the production of voltage when two different materials of different composition are subjected to a temperature difference at their junction. The thermal gradient effect in certain materials cause diffusion of charge concentration due to the flow of heat energy due to generation of electromagnetic force. Devices can operate on this effect to generate thermoelectric energy if sufficient

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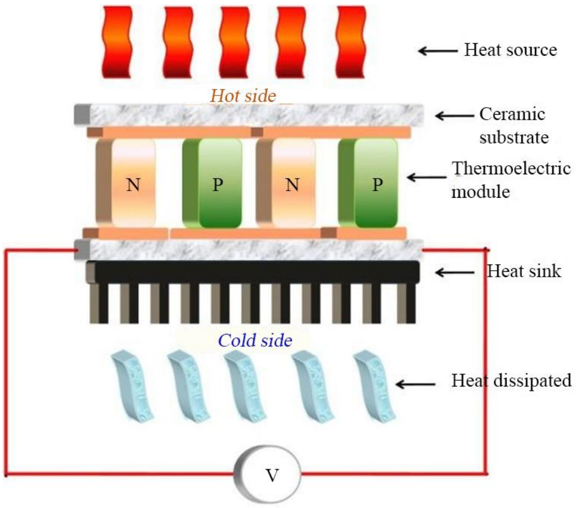

Figure 1. Schematic of thermoelectric generator model

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temperature gradient is maintained. A constant supply of heat flow can generate corresponding electrical energy if sufficient amount of heat is rejected from to maintain a temperature gradient. The large temperature gradient with a constant value is desirable for greater energy generation (Figure 1).

The past decade recorded a rapid development and deployment of compact, low power smart electronic devices called sensor nodes forming wireless sensor networks. These sensors deployed for monitoring and data acquisition networks consist of many sensor nodes for processing but with limited battery capacity. As the location of deployment of these devices is often difficult to access for human beings providing continuous power supply is a challenging job [1]. Also, with the advancement of technology these devices are interconnected not in particular geographical area but across different countries. Advanced networking technologies like Internet of Things is a very good example of such interconnected devices. Looking at enormous number of devices or sensor nodes connected in such applications, their power needs increases manifolds. Along with larger amount of power these devices demand uninterrupted supply of power for reliable and unambiguous results [2-5]. Currently, they are powered using batteries of different ratings and size depending on the type of application. Battery provides a stable power source and for low-power devices, may last for longer duration. But the replacement of these power sources in case of complete discharge is not easy. Due to inaccessible locations replacement becomes costly and takes longer time. This increases the overall system cost and decreases the system reliability. This motivated researchers worldwide to search for some alternate sources which could fulfill the power requirement of such devices. The devices and sensors discussed above are often low-powered and consumes very small amount of power for operation.

A detailed review on waste heat recovery highlighted for existing technologies and future potential applications are discussed. Recent advancements have seen the use of solar energy to improve the performance of TEGs. Electrical power generation from thermoelectric devices using thermal energy from sunlight attracted the researchers worldwide [6]. These systems have three basic components, a heat collecting surface, thermoelectric module and heat sink for generating optimum temperature gradient. The incident heat flux from solar energy can be concentrated on the hot side of thermoelectric module. Non-concentrating mechanisms have also existed with good output electrical power levels. Solar thermoelectric generators referred as STEG can use almost all the spectrum of sunlight as compared to PV designed for fraction of spectrum. This may result in higher energy conversion capability for these systems Early investigations into STEG reported a very low conversion efficiency of about **0.63%**, primarily due to the lack of suitable thermoelectric materials.. A comparative performance analysis of parabolic and flat-plate collector–based STEG systems for power generation was reported in 205.The actual model was designed and studied in a software using coding-based TE module component [7-10]. Two STEG models were presented, one using heater for heating and other dependent on reflected sunlight from aluminium foil. This helped in the study of feasibility for developing such models for future investigations. A solar-based thermoelectric generator was developed using a flat-panel configuration to achieve high thermal energy concentration, resulting in a comparatively higher efficiency of **4.6%**.A vacuum enclosure was used to increase the heat absorption. This work presented the potential of using sunlight without complex concentration mechanism deployed for STEG electricity generation systems. Such systems are good candidate for large-scale electricity generation by rooftop deployment of thermoelectric generators [8]. The feasibility of producing small-scale power from a cleaner energy source such as solar energy was successfully demonstrated. The thermal energy crossing the PV module is harvested by distributing the gathered energy onto thermoelectric module. The heat energy was transferred to TE module using a metal sheet and natural ambient air flowing in vicinity was used for cooling the opposite side. This cost-efficient system produced output voltage of 2.5 V which is enough to power low-power devices. This work also revealed the fact that certain metals sheets when integrated with hot-side surface of TEG module can enhance the heat absorption capability [9].

The efficiency of energy conversion by a thermoelectric generator is expressed by the property of material, ZT, known as figure of merit

The work presented here was carried out to examine the effect on output voltage due to improved heat absorption by thermoelectric surface when connected to a metal surface. In literature review presented above, it was reported that heat distribution by metallic surface resulted in increased energy conversion efficiency. A study was conducted to select a metal for maximum output voltage from thermoelectric energy generation from selected conducting materials. The performance analysis was carried out for different material sheets configured to a thermal module for allocating maximum possible heat energy for open circuit voltage generation. A commercially available module, Peltier cell working on the principles of thermoelectricity, is used as thermoelectric power generation device. Initially two materials Aluminium (AL) and Iron (Fe) were selected due to their good heat transfer capability. A comparative study for Al and Fe metal sheets was done to select the better material for consecutive heat absorption from sunlight. For further investigation, aluminium and iron sheets with black paint coating was integrated with system under test to examine any improvement in output power levels. Black surface is known to absorb all the incident sunlight and can capture the maximum amount of heat energy. This directly increases the heat absorption capacity [10-15]

SYSTEM DESIGN

Experiment was carried out using single module first, later three modules were connected in series to increase the output voltage. For producing an output voltage from selected peltier cells a constant temperature difference should be maintained between two opposite sides of the cell. For experimental set-up, Peltier modules of make TEC1-12706, were procured from the local market. Each module is 40 x 40 mm wide and 3.9 mm thick and being used in Seebeck mode for power generation. The thermocouple material used in these modules is Bi2Te3 (Bismuth Telluride) with operating temperature up to 200ºC. 127 such thermocouples are fabricated inside each module which are connected in series electrically and sandwiched between two ceramic plates for mechanical strength. As it is desired to generate higher temperature gradient among two opposite sides of the thermoelectric modules one side is exposed to a heating source while other is cooled simultaneously using a heat sink mechanism. A heat sink with equally spaced aluminium fins for maximum heat dissipation was integrated for cooling the surface [16]. The cold side of the module also tends to become hotter with time due to heat transfer, so an active arrangement for continuous heat release was required. For continuous cooling an aluminium heat sink connected to a CPU fan was deployed to cool one side of the surface. to eliminate the chances of developing air gaps between ceramic surface of module and aluminium heat sink a thermal interfacing material can be used. In this work we have used thermal grease to attach heat sink to thermoelectric module for better heat transfer. This allows maximum heat conduction as thermal grease is known to have high thermal conductivity. To further maximize the quantity of heat dissipated by the system a CPU fan was used beneath the heat sink. The other side should be exposed to a continuous heating source to receive heat energy required for heating. Easily available ambient solar energy was used for heating the other side of the module here [17-20].

EXPERIMENTAL

First the module was put directly in an open area for unobstructive sunlight incidence on the hotter side. This generated a very low output voltage when recorded for an open-circuit configuration. Next, the process was repeated to investigate the performance of chosen materials on amount of heat transferred. A flat aluminium sheet was attached to the hotter side using thermal grease. Aluminium was chosen owing to easy availability, high thermal conductivity and low-cost. Other materials with better heat conduction are Gold and Copper but their cost is much higher than aluminium. Table 1 lists the thermal conductivity of some materials like Iron, Copper etc. Another good candidate for good conduction of heat is Iron (Fe) which is again a low-cost metal. A thin sheet of iron was also selected to test and analyze the effect on amount of heat absorbed as compared to aluminium sheet. The zenergy from sun was incident directly on aluminium and iron sheets when placed over TEG surface and the corresponding open-circuit voltages were recorded with respect to time. The same process was repeated for black paint by applying a single coat paint onto aluminium and iron sheet. The paint used in this study was black paint with matte finish again procured from the local market. A DC voltage generated from thermoelectric generator was recorded for all the configurations for 60 seconds using a measuring instrument [21-30]. A Fluke make multimeter was used to store the voltage readings at uniform intervals of one second. The data was stored and used to plot the DC voltage graphs for all the materials under test [31-35].

In the initial comparative analysis between aluminium and iron sheets it was recorded that aluminium sheet delivered higher output voltage as compared to iron sheet. As the thermal conductivity of aluminium is higher better heat transfer was achieved using aluminium. The heat when evenly distributed over larger sheet are was able to heat the thermoelectric module. This resulted in development of higher temperature gradient between the two surfaces of thermal module. The heat sink on the other hand was able to dissipate the heat from other side continuously to generate a constant temperature difference. The use of thermal grease helped in better power generation due to better thermal connection between the source and device. When the sheets were directly connected to the surface the voltage levels were less as compared to sheets connected with thermal grease to the module [36-40]. As the intermediate results revealed that higher voltage levels can be generated using aluminium sheet further investigation was done with aluminium sheets only. For our next analysis black metal paint was coated on aluminium sheet to further augment the heat photographic density and generate higher output voltage. Due to intrinsic property of black surface, coated aluminium sheet received high amount of heat energy directly from sunlight. A further increase in open- circuit output voltage was observed. The experiment was repeated again to validate the results and findings.

Table 1. Thermal conductivity of different materials

Material	Thermal conductivity (W m-1K-1)
Diamond	543
Silver	427
Copper	390
Gold	318
Aluminium	237
Iron	80

Although, the painted aluminium sheet attached to TEG module delivered a significant amount of output voltage but it was desired to enhance the power levels further. Other high-cost materials may have delivered better output power but owing to their high material cost they could not be employed for enhancing the voltage levels. Another possible combination is to cascade a number of modules to generate higher power. Using the previously designed mechanism three such Peltier cells were combined to generate better results. These three modules were connected in series electrically to add up the voltage levels generated by them individually. The modified configuration with three peltier cells was again connected to black paint coated aluminium sheets. Separate heat sink modules were connected with peltier cells to achieve required temperature gradient in all three modules. As recorded from the received voltage levels, the series connected cells were able to generate a higher amount of voltage which was sufficient enough to power a low-power device. A maximum voltage of 2.28 V was recorded for series configuration proving the potential to harness substantial amount of electrical energy from a renewable energy source [41-44].

RESULTS AND DISCUSSION

A TEC1-12706 peltier module based thermoelectric generator system was designed and tested for maximizing the power output by increasing the amount of heat being absorbed. In order to increase the available thermal energy from thermal source a comparative analysis was done by attaching Al and Fe sheets on one side of thermoelectric module. The readings presented here were recorded at 11:30 a.m. on 11th Oct, 2025 at average room temperature of 31oC in Delhi. Initially the effect of placing a metal sheet on the power output of the thermoelectric module was tested. A visible increase in open-circuit output voltage was recorded when a metal sheet was connected to TEG as compared to direct heating results. Fig. 4.3. shows the open-circuit output DC voltages generated by heating the module directly under sunlight and heating through Al sheet. It can be noted from the graph that output voltage increased more than twice when an Al sheet was deployed for transferring the heat energy from sunlight evenly throughout the surface[45]. The output voltage increased gradually after engaging the complete set-up in ambient sunlight. The open-circuit voltage was recorded for sixty seconds time duration. A number of samples of generated voltage were recorded at uniform intervals of one second each and total sixty values were stored. The first usual set of readings was taken for heating effect by energy coming directly from sunlight in absence of any heat absorbing surface. To achieve this hot side of the TEG module was placed facing directly under sunlight. The direct application of heat energy from sun yielded a maximum voltage of 0.24 V. A second set of readings were taken for visualizing the effect of aluminium sheet on the amount of open-circuit voltage recorded by the set- up still placed under sunlight. An aluminium sheet when placed on the hot side of the system placed under sunlight generated 0.48 V output voltage. A two-times increase in output voltage was recorded using same thermoelectric power generation system. It validated the potential of using metal sheet for enhancing the electrical output. Figure 2 gives the output voltage plot for open-circuit voltage generated using direct heating and heating using aluminium sheet. After coating matte finish black paint on aluminium sheet, it was connected to the hot side of module placed under sunlight [46-50].

Figure 3 shows the graphs for output voltage for Al and Fe sheet heating. As evident from the figure output voltage with Al sheet mounted on peltier cell is higher as compared to iron sheet.

Figure 4 shows the graph of output voltage using black paint. A noticeable change in output voltage is visible from plotted results. Maximum recorded output voltage was 0.76 V which is clearly higher than aluminium sheet heating result and much higher than higher than the voltage generated by direct heating. It was desired to further increase the output voltage and reach appreciable value of around 2 V. A normal battery cell available in the market is designed to deliver 1.5 V stable voltage. For recharging such battery, a voltage source should be able to generate appropriate amount of output voltage. The above experiment was repeated for an array of three peltier cells connected in series. Initially an aluminium sheet was placed on top of every peltier cell and complete set-up was placed under sunlight. A large increase in output voltage was recorded for this configuration. While single aluminium sheet mounted peltier module could generate 0.48 V output voltage, three such modules

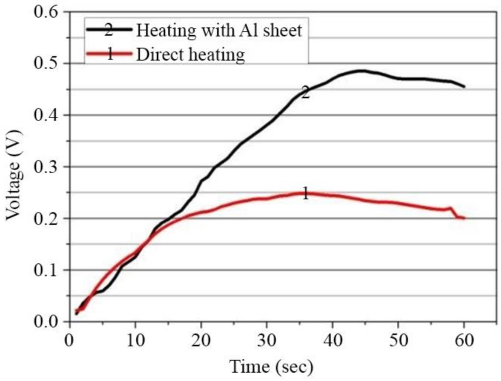

Figure 2. Output voltage for direct heat application and Al sheet on single peltier cell

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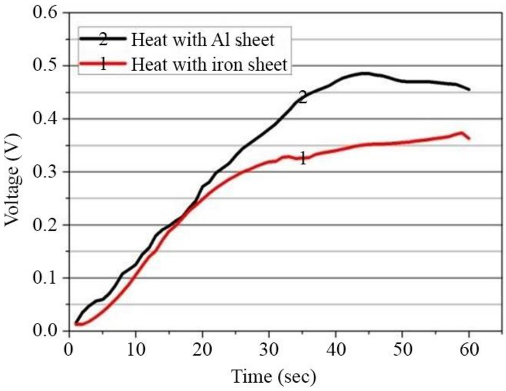

Figure 3. Output voltage for Al and Fe sheet on single peltier cell

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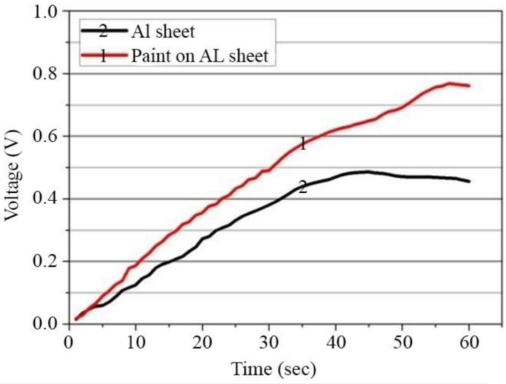

Figure 4. Output voltage for plain Al sheet and painted Al sheet on single peltier cell

Commented [q4]: Pls check typographical error were able to deliver 1.5 V output voltage. This amounts to much higher output voltage as compared to results from single cell. When compared to the output generated using direct heating, output voltage increased significantly using the array of three peltier cells. This demonstrated an alternate approach to enhance the performance of the system under test [51-55].

Figure 5 shows the output voltage graph receive from three peltier cells as compared to the output voltage from single cell when mounted by an aluminium sheet. The excellent results from three peltier cells motivated for further investigation using black paint coated aluminium sheet. The three cells placed under heat energy source were connected to black paint coated aluminium sheets. All the three cells were mounted with painted sheets and combined voltage in series connection was recorded. This configuration resulted in 2.28 V output voltage which is an appreciable increase in device performance. When compared to aluminium sheet mounted three cells, further enhancement in output voltage was recorded. If compared to single peltier cell with same formation which produced 0.78 V, an appreciable increase in open-circuit voltage was recorded. This demonstrated the capability of increasing the electrical energy generation from designed thermoelectric generator. The final arrangement of three peltier cells with black painted surface elevated the output voltage from a lower value of 0.24 V to substantial level of 2.28 V. This amount to overall 850% increase in output voltage. Figure 6 shows the output voltage graph for paint coated aluminium sheet using single and three modules. Figure 7 gives combined output voltage graphs for all the configurations discussed above. Clearly, an appreciable increase in the output voltage with black painted Al sheet mounted on the cell as compared to direct heating cell is visible.

Although, output voltage increased for other configurations also but former case provided a voltage reading which can be further enhanced using appropriate electrical circuit. These elevated voltage levels may be employed directly for operating low- power devices. The results presented above demonstrated the capability of harnessing low-power energy from a simple thermeoelctric generator assembly. This study can help to further investigate the approach of increasing device performance for thermoelectrcity generation. These TEG modules can be integrated with systems using solar system for water heating on rooftops. This PV-TEG power co-generation system can generate noticable amount of energy using single renewable source of energy. At locations with ample amount of sunlight availablity, output voltage from simple peltier module is large enough to motivate further research for boosting this voltage. Even for places where a supply of heat energy from sun is difficult to maintain, availability of waste heat can be considered for heating the metal plates evenly.

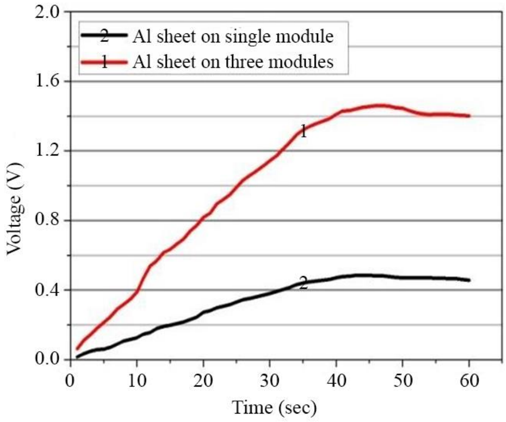

Figure 5. Output voltage from single peltier cell and three peltier cells with mounted Al sheet

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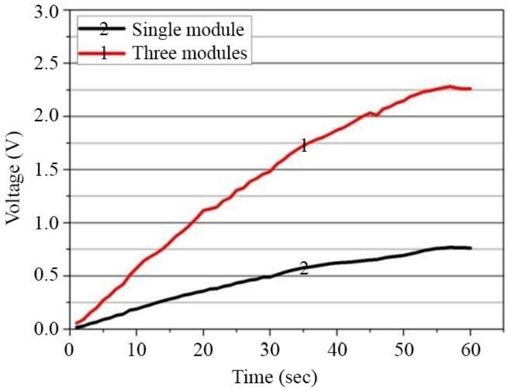

Figure 6. Output voltage from paint coated sheet on Single peltier cell and three peltier cells

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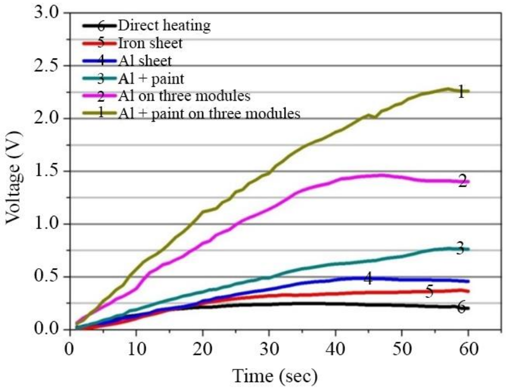

Figure 7. Open circuit output voltage for all the materials

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CONCLUSION

A simple thermoelectric generator was designed and tested to translate the heat energy received from sunlight into useable electric energy. Some materials with better thermal conductivity were selected for performance enhancement of the designed system. Experimental investigation conducted by connecting single commercial Peltier cell in an open circuit recorded 0.24V output voltage. This cell generated 0.48V when attached to aluminium sheet for enhanced heating while an iron sheet delivered 0.37V. Further study revealed that black paint coated aluminium sheet improved the generated voltage to 0.76V. To further increase the voltage three such modules were connected in series and an impressive 2.28V output voltage was recorded. Clearly, three cascaded modules mounted by black paint coated aluminium sheet delivered maximum output voltage. The attached aluminium sheet can provide additional protection to thermoelectric module from physical wear and tear. The generated voltage is sufficient to provide required electrical energy to micro/low power devices. No special fabrication process or material preparation process was required during this experimental analysis. Although, the overall size of the system increased as compared to single peltier cell arrangement but an impressive increase in output voltage was recorded with black absorbing surface. to reduce the number of cells required for generating sufficient amount of output power study for integration of voltage amplification circuits can be considered for future work.

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