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Editorial

Innovations in Thermoelectric Technology: From Materials to Applications

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1. Introduction

Over the past two decades, significant advances have been made in the field of energy harvesting, which involves the collection of energy from various environmental sources, including light, thermal gradients, electromagnetic radiation, and mechanical vibrations [1]. Thermal energy is ubiquitous and can be found in electronic devices (such as integrated circuits, smartphones, and computers), vehicles, buildings, and even within the human body, representing a significant and accessible source of energy [2]. Devices known as thermoelectric generators (TEGs) play a crucial role in harvesting this energy by transforming thermal energy directly into electrical energy without the need for mechanical processes, unlike conventional turbine-based power generation methods [3]. TEGs are characterized by energy efficiency, negligible maintenance requirements, and durability, making them increasingly popular in energy harvesting for a broad range of applications. Despite their low efficiency of about 5%, the versatility of TEGs makes them ideal for diverse operational settings, including space use, medical applications within the human body [4], and even aircraft engines [5], where price is not an essential parameter [6]. Small, affordable, and efficient TEG systems are a good alternative to batteries for many uses [7,8]. For example, a TEG system that makes 1.5 mW of power from a temperature difference ΔT = 10 °C can run a small preamplifier and a sensor controller [6]. On the other hand, the Internet of Things (IoT) refers to the network of physical objects embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the Internet. IoT gathers large amounts of data automatically without human aid by using smart, small devices that can sense, compute, and connect to each other. TEG is a good method for converting thermal energy into electricity for these IoT devices, also promoting the use of renewable energy [9]. TEGs are a promising technology for powering wearable electronics and IoT node sensors. They offer a number of advantages over traditional batteries, including their small size, light weight, and ability to harvest energy from a variety of sources [10].

TEGs can be used in vehicles to convert waste heat into electricity. Waste heat energy is described as unconsumed heat energy that is rejected from a thermal process [11]. For example, Kim et al. [12] put a hexagon-shaped TEG in the exhaust pipe of a hybrid electric car. Shu et al. [13] proposed a way to use the waste heat from a diesel engine to run a thermoelectric generator system. This new setup increases its maximum power by 13.4% compared to the old setup. Lan et al. [14] created a model to predict the temperatures and power output of a TEG, which operates using the recovered waste heat energy from a large truck in transit. Li et al. [15] arranged TEG units around the exit of the exhaust pipe of a passenger car. Agudelo et al. [16] explored the capture of waste heat energy from the exhaust gases of a diesel car. Ge et al. [17] also aimed to improve the functioning of this kind of system. Muralidhar et al. [18] conducted a study on the benefits of using a thermoelectric generator in a heavy-duty hybrid electric bus. Their findings indicated

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that this could lead to reductions of up to 7.2% and 7.58% in fuel use and CO_2 emissions, respectively.

TEGs also offer a promising method for generating power in hypersonic vehicles, which are capable of travelling significantly faster than the speed of sound, usually defined as speeds of at least Mach 5. Hypersonic vehicles are used in a variety of sectors, ranging from military applications, such as missiles and reconnaissance aircraft, to potential future uses in civilian space travel and rapid long-distance transportation. For long-distance travel at hypersonic speeds, creating electricity on the spot is crucial for powering a vehicle, especially in terms of fuel, control, and radar systems [19]. Cheng et al. [20] and Cheng et al. [21] introduced a method for generating power in these vehicles using a sophisticated multi-stage (cascade) TEG system. They managed to reach a peak efficiency of 18.4% by using cutting-edge thermoelectric materials. Furthermore, Cheng et al. [22] conducted a study comparing single-stage and multi-stage TEG setups to identify the most efficient performance conditions for the system.

Recent advancements in thermoelectric materials focus on overcoming the limitations of traditional semiconductors by developing novel materials with higher figures of merit (ZT). The efficiency of thermoelectric materials, crucial for converting heat to electricity, is bound by their Seebeck coefficient, electrical conductivity, and thermal conductivity. While metals offer low electrical resistivity and high thermal conductivity, their low Seebeck coefficients result in poor thermoelectric performance, making semiconductors with high ZT values, such as Bi2Te3, PbTe, and CoSb3, more desirable. Recent research has yielded materials such as Cu2−xSe and PbTe0.7S0.3, achieving ZT > 2, marking a significant step forward. These innovations, alongside the development of segmented thermocouples designed to operate across different temperature ranges, aim to enhance the efficiency and practicality of thermoelectric generators (TEGs), despite the challenges posed by the high development and industrialization costs of these materials [2].

The above-mentioned aspects indicate the range of current studies on thermoelectric system technologies and applications, and significant progress in different research directions is expected in the coming years, from the evolution of materials to the identification of more effective solutions in the power and energy sector. This context is the motivation behind the collection of specific contributions that form this Special Issue.

2. An Overview of the Contributions to the Special Issue

This Special Issue includes a variety of research papers that provide insights into the technology and applications of thermoelectric systems. The featured papers, written by 42 authors with affiliations in nine countries, cover a range of topics, from theoretical research to practical applications in different fields. This collection not only addresses existing challenges in the field but also opens new areas for future research. The Special Issue is divided into two main themes:

1. TEG design and optimization;
2. Advances and applications of thermoelectric materials and technologies.

For the first theme, TEG design and optimization is a key area for thermoelectric research. Four contributions address specific aspects concerning the geometry, durability, and performance enhancement of TEGs, as follows:

- In “Design of Thermoelectric Generators and Maximum Electrical Power Using Reduced Variables and Machine Learning Approaches”, Vargas-Almeida et al. investigated the geometric optimization of TEGs through a combination of a technique to reduce variables and machine learning. The article concludes that combining supervised machine learning with the technique of reduced variables is effective for designing TEGs. This approach is beneficial for estimating thermoelectric properties at various temperatures and designing TEGs with limited amounts of experimental data. The key findings include the ability to analyze and optimize power for different temperature ranges and the potential of using this methodology for TEG design without extensive laboratory resources. Additionally, the study highlights the application of artificial intelligence in predicting thermoelectric properties and electrical power, demonstrating high accuracy and efficiency in modelling TEGs. This study represents a significant advance in predicting thermoelectric properties and maximizing the power output of TEGs, blending computational methods with practical applications.

- In "Experimental Analysis of the Long-Term Stability of Thermoelectric Generators under Thermal Cycling in Air and Argon Atmosphere", Schwab et al. investigated the durability of TEGs under different environmental conditions. The study determined the degradation of TEGs at the system level, particularly emphasizing the impact of the atmosphere on their performance. This degradation is attributed to increased inner resistance, influenced by oxidation and crack formation, especially at electrode interfaces. The experiments demonstrated a significant reduction in the maximum output power in an air atmosphere, which stabilizes at about 57% of its initial maximum power after 50 cycles, while an argon atmosphere mitigates this degradation, maintaining a constant output power during the cyclic tests. The paper recommends developing standard testing procedures based on application-oriented thermal cycles to enhance the design and longevity of TEG systems. The gaps identified in the paper include the need for a broader range of thermoelectric materials and test conditions, as well as a standardized approach to testing, to comprehensively understand and mitigate degradation phenomena in TEGs. This study is crucial for understanding the practical challenges in deploying TEGs in various atmospheric conditions, emphasizing the importance of long-term stability.
- In "Analyzing the Performance of Thermoelectric Generators with Inhomogeneous Legs: Coupled Material–Device Modelling for Mg2X-Based TEG Prototypes", Camut et al. present an innovative method for the performance analysis of TEGs with inhomogeneous material properties. Their study introduces a new analytical approach, the Constant Property for Inhomogeneous Materials (CPIM) approach, which integrates experimental carrier concentration profiling with the Single Parabolic Band (SPB) model and continuum theory to accurately assess the inhomogeneity of thermoelectric materials at macro/mesoscopic levels. Applied to an Mg2(Si,Sn)-based TEG, this method reveals discrepancies between predicted and observed heat flows and thermal losses in N-type legs when considering material inhomogeneity, exceeding measurement uncertainties and suggesting higher thermal losses at TEG/heat exchanger interfaces. The significant difference between calculated and measured electrical resistance points to crack formation as a prevalent degradation mechanism. The CPIM approach, by capturing property inhomogeneity, offers a more accurate analysis of TEG performance under a thermal load, identifying the need for precise heat flow measurements in small TEG prototypes as a critical future challenge. This highlights gaps in current modelling approaches, especially in accounting for material inhomogeneity and accurately measuring thermal and electrical properties in experimental settings.
- In "Thermoelectric Performance Evaluation and Optimization in a Concentric Annular Thermoelectric Generator under Different Cooling Methods", Yang et al. offer a comprehensive analysis of a concentric annular TEG. This study addresses the key aspect of thermal management in TEGs, exploring various cooling methods to optimize performance. This study focused on creating a detailed simulation model that looks into how heat from a car's exhaust can be turned into electricity using a new type of TEG with a special design called a concentric annular heat exchanger. The model considers how temperature affects the materials used in the TEG, how heat is transferred within it, and how the setup of the heat source impacts its efficiency and the temperature differences inside the TEG. The study specifically examined how changing the heat source and cooling methods can affect the TEG's power output and efficiency under various car operating conditions. The study discovered the potential of using advanced TEG systems to recover energy from automotive exhaust fumes, suggesting that with the right cooling method, these systems can significantly

improve their efficiency and power output. However, it also highlights gaps, such as the need for more material for optimal performance in some configurations and the varying effectiveness of cooling methods based on the temperature of the heat source.

The second theme includes new developments in thermoelectric materials and their uses in different applications. The contributions on this theme address the use of dedicated materials and discuss the effectiveness of applications relevant to personal comfort and engineering applications. In particular:

- In "Nanostructured Thermoelectric PbTe Thin Films with Ag Addition Deposited by Femtosecond Pulsed Laser Ablation," Bellucci et al. explore the development of nanostructured thermoelectric materials. Their study contributes to the field of nanomaterials and their application in thermoelectric devices, focusing on thin films for low-power applications. In this paper, the focus was on enhancing the thermoelectric efficiency of PbTe thin films through the addition of silver (Ag) using Pulsed Laser Deposition (PLD). Previous efforts achieved a lower thermal conductivity in PbTe films by creating nanocrystalline structures, yet these did not significantly improve the power factor compared to bulk materials. Bellucci et al. explored Ag as a dopant, observing its effects on the electrical and thermal properties of the films. Their findings indicate that Ag can reduce resistivity and alter the Seebeck coefficient, suggesting increased carrier concentration. The optimal thermal performance was identified in the 510–540 K range, with the materials showing stability under prolonged heat treatment. Despite achieving an improved power factor with specific Ag concentrations, the performance still fell short of that of bulk materials and other thin film techniques. This gap underscores the need for further exploration into co-doping strategies and complex alloys to advance the thermoelectric properties of thin films.
- In "Influence of Charge Transfer on Thermoelectric Properties of Endohedral Metallofullerene (EMF) Complexes", Alshammari et al. analyze the thermoelectric properties of EMFs. The paper focuses on how charge transfer within these complexes can be harnessed to improve electrical conductance and thermopower, offering insights into the material science of thermoelectrics. Their study investigates the charge transfer mechanisms in donor–acceptor complexes, focusing on three different analysis methods: Mulliken population, Hirshfeld, and Voronoi. These techniques were applied to understand how charge is transferred between molecular components. The findings from all three charge transfer methods consistently indicate that charge moves from the metallic components to Ih-C80 cages, with the extent of charge transfer varying depending on the type of metallic moiety involved. This behavior suggests a pathway to enhance both the conductance and thermopower in these complexes, pointing to novel design strategies for electronic and thermoelectric devices by modulating charge transfer through different metallic moieties. However, the study highlights a knowledge gap in comprehensively understanding the relationship between different types of metallic moieties, their specific influence on charge transfer efficiency, and the resultant electronic properties, signaling the need for further targeted research in this area to fully leverage these findings for practical applications.
- In "Heat Transfer Mechanisms and Contributions of Wearable Thermoelectrics to Personal Thermal Management", Enescu discusses the conceptual aspects of heat transfer in the application of wearable TEGs. This paper offers a new viewpoint on wearable TEGs (w-TEGs), focusing on their use for personal thermal management, rather than providing a detailed exploration of the specific materials and devices, as was the case in other reviews. Enescu emphasizes the critical role of understanding how heat transfer between w-TEGs and the human body can enhance local thermal comfort without changing the room temperature. This approach provides innovative ways to improve energy efficiency by considering the body as a heat source and optimizing how the device interacts with the skin through various heat transfer methods, including evaporation. Future progress relies on developing materials with improved thermal performance and designing devices that are flexible, lightweight,

and affordable, with a particular interest in biobased materials and organic composites due to their lower environmental impact. The review points out the need for a collective effort to increase the efficiency of energy conversion, suggesting the use of multistage thermoelectric modules and smart sensors for more adaptable thermal regulation. However, it identifies a gap in fully integrating these technologies into everyday wearable items that can adjust to body movements and cater to individual thermal needs in an environmentally friendly and cost-effective manner.

- In "Evaluation of Performance and Power Consumption of a Thermoelectric Module-Based Personal Cooling System—A Case Study," Dąbrowska et al. present an evaluation of a personal cooling system using flexible thermoelectric modules. Their research focused on developing and testing a novel personal cooling system (PCS) for workplace use, using flexible thermoelectric (TE) modules and heat sinks to combat heat effects. The study aimed to assess the effectiveness of these TE modules in reducing thermal discomfort under conditions of increased physical activity and elevated ambient temperatures, while also evaluating the system's electrical power consumption and controller efficiency. Laboratory tests involving human participants compared active cooling by TE modules against passive cooling through wet heat sinks and examined the influence of ambient temperature on the system's performance. The results indicate that TE modules effectively lowered skin temperature over several hours and highlighted the need for the cooling device to adhere closely to the body for optimal heat removal. Additionally, a combination of TE modules with evaporative heat sinks was found to enhance cooling effects. The study also showed that ambient temperatures between 25 °C and 35 °C had a minimal impact on cooling efficiency. A limitation of the study was its reliance on a single participant, suggesting the need for future testing with a broader user base to more comprehensively explore usability, ergonomics, and market viability. This research lays the groundwork for refining the PCS prototype, indicating gaps in understanding user interaction and optimization of TE module count for cost-effectiveness and market success.
- In "Employing the Peltier Effect to Control Motor Operating Temperatures", Lucas et al. examine the application of thermoelectric coolers in electric motors. Their research explores the use of thermoelectric coolers (TECs) not for cooling but for heating electrical motors to minimize thermal gradients and stresses, and to address issues such as internal condensation and water absorption. By reversing the supply polarity, TECs can pump heat energy into the core of the motor, potentially allowing control over internal temperatures, particularly at winding locations. This approach aimed to maintain warmth within the motor's internals and windings. The study involved integrating TECs into three different setups on a standard electrical motor equipped with temperature sensors, marking the first trial of such technology for internal temperature regulation in operational conditions to enhance motor reliability and reduce maintenance costs. The findings revealed that TECs, when mounted on motors using simple or complex adapter plates depending on the motor's exterior design, can significantly increase internal temperatures, surpassing dew points and eliminating condensation problems. This application of TECs presents a cost-effective alternative to traditional heating methods by directly heating the volume of the motor. The potential for TECs to be included in new motor designs during the manufacturing phase was also noted, suggesting a proactive approach to incorporating this technology. While the study successfully demonstrated the capability of TECs to heat motor cores effectively across different configurations, it also opens the door for further investigation into dynamically managing motor temperatures under varying ambient conditions.
- In "Design Modifications for a Thermoelectric Distiller with Feedback Control," Nasir et al. propose a novel design for a thermoelectric distiller. This study introduces a redesigned thermoelectric (TE) distiller that enhances water distillation efficiency by incorporating both the heating and cooling functions of a thermoelectric module.

Key innovations include a new thermoelectric configuration with an added heat sink and cooling fan to better manage the cold tank's temperature, and the development of a feedback control system that optimizes the distiller's performance by adjusting the fan's speed and the TE module's voltage. Specifically, the study explores the use of PID and MPC controllers to maintain the desired operational conditions despite external disturbances and introduces an angled cover design to improve the collection of distilled water. The research assesses the upgraded distiller's effectiveness under various conditions, aiming to maximize pure water production. The findings from the mathematical modelling and comparative analysis of the PID and MPC control systems demonstrate that the MPC controller achieves a superior dynamic performance, enhancing productivity by up to 150% compared to traditional open-loop systems. This productivity boost is attributed to improved heat recovery and vapor production, alongside reduced vapor loss. The advancements outlined in the study suggest a significant step forward in thermoelectric distillation technology, offering a more efficient method for water purification.

3. Concluding Remarks

This Special Issue, entitled "Advanced Studies of Thermoelectric Systems", brings together a collection of innovative papers that highlight the diverse and progressive research on thermoelectric technology. The contributions emphasize how collaboration across various disciplines—such as physics, chemistry, and engineering—leads to significant advances in thermoelectric technology. Such collaboration is fundamental for creating solutions to enhance the energy efficiency of the systems. The importance of the progress made in thermoelectric technology is illustrated by these contributions and highlights directions for advancing the field. Research undertaken in areas such as material science, device design, and optimization strategies addresses major obstacles to the broader application of thermoelectric technology. The major obstacles include the development of materials with improved thermoelectric properties, the reduction in heat loss in devices, and the enhancement of scalability of the practical solutions. Insights derived from these studies offer a deep understanding of the fundamentals of thermoelectric systems and suggest promising directions for ongoing research.

Conflicts of Interest: The author declares no conflicts of interest.

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