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Thermoelectric Generators: Principles, Materials, and Emerging Applications

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Abstract

Thermoelectric generators (TEGs) are solid-state devices that convert thermal energy into electrical power using the Seebeck effect, offering a sustainable solution to mitigate rising energy costs, environmental pollution, and global warming. These generators are advantageous due to their lack of moving parts, silent operation, long lifespan, and compatibility with various substrates such as silicon, ceramics, and polymers. TEGs are categorized based on their design—planar, vertical, and mixed—and can be enhanced through different configurations like conventional, segmented, and cascaded arrangements. The performance of TEGs is often evaluated using the figure of merit (ZT), which considers the Seebeck coefficient, electrical conductivity, and thermal conductivity. Advances in thermoelectric materials, including bismuth telluride (Bi_2Te_3), lead telluride (PbTe), and silver selenide (Ag_2Se), have improved efficiency, making TEGs suitable for a range of applications. In low-power domains, they are utilized in medical devices, wearable technologies, and wireless sensor networks, while in high-power sectors, they contribute to energy recovery in automotive engines, industrial electronics, and aerospace systems. The integration of TEGs into various technologies underscores their potential in energy harvesting and sustainable power generation.

Keywords: *Thermoelectric generator (TEG), Seebeck effect, Energy harvesting, Thermoelectric materials, Figure of merit (ZT), Bismuth telluride (Bi_2Te_3), Lead telluride (PbTe), Silver selenide (Ag_2Se)*

1. Introduction

The utilization of natural gas, fuel oil, and coal for electricity generation has become increasingly detrimental due to their significant contributions to atmospheric pollution and global warming. Despite these adverse effects, the U.S. Energy Information Administration (EIA) reported a steady rise in electricity generated from natural gas, reaching 35% in 2018 and 36% in 2019, up from 28% in 2014. Additionally, global consumption and production of liquid fuels escalated from 94 million barrels per day in mid-2014 to 100 million in mid-2018, leading to escalating energy costs. In response to the growing environmental concerns and the escalating costs associated with fossil fuels, there has been a significant shift towards renewable energy sources. Innovations in harnessing natural energy from various environmental sources—such as radio frequency (RF) radiation, thermal gradients, solar radiation, and vibrational or mechanical energy—have gained momentum. These technologies aim to provide sustainable, green, and cost-effective electrical power. As Nikola Tesla once envisioned, “Electric power is everywhere present in unlimited quantities and can drive the world’s machinery without the need of coal, oil, gas or any other of the common fuels.” This foresight aligns with the current trend of tapping into ambient environmental energy to meet the world's growing demand for electricity. (Figure 1) Thermoelectric generators (TEGs) are devices that convert thermal energy into electrical energy using the Seebeck effect. They consist of dissimilar thermocouples connected electrically in

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series and thermally in parallel. TEGs are utilized in various applications, including electronics, vehicles, buildings, and even the human body, due to their energy efficiency, low maintenance, and long lifespan. This paper provides a comprehensive review of TEGs, differentiating it from previous studies by focusing on the different types (planar, vertical, and mixed) and technologies (silicon, ceramics, and polymers) of TEGs. It also explores the latest thermoelectric materials and strategies for generating high-efficiency power factors through various thermoelectric material arrangements (conventional, segmented, and cascaded). Furthermore, the paper examines the use of TEGs in both high and low-power applications, including medical devices, wearables, IoT, wireless sensor networks (WSNs), industrial electronics, automobiles, and aerospace applications. Recent advancements in TEGs have led to the development of novel materials and designs aimed at enhancing energy conversion efficiency and adaptability across diverse environments. These innovations are particularly relevant in the context of sustainable transportation systems, where TEGs can contribute to energy harvesting and waste heat recovery. TEGs represent a promising technology for converting waste heat into usable electrical energy, with ongoing research focused on improving their efficiency and expanding their applications across various sectors.

Figure 1 Renewable Energy Sources

2. Thermoelectric Generators: Harnessing Heat to Generate Electricity

Thermoelectric generators (TEGs) convert thermal energy into electrical energy using the Seebeck effect. This phenomenon occurs when two dissimilar conductors are joined at two junctions maintained at different temperatures, generating a voltage proportional to the temperature difference.

2.1. Structure and Operation

- **Thermocouples:** The fundamental units of TEGs are thermocouples, each consisting of two dissimilar materials (e.g., copper and constantan) joined at their ends. When one junction is heated and the other is cooled, a voltage is generated due to the Seebeck effect.
- **Thermopiles:** To enhance the power output, multiple thermocouples are connected in series to form a thermopile. This configuration increases the total voltage generated, making TEGs suitable for practical applications.
- **TEG Modules:** These consist of numerous thermocouples arranged in a series-parallel configuration, optimizing the voltage and current output to match the requirements of specific applications.

2.2. Advantages of TEGs

- **Simplicity:** TEGs have a straightforward design with no moving parts, reducing mechanical complexity.
- **Durability:** The absence of moving components leads to a longer lifespan and minimal maintenance requirements.
- **Environmental Friendliness:** TEGs do not rely on chemical reactions, making them environmentally benign.
- **Scalability:** The modular nature of thermocouples allows for scalability in power generation.

2.3. Applications

TEGs are employed in various fields, including:

- **Space Exploration:** Powering spacecraft instruments and systems. Research Gate
- **Remote Sensing:** Supplying power to remote sensors and monitoring devices.
- **Waste Heat Recovery:** Converting industrial waste heat into usable electricity.
- **Portable Power:** Providing power for portable devices in off-grid locations. real-time location tracking with lower latency,

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better visualization, and data storage for future reference. Despite these improvements, many systems still focus solely on tracking without integrating safety or driver behaviour monitoring features.

2.4. TEG-Working Principle

Thermoelectric Generators (TEGs) are solid-state devices that convert heat directly into electrical energy using the Seebeck effect. They consist of three main components:

- **Heat Exchanger (HEX):** Absorbs thermal energy from the heat source and transfers it to the thermoelectric modules.
- **Thermoelectric Modules (TEMs):** Comprise multiple pairs of p-type and n-type semiconductor elements. When a temperature gradient exists between the two sides of a TEM, charge carriers (electrons and holes) move, generating an electric current. This phenomenon is governed by the Seebeck effect, where a voltage is induced in a circuit due to a temperature difference across the junctions of two dissimilar metals or semiconductors.
- **Heat Sink:** Dissipates the heat from the cold side of the thermoelectric modules to maintain the temperature gradient necessary for efficient operation. The efficiency of a TEG is influenced by the temperature difference between the hot and cold sides, the properties of the thermoelectric materials, and the design of the system. Materials with high electrical conductivity and low thermal conductivity are ideal for TEGs, as they enhance the Seebeck effect and reduce heat loss. Common thermoelectric materials include Bismuth Telluride (Bi_2Te_3) for low-temperature applications and Lead Telluride (PbTe) for higher temperatures. TEGs offer a compact and reliable method for converting waste heat into usable electrical power, making them suitable for applications in automotive, aerospace, and industrial sectors.

2.5. Seebeck Effect

The phenomenon where a temperature differential generates a voltage is known as the thermoelectric effect, or more specifically, the Seebeck effect. Traditionally, this effect was believed to have been first defined in the 1820s by the German physicist Thomas Johann Seebeck. However, recent evidence suggests that Alessandro Volta had observed a similar effect 27 years earlier. In an experiment conducted in 1794, Volta designed a U-shaped iron rod, with one end heated by immersion in hot water. He then connected the unevenly heated rod electrically to the leg of a dead frog. The resulting current caused the frog's muscles to contract. This experiment is now considered an early example of the Seebeck effect in action. (Figure 2,3)

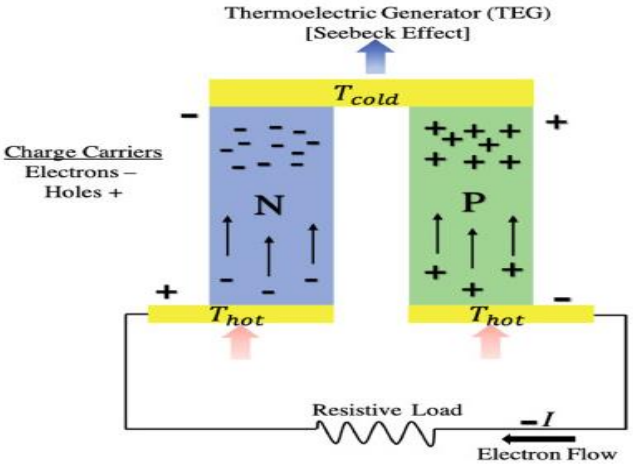

Figure 2 TEG-Working Principle

Seebeck Effect 'couple' showing one set of *n* and *p* type semiconductors using bismuth telluride material.

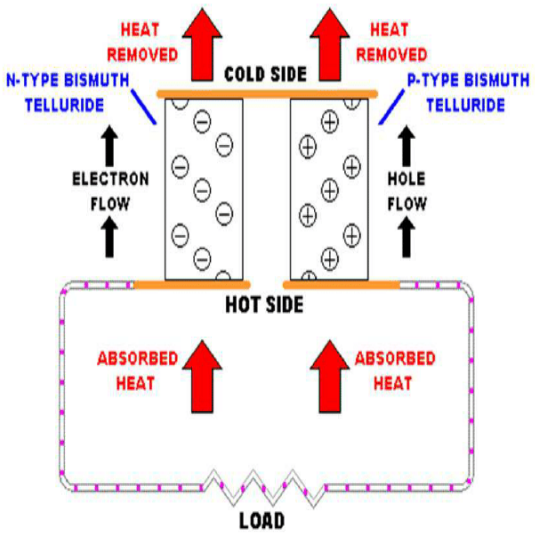

Figure 3 Seebeck Effect

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2.6. Peltier Effect

In 1821, German physicist Thomas Seebeck discovered that electricity could be generated in a circuit composed of two different conductors if the junctions connecting them were maintained at different temperatures. Although Seebeck failed to explain the underlying mechanism and incorrectly assumed that flowing heat produced the same effect as flowing electricity, his discovery laid the foundation for thermoelectric research. In 1834, French scientist Jean Peltier, while studying Seebeck's work, found that heat could be absorbed at one junction and released at the other in a circuit made of dissimilar metals—this phenomenon later became known as the Peltier effect. In the 1850s, Lord Kelvin (William Thomson) theoretically validated and linked the findings of both Seebeck and Peltier. Despite these early insights, the thermoelectric effect remained a laboratory curiosity until the 1930s, when Russian physicists revisited earlier experiments and helped develop practical thermoelectric devices. [1]

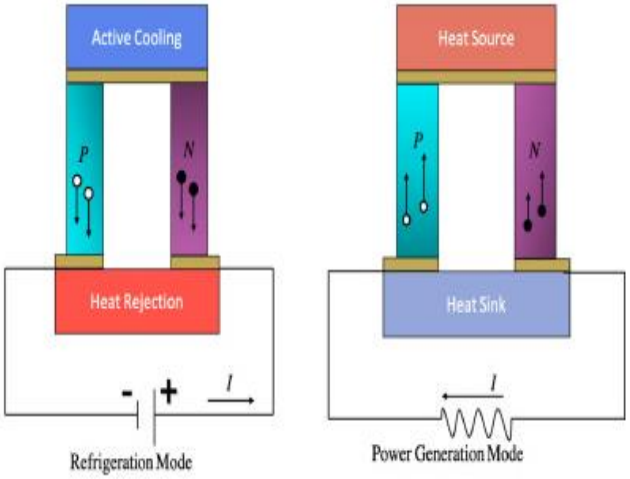

Figure 4 Peltier Effect

The Peltier effect, considered the reverse of the Seebeck effect, occurs when an electric current passes through the junction of two different materials, generating or absorbing heat to balance differences in their electronic structures. This effect, which arises because electrons carry different average energies in different conductors, enables the creation of devices such as Peltier coolers—solid-state electronic refrigerators. Factors like the energy range of electrons, their distribution within the material, and scattering interactions with atoms under an applied voltage all influence thermoelectric behavior, as illustrated in Fig. 2, which shows the thermoelectric module's capacity for both power generation and electronic cooling. (Figure 4)

2.7. Thomson Effect

Thomson demonstrated that when an electric current flows through a conductor with a temperature gradient, thermal energy is either absorbed or released within the material's structure. This phenomenon, known as the Thomson effect, refers to the generation of reversible heat in a single conductive material when an electric current passes through it under non-uniform temperature conditions. Unlike the Seebeck and Peltier effects—which require two dissimilar materials and only allow for measurement of the net effect at their junctions—the Thomson effect occurs within a single material and results in a directly observable transfer of heat. This makes it distinct, as it reflects the continuous interaction between electric current and the internal thermal gradient of the conductor. [2]

2.8. Positive and Negative Thomson Effect

Figure illustrates the Thomson effect using a copper bar extending from point A to point B, with localized heating applied at the center point C. When no electric current flows through the bar, the temperatures at points M and N—located equidistant from C—are equal. However, when an electric current is applied from point A to point B, point N shows a higher temperature than point M. Likewise, the temperature at point B becomes higher than at point A. This observation suggests that heat is absorbed as the current flows from point A to C and released from point C to B. This behavior exemplifies the positive Thomson effect, observed in metals such as antimony, silver, zinc, and cadmium. In contrast, when a similar experiment is conducted with iron, heating the bar at point C and directing current from A to B causes point M to become warmer than point N. This implies that heat is released between points C and A and absorbed between C and B, a phenomenon known as the negative Thomson effect. Similar negative Thomson effects are observed in materials

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like platinum, bismuth, cobalt, nickel, and mercury. (Figure 5) [3]

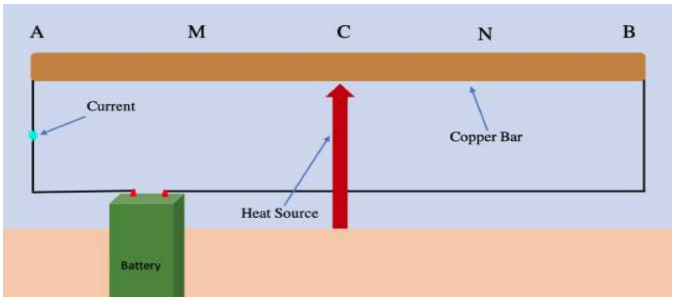

Figure 5 Thomson Effect Using a Copper Bar

2.9. TEG Materials, Design & Optimization

As previously discussed, thermoelectric generators provide a reliable, solid-state solution for energy conversion. Devices incorporating advanced thermoelectric materials present a promising alternative to conventional heat engine-based power generation, particularly in applications requiring lightweight heat recovery systems. The maximum efficiency of thermoelectric energy conversion is generally expressed in terms of the temperatures of the heat reservoirs and the material's thermoelectric figure of merit (zT). Since an increase in zT directly enhances thermoelectric efficiency, significant research efforts have been dedicated to developing and optimizing materials with high zT values. Analysis of thermoelectric material properties Effective thermoelectric (TE) materials must exhibit the following key properties: High electrical conductivity, to minimize Joule heating (the undesired temperature rise caused by electrical resistance). A high Seebeck coefficient, to ensure efficient conversion of thermal energy into electrical power (or vice versa, in cooling applications). Low thermal conductivity, to reduce heat transfer through the material, thereby maintaining the temperature gradient necessary for thermoelectric operation. These three properties are typically combined into a single performance metric known as the figure of merit, denoted as z. Since z has units of inverse temperature, a more practical and widely used form is the dimensionless figure of merit, expressed as zT, where T (in Kelvin) is the average operating temperature. The zT value is a critical parameter that governs the maximum achievable power conversion efficiency of thermoelectric devices. Historically, Bismuth Telluride (Bi_2Te_3) was the only material used commercially for thermoelectric modules. Its figure of merit values are approximately 1.35 for p-type and 0.9 for n-type materials. The lower performance of n-type Bi_2Te_3 relative to its p-type counterpart significantly limits the overall efficiency of Bi_2Te_3-based thermoelectric modules. Nevertheless, Bi_2Te_3 and its alloys have been widely used in thermoelectric cooling applications and select low-power energy generation systems, with an effective operating temperature range of approximately 180 to 450 K. Alcohol detection systems have been widely researched in the context of improving road safety. These systems typically employ gas sensors such as the MQ-3 or MQ-135, which are sensitive to ethanol and other volatile substances. These sensors detect alcohol content in the breath of the driver and generate an analog signal based on concentration. This signal is processed by a microcontroller, which then takes necessary actions such as triggering a buzzer, displaying a warning, or preventing vehicle ignition. Several studies have proposed vehicle ignition interlock systems based on alcohol detection, where the car will not start if the sensor detects a high alcohol concentration. Other projects integrate alert mechanisms that notify family members or authorities using GSM modules. While these systems serve the intended purpose, most of them are standalone and do not provide any location or tracking information, which limits their effectiveness in public transportation scenarios. Furthermore, the majority of them use microcontrollers like Arduino Uno or ATmega328, which have limited connectivity options. [4]

2.10. Fermi level

The Power Factor (PF) is a key metric used to evaluate thermoelectric performance, as it depends on both electrical conductivity, which is directly proportional to carrier density, and the Seebeck coefficient, which is inversely proportional to carrier density. Consequently, optimizing the Fermi level is essential for maximizing thermoelectric efficiency. As defined by Ohtani, the Fermi level represents the electrical equilibrium energy within a solid, and the

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Fermi energy corresponds to the energy of the most energetic electron at absolute zero temperature (T = 0 K). Both the power factor and the figure of merit (zT) are highly sensitive to the Fermi level's position. (Figure 6) [5]

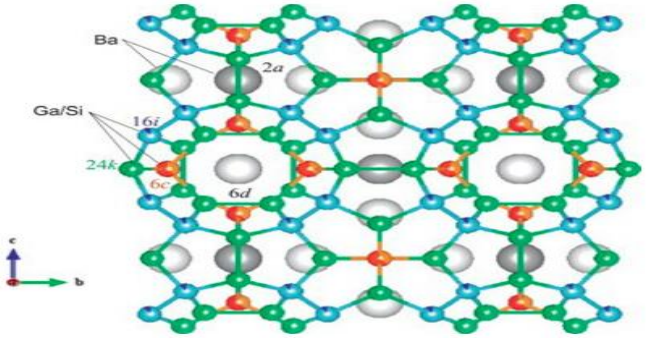

Figure 6 Clathrate Crystal Structure

The power factor is typically maximized when the Fermi level is located near the bottom of the conduction band, with the precise optimal position slightly below or above this point depending on the material's band structure and scattering mechanisms. When plotted against the Fermi level, as illustrated in Fig., the power factor reaches its peak near this critical energy level, highlighting the contrasting dependencies of electrical conductivity and the Seebeck coefficient on the Fermi level. (Figure 7)

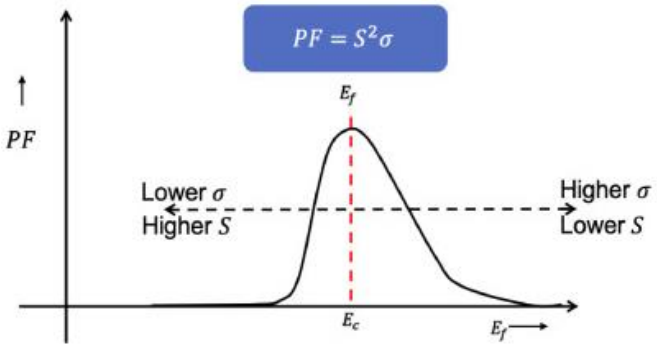

Figure 7 Fermi Level

2.11. Nanotechnology

Achieving high zT values has long been a challenge due to the intrinsic coupling between electrical conductivity and thermal conductivity in most materials. While high electrical conductivity is essential to minimize Joule heating and enhance the performance of thermoelectric (TE) devices, low thermal conductivity is necessary to maintain a stable temperature gradient between the hot and cold sides of the module. One effective strategy to improve the figure of merit (zT) involves reducing the total thermal conductivity (K_{total}), particularly the lattice component. To this end, researchers have successfully employed nanoscale engineering to manipulate material structures and selectively lower lattice thermal conductivity without significantly degrading electrical conductivity. As illustrated in Fig., this is achieved by introducing a high density of grain boundaries and other phonon-scattering centers, which effectively disrupt phonon transport while having minimal impact on electron flow. This targeted reduction of lattice thermal conductivity through nanostructuring has recently emerged as a promising and practical approach for enhancing thermoelectric performance. (Figure 8) [6]

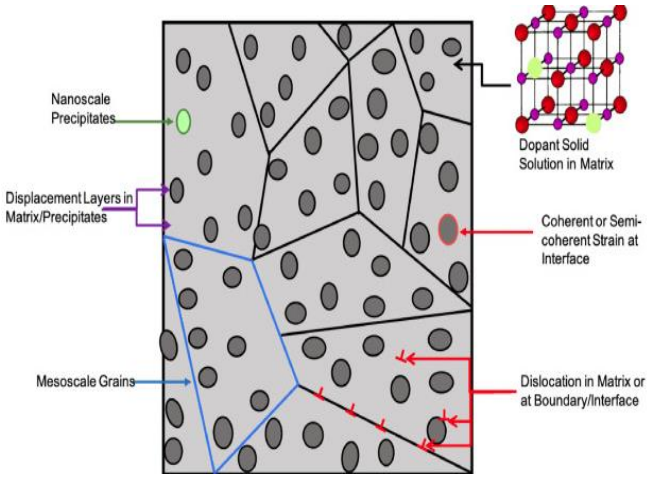

Figure 8 Nanotechnology

3. TEG Case Studies & Applications

Thermoelectricity, particularly in the form of thermoelectric generators (TEGs), holds significant potential for waste heat recovery and has been extensively explored in both experimental and theoretical studies. By integrating a thermoelectric generator into an energy system, a portion of the heat typically lost during production processes can be efficiently converted into usable electrical power. Among the various application areas, the transportation sector presents one of the most promising opportunities for thermoelectric waste heat recovery. In particular, recovering heat from engine

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exhaust gases has long posed a challenge, with limited viable solutions to date. The automotive industry has emerged as the most successful field for implementing TEGs, driven by intense competition for cleaner, more energy-efficient vehicles and supported by robust government regulations and incentives aimed at reducing emissions and improving fuel economy. [7-8]

3.1. Automotive Waste Heat Conversion to Electric Power

Given the wide temperature range associated with internal combustion engines, employing more than one type of thermoelectric material is essential to improve overall conversion efficiency. Segmented thermoelectric materials are particularly suitable for such applications, as they can effectively operate across a broad temperature spectrum. LaGrandeur et al. classified segmented TE materials into three categories based on temperature range: n- and p-type Bi_2Te_3 for low temperatures (<250 °C), p-type TAGS and n-type PbTe for medium temperatures (250–500 °C), and skutterudite-based materials (p-type $CeFe_3RuSb$ and n-type $CoSb_3$) for high temperatures (500–700 °C). To optimize performance, the authors proposed a novel TE module design using a flat thermoelectric cooler (TC) configuration that incorporates segmented materials between the heat source and the heat sink. This approach allows for customization in terms of material thickness, thermal expansion coefficients, and temperature region targeting, thereby enhancing module compatibility and efficiency. Additionally, cascaded thermoelectric generators (TEGs) have been explored for vehicle applications to overcome material incompatibility in segmented systems. For instance, Wilbrecht and Beitelschmidt developed a cascaded TEG system using Bi_2Te_3 (operating at 220 °C) and $Mg_2SiSn/MnSi$ (operating at 410 °C), capable of generating up to 2.5 kW of electrical power for railway vehicles. In the context of internal combustion engines, two primary locations for TEG integration have been identified in the literature: the cooling system (radiator) and the exhaust heat exchanger. The radiator-based TEG concept was first introduced by Crane et al. [93], who demonstrated through modeling that sufficient electrical power could be extracted from the engine's cooling system to support alternator functions. (Figure 9) [9]

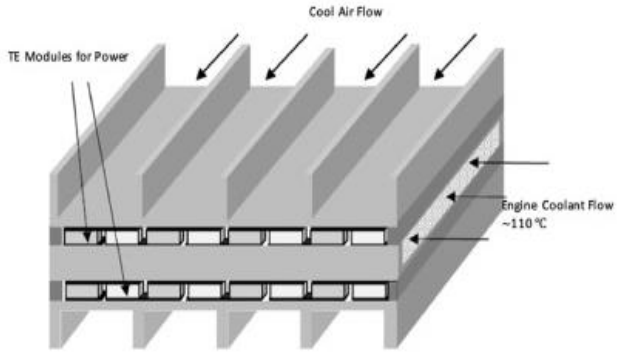

Figure 9 Automotive Waste Heat Conversion to Electric Power

3.2. Recovery of Waste Heat in Industries

Industry is a major source of waste heat, which is often a by-product of operational processes. While some of this heat is reused—for instance, in district heating networks or converted into electricity using steam turbines, Rankine, or Stirling engines—a significant portion is still lost to the atmosphere. To address this, several waste heat recovery projects using thermoelectric generators (TEGs) have been explored. A notable field test was conducted at a carburizing furnace, where residual gas containing CO, H_2, and N_2 was burned to generate 20 kW of heat, continuously supplying the hot side of a TEG system. This system, which included 16 Bi_2Te_3 modules and a heat exchanger, captured around 20% of the heat (approximately 4 kW), producing a peak electrical output of 214 W, reflecting an efficiency of 5% (excluding the energy consumed by the cooling system). In another study, Aranguren et al. performed laboratory and mathematical analyses on a TEG designed to recover waste heat from a combustion chamber. Their results, which accounted for the energy used by the cooling system and examined different heat exchangers, showed a theoretical output of 100 W/m². When scaled to a large industrial chimney on a ceramic tile furnace with a flue gas flow of 18,400 Nm³/h at 187 °C, the projected annual electrical generation was 136 MWh. The steel industry also produces significant amounts of radiant heat, particularly from molten metal, making it a

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suitable candidate for TEG applications. One company developed a 10 kW TEG system (measuring 4 m × 2 m) to capture radiant heat from continuous casting slabs, utilizing 896 Bi_2Te_3 modules (organized into 56 TEG units), which generated around 9 kW of electricity when slab temperatures reached 915 °C [98]. Similarly, cement production is a highly energy-intensive process. Luo et al. [99] investigated the feasibility of applying TEGs in Portland cement manufacturing, where 10–15% of the process energy is lost directly through the outer surface of the rotary kiln, representing a promising opportunity for thermoelectric recovery. (Figure 10) [10]

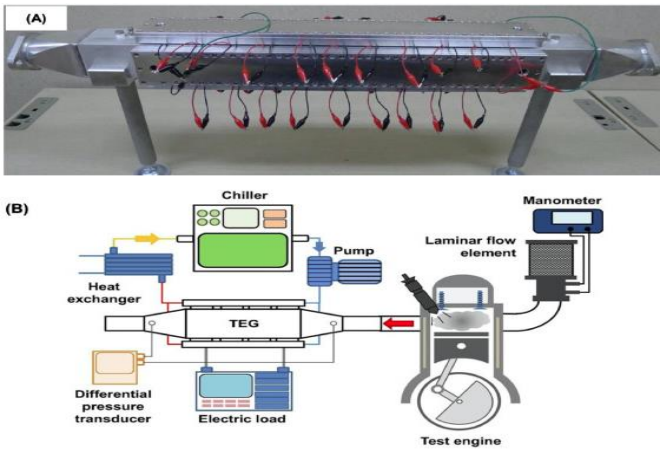

Figure 10 (A)The Used DCTEG when Assembled (B) Schematic Diagram of the Experimental Setup

Conclusion

In conclusion, this review presents a comprehensive analysis of thermoelectric generation (TEG) technology, beginning with a detailed explanation of its operating principles, configurations, materials, figure of merit (zT), and strategies for performance enhancement, including the use of optimized material arrangements and device substrate designs. A major challenge remains the development of advanced thermoelectric materials that exhibit high and balanced figures of merit and power factors for both n-type and p-type elements, as their performance symmetry is crucial for efficient module operation. However, material compatibility and mechanical rigidity continue to pose limitations for next-generation TEG designs, although flexible contacts offer a potential solution. Significant progress in materials science and nanotechnology has led to notable improvements in zT values, enhancing the feasibility of TEGs for various applications, particularly where heat source temperatures fluctuate or long thermal cycles occur. TEGs have proven effective for directly converting industrial waste heat into electrical energy, thereby reducing overall energy consumption. In both transportation and manufacturing sectors, where waste heat presents a major energy loss challenge, TEGs—despite their relatively low conversion efficiency—offer compact, low-maintenance solutions that can contribute modest but valuable gains in overall system efficiency and environmental impact reduction. Nevertheless, the high cost of commercially available TEG materials and their limited electrical output remain key barriers to widespread adoption. These challenges can be mitigated through intelligent system design and the continued development of low-cost thermoelectric materials and scalable automated manufacturing processes. Ultimately, the future of TEGs lies in their potential to enable affordable, mass-produced combined heat and power systems that offer both economic and environmental benefits.

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