THERMAL ENERGY HARVESTING

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Outline

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- Thermoelectric Generator
- Thermoelectric Materials
- Figure of Merit → parameter pengukuran
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Introduction to Thermal Energy Harvesting

- Energy harvesting is the process of extracting small amounts of energy from the ambient environment through various sources of energy such as light, radio frequency, thermal, and mechanical sources (Caliò et al., 2014).
- Examples of applications: IoT, wearable devices, and industrial sensors.

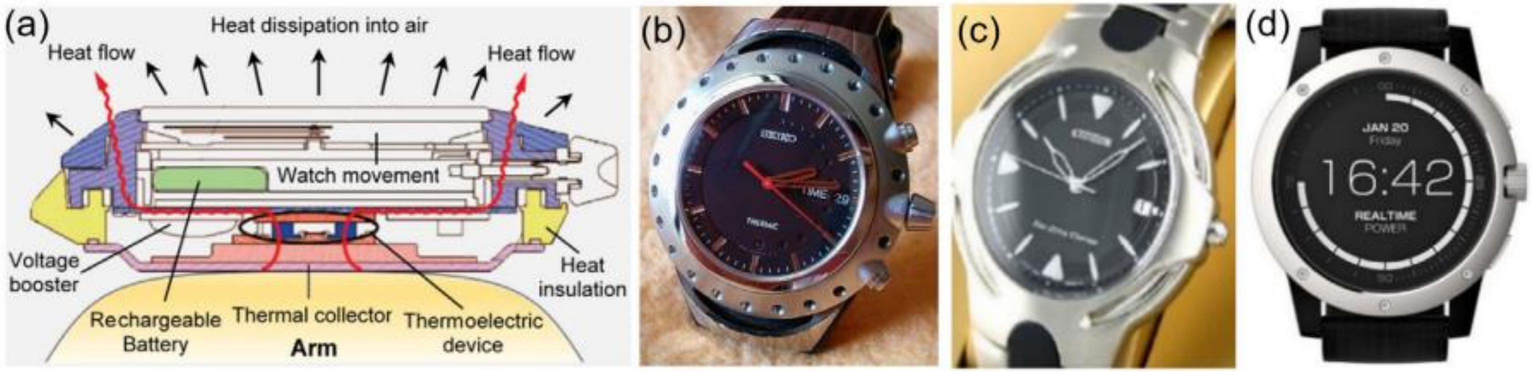


Fig. 3. (a) The schematic of a thermoelectric powered wristwatch concept. The back plate (hot side) acts as a thermal collector receiving heat from the wrist and directing it into the TEG. The watch case (cold front) radiates the heat acting as a heat sink on top of the TEG. (b) Seiko Thermic watch generated about 25 μW from body heat to power the watch [29]. (c) Citizen eco-drive watch generated 13.8 μW power [6]. (d) Commercialized body heat-powered smartwatch made by Matrix Industries [32]. All References with permission.

(Nozariasbmarz et al., 2020)

Thermal Energy Harvesting

otomotive → heat from exhaust syst :

- Thermal energy is a source of renewable energy that can be harvested from various natural and industrial waste heat sources (Yanagisawa et al., 2023).
- Thermoelectric generators can convert thermal gradients directly into electricity, making them a promising technology for energy harvesting.
- Temperature gradient is the key requirement for thermoelectric energy conversion. The higher the temperature difference, the greater the electrical potential generated.

Thermoelectric Effect Basics

Seebeck = $T \to V$
Peltier = $V \to T$

- Seebeck effects are the fundamental principle behind thermoelectric energy harvesting. Temperature differences between two dissimilar electrical conductors or semiconductors produce a voltage difference (Caliò et al., 2014).
- Peltier effects are the reverse of the Seebeck effect, where applying a voltage difference results in a temperature difference.
- Thomson effects describe the heating/cooling of a current-carrying conductor in the presence of a temperature gradient.
- The efficiency of thermoelectric energy conversion depends on the properties of the thermoelectric materials used, such as Seebeck coefficient, electrical conductivity, and thermal conductivity.

σ

k

Working Principle of TEGs

- Thermoelectric generators convert thermal energy directly into electrical energy through the Seebeck effect (Kiziroglou et al., 2013)(Rahman et al., 2014).
- The hot side of the device absorbs heat, which causes a flow of charge carriers (electrons or holes) to the cold side, generating a voltage.

Types of Thermoelectric Materials

most used commercially → low & room temp.

- Examples: Bismuth telluride, lead telluride, and organic materials.
- Bismuth telluride (Bi2Te3) and lead telluride are some of the most commonly used thermoelectric materials due to their high figure of merit at room temperature and below.
- Organic thermoelectric materials, such as conducting polymers, have also shown promise due to their low cost, flexibility, and potential for large-scale production.
- The choice of thermoelectric material depends on the specific application and the temperature range of operation.

Figure of Merit of TEGs

- To maximize the efficiency of a thermoelectric generator, materials with a high Seebeck coefficient, high electrical conductivity, and low thermal conductivity are preferred.
- This combination of properties is known as the figure of merit (non-dimensional parameter), which is a measure of the thermoelectric material's performance.

$$\underbrace{ZT}_{\text{no unit}} = \Big(\overbrace{\underbrace{S}_{\text{seebeck coef}}{}^2\sigma}^{\text{power factor}} / \underbrace{\kappa_e}_{\text{electrical}} + \underbrace{\kappa_L}_{\text{latice}}\Big)\, T \rightarrow \text{in Kelvin}$$

ZT → the higher the better

Figure of Merit of TEGs

$$ZT = \left(S^2\sigma/\kappa_e + \kappa_L\right) T$$

- T is the absolute temperature, S is the Seebeck coefficient, κ_e is electronic thermal conductivity, κ_L is lattice thermal conductivity, and σ is the electrical conductivity.
- Electronic thermal conductivity (κ_e) is the heat transport due to the movement of free electrons. Lattice thermal conductivity (κ_L) is heat transport due to lattice vibrations, also known as phonons.
- The figure of merit, ZT, is a dimensionless quantity that represents the efficiency of a thermoelectric material at a given temperature (Yazawa & Shakouri, 2011).
- Maximizing the figure of merit is crucial for improving the performance of thermoelectric generators.

Adjustments of Carrier Parameters to Improve *ZT*

- The fundamental challenge of high *ZT* thermoelectric material design stems from *S*, *σ*, and *κ*. Through the strong correlation of carrier concentration n, the energy level can generally be adjusted by controlling the doping.
- The Seebeck coefficient can be calculated by

$$S = \frac{8\pi^2 k_B^2}{3eh^2} m^* T \left(\frac{\pi}{3n}\right)^{2/3}$$

→ formula for hard metal

S σ

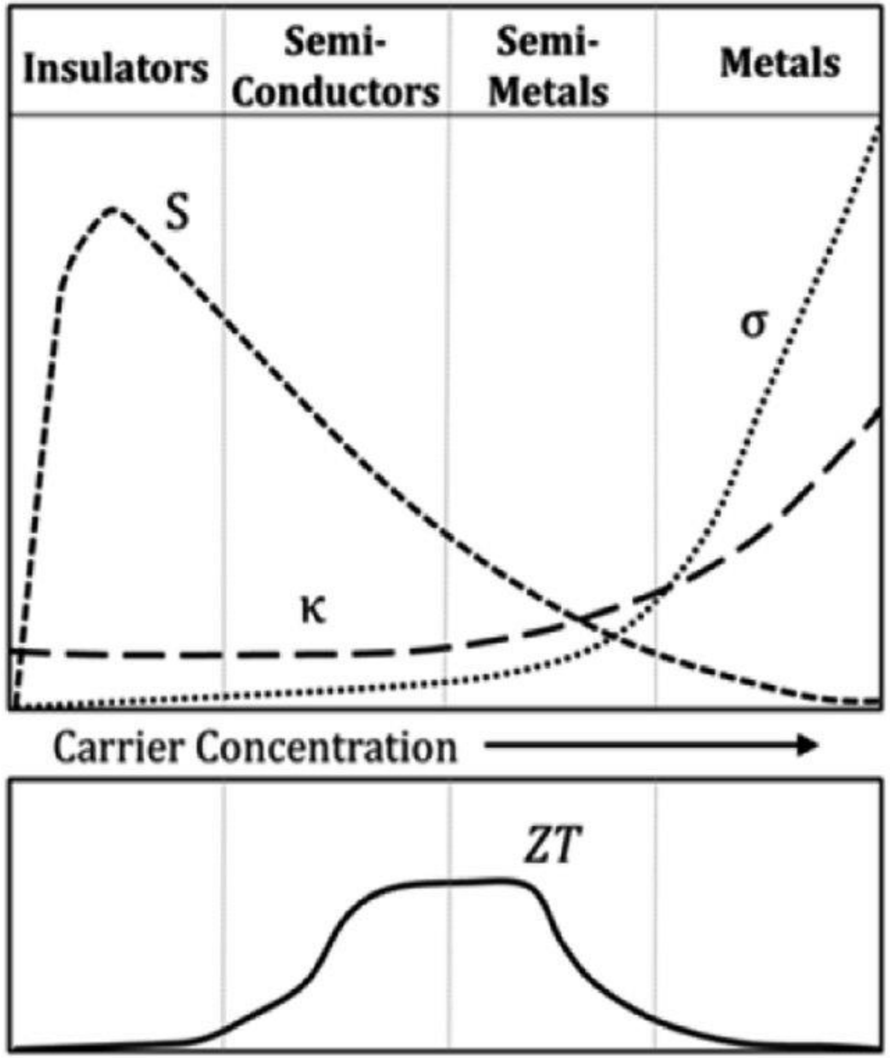
- k_B is Boltzmann's constant, m^* is the effective carrier mass, h is Planck's constant, and n is the carrier concentration.
- According to Wiedemann-Franz law $\kappa_e = L\sigma T$, where L is the Lorentz constant. It can be seen that the electronic thermal conductivity and electrical conductivity are proportional.

Adjustments of Carrier Parameters to Improve *ZT*

- The carrier concentration can be expressed as:

$$n_H = \frac{1}{eR_H} = A^{-1}\frac{N_v\left(2m_b^* k_B T\right)^{3/2}}{3\pi^2 h^3}F_0^{3/2}$$

- where N_v is the degree of degeneration, F_0 is the Fermi integral function, which is the reduced Planck constant.



Fermi Function and Energy

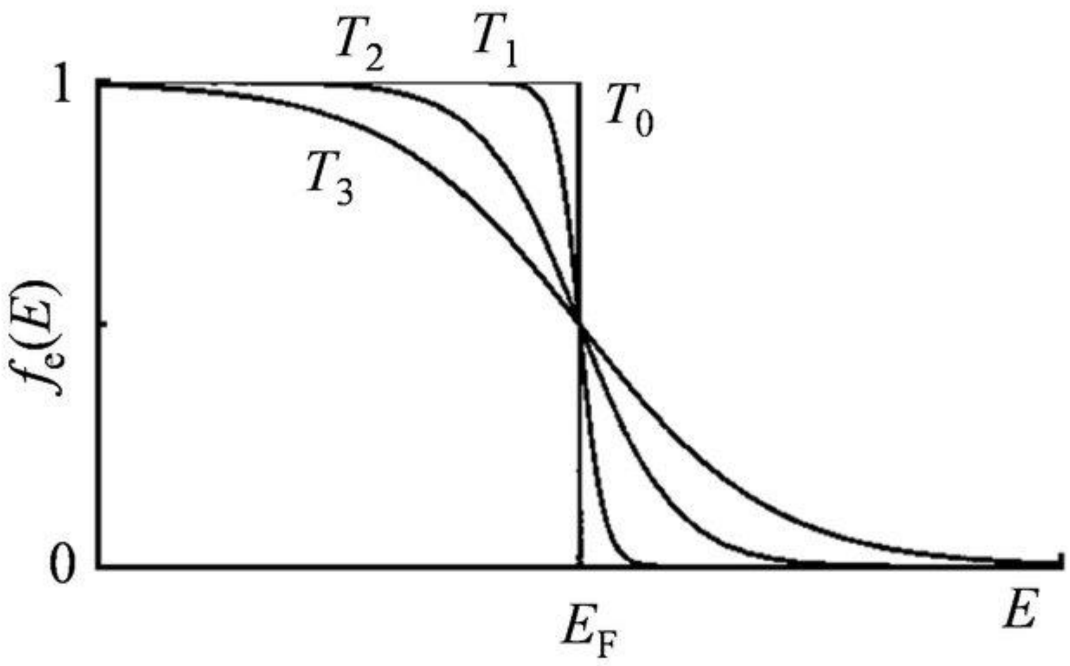
- The **Fermi-Dirac distribution function**, or simply the **Fermi function**, describes the probability that an energy state E is occupied by an electron at a given temperature T.

$$f(E) = \frac{1}{e^{(E-E_F)/k_BT} + 1}$$

where:

- $f(E)$ = probability of an energy state E being occupied by an electron.
- E_F = **Fermi energy**, the energy level at which the probability of occupancy is 50%.
- k_B = Boltzmann constant (8.617×10^{-5} eV/K).
- T = absolute temperature in Kelvin.

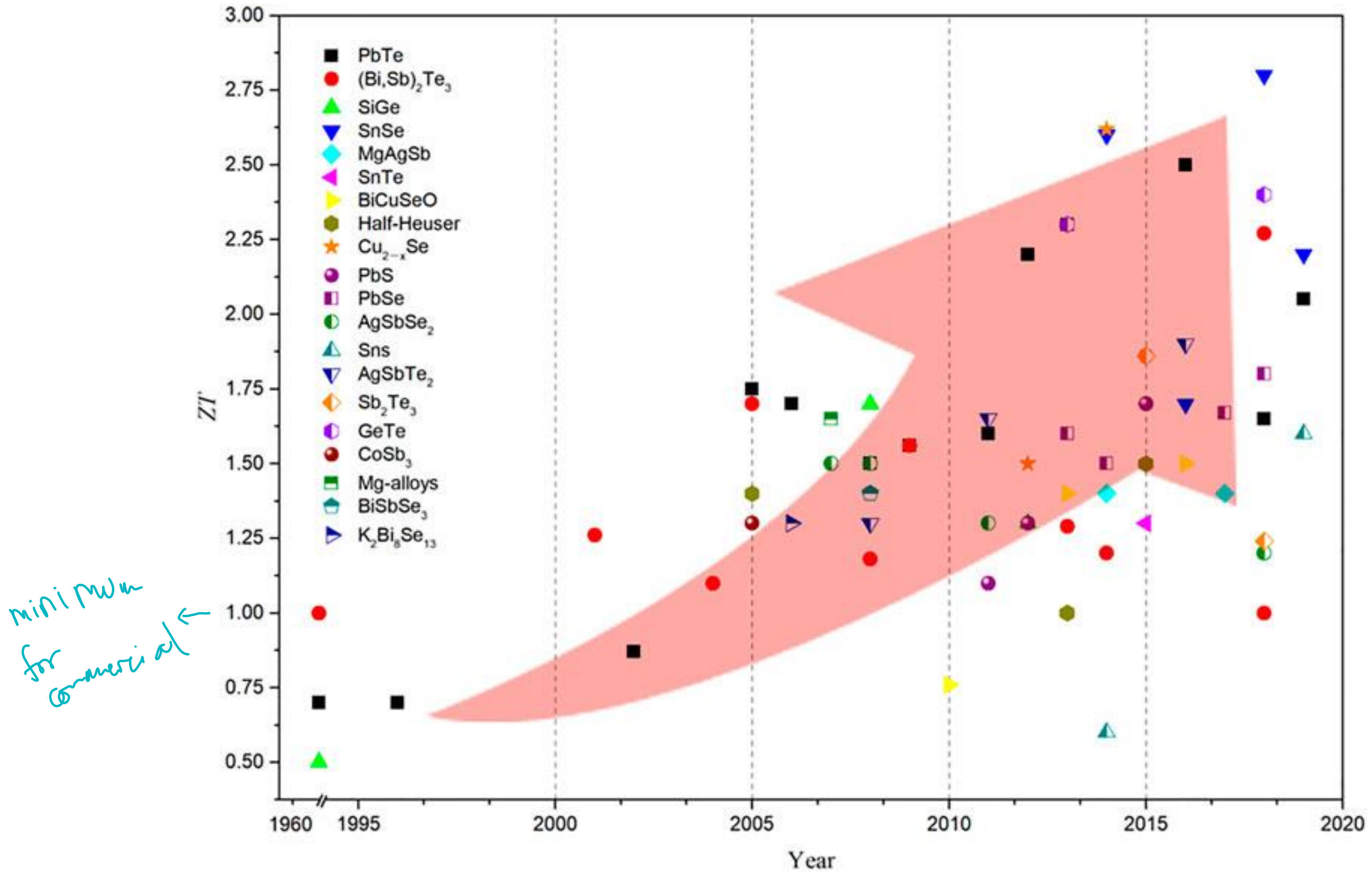
Fermi Function and Energy



- Fermi Energy (Fermi Energies, Solid Properties) is the level of energy when the fermi function is ½ or the probability of finding an electron is 50% at certain temperature.
- Fermi-Dirac distribution function at different temperatures: $T_3 > T_2 > T_1$ (and T_0 = 0 K). At the absolute zero temperature (T_0), the probability of an electron to have an energy below the Fermi energy E_F is equal to 1, while the probability to have higher energy is zero.

(PDF) METAL OXIDE PHOTOCATALYTIC NANOSTRUCTURES FABRICATED BY DYNAMIC SHADOWING GROWTH

Figure of Merit of Various Materials



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Design and Structure of TEGs

- A typical thermoelectric generator consists of an array of p-type and n-type thermoelectric elements connected electrically in series and thermally in parallel.
- Heat is absorbed at the hot side, where it flows through the thermoelectric elements, and rejected at the cold side, generating a voltage difference.
- The overall efficiency of a thermoelectric generator depends on the design of the hot and cold side heat exchangers, the thermal insulation, and the electrical interconnections.
- Recent advancements in module design and thermal management have improved the overall efficiency of thermoelectric generators.
- The design of the heat exchangers and thermal interfaces is crucial for maximizing the temperature difference across the thermoelectric module.

Efficiency and Limitations

(ideal)

1. The theoretical maximum efficiency of a thermoelectric generator is limited by the Carnot efficiency, which is a function of the temperature difference across the device.
2. However, the actual efficiency of a real-world thermoelectric generator is significantly lower due to various losses, such as thermal conduction, electrical resistance, and imperfect heat exchange.
3. Ongoing research aims to improve the figure of merit of thermoelectric materials and the overall system design to increase the efficiency of thermoelectric generators (Bell, 2008) (Yazawa & Shakouri, 2011).
4. Factors such as thermal and electrical losses, imperfect thermal contacts, and the inherent limitations of the thermoelectric materials themselves can limit the real-world efficiency of thermoelectric generators.

Efficiency of TEGs

- The energy conversion efficiency of TE material power generation equipment is defined as the output electric energy (*P*) divided by the provided thermal energy (*Q*)
- When *ZT* increases to a very large number, the part inside the bracket becomes closer to 1 and the material reaches the maximum theoretical efficiency, which is the Carnot efficiency.

$$\eta = \frac{P}{Q} = \frac{\Delta T}{T_H}\left(\frac{\sqrt{1+\overline{ZT}}-1}{\sqrt{1+\overline{ZT}}+\frac{T_C}{T_H}}\right)$$

Carnot eff.

eff TEG 10%

ratat

Advancements in TEG Technology

1. Advances in materials science have led to the development of nanostructured thermoelectric materials with improved figures of merit, such as superlattices and quantum dots.
2. Novel module designs, such as segmented or cascaded thermoelectric generators, can further improve the overall efficiency by optimizing the temperature distribution and material selection.
3. Flexible and wearable thermoelectric generators are also being explored for applications in body heat harvesting and self-powered wearable electronics (Yang et al., 2023).
4. Continued research and development in thermoelectric materials and system design will be crucial for increasing the efficiency and widespread adoption of thermoelectric generators.

Power Output of TEGs

$$P = \frac{\alpha^2 \Delta T^2}{(R+R_L)^2} R_L$$

- $P = I^2 R_L$
- $P = \left(\frac{V_{OC}}{R+R_L}\right)^2 \times R_L$
- $P = \left(\frac{\alpha \Delta T}{\frac{\rho L}{A}+R_L}\right)^2 \times R_L$

$$P = \frac{S^2 \Delta T^2}{(R+R_L)^2} R_L$$

internal resistance

$P_{max} \to R = R_L$

dominan

$$P_{max} = \frac{(S\Delta T)^2}{4R} = \frac{(S\Delta T)^2}{4\rho} \frac{A}{L}$$

$$Q_H = \alpha I T_H - \tfrac{1}{2} I^2 R + K \Delta T \quad (1)$$

$$P = I^2 R_L \quad (2)$$

$$I = V_{oc} / (R + R_L) \quad (3)$$

$$\Delta T = T_H - T_C \quad (4)$$

$$V_{oc} = \alpha \Delta T \quad (5)$$

$$R = \rho L / A \quad (6)$$

$$K = \kappa A / L \quad (7)$$

$$Q_H = P + Q_C \quad (8)$$

$$Z = \alpha^2 / \rho / \kappa \quad (9)$$

Q_H = heat input to the thermoelectric generator
α = Seebeck coefficient
κ = thermal conductivity
T_H = hot side temperature
P = output power
V_{OC} = open circuit voltage
L = length of pellet
Q_C = waste heat
Z = figure-of-merit
ρ = electrical resistivity
I = current
T_C = cold side temperature
R_L = load resistance
A = cross sectional area of pellet

Lau, P.G., & Buist, R. (1997). Calculation of thermoelectric power generation performance using finite element analysis. XVI ICT '97. Proceedings ICT'97. 16th International Conference on Thermoelectrics (Cat. No.97TH8291), 563-566.

Power Output of TEGs

- Because the TEG consists of multiple thermocouple each with *n* and *p* legs, the load voltage of the device (V_L) can be expressed as:

$$V_L = \frac{R_L V_{oc}}{R + R_L}$$

→ absolut

$$V_{oc} = n(|S_p| + |S_n|)\Delta T$$

The output power of the device (P_L) can be expressed as:

$$P_L = P = \frac{{V_L}^2}{R_L} = \frac{\left(\frac{R_L V_{oc}}{R + R_L}\right)^2}{R_L}$$

$$P_{max} = \frac{{V_{oc}}^2}{4R} = \frac{\left(n(|S_p| + |S_n|)\Delta T\right)^2}{4R}$$

Power Output of TEGs

$$R_n = \frac{\rho_n L}{A}$$

$$R_p = \frac{\rho_p L}{A}$$

jml. series → misal 50 renetan seri

$n = 50$

$$P_{max} = \frac{{V_{oc}}^2}{4R} = \frac{\left(n(|S_p| + |S_n|)\Delta T\right)^2}{4\left(\frac{\rho_p L}{A} + \frac{\rho_n L}{A}\right)}$$

Common Heat Sources

1. Thermoelectric generators can be used to harvest waste heat from various sources, such as industrial processes, vehicles, and power plants.
2. Solar thermal energy can also be used to create the necessary temperature gradient for thermoelectric power generation.
3. Waste heat from industrial processes, such as power plants, furnaces, and engines, can be captured and converted into electricity using thermoelectric generators.
4. Body heat from humans can also be used to power wearable and implantable electronic devices through thermoelectric energy harvesting.
5. The availability and quality of the heat source are crucial factors in determining the feasibility and performance of a thermoelectric generator.

Thermal Gradients in Practical Applications

1. In small-scale applications, such as wearable devices, the temperature difference between the human body and the ambient environment can be used to generate power (Yang et al., 2023).
2. Thermoelectric generators require a significant temperature difference, typically ranging from 20°C to 300°C, to generate meaningful amounts of electricity.
3. Large-scale applications, such as industrial waste heat recovery, can provide larger temperature gradients, which can lead to higher power output but also present additional challenges in heat exchange and system design.
4. The available temperature gradient is a critical factor in determining the performance and feasibility of a thermoelectric generator in a given application.

Thermal Management in Systems

1. Effective thermal management is crucial for maintaining the desired temperature gradient across the thermoelectric generator and optimizing its performance.
2. It includes designing efficient heat sinks, heat exchangers, and thermal insulation to minimize heat losses and maximize the temperature difference.
3. Innovative cooling solutions, such as heat pipes, liquid cooling, or forced convection, can be employed to enhance the heat transfer and maintain the required temperature gradient.

Challenges in Harvesting from Low-Grade Heat

1. Harvesting energy from low-grade heat, such as waste heat from industrial processes or the human body, presents significant challenges due to the small available temperature differences.
2. Strategies to address this challenge include using phase-change materials to create a larger temperature gradient, developing advanced thermoelectric materials with higher figures of merit, and implementing optimized system designs to minimize thermal and electrical losses.

IoT and Wearable Devices

Case studies on sensors and health monitors.

1. Thermoelectric generators can be used to power IoT sensors and wearable health monitoring devices by harvesting energy from the human body's heat.
2. This allows for the development of self-powered, battery-less devices that can continuously monitor vital signs without the need for regular battery replacements.
3. Examples include wearable sensors for activity tracking, heart rate monitoring, and temperature sensing, all powered by the body's thermal energy.

Industrial Applications

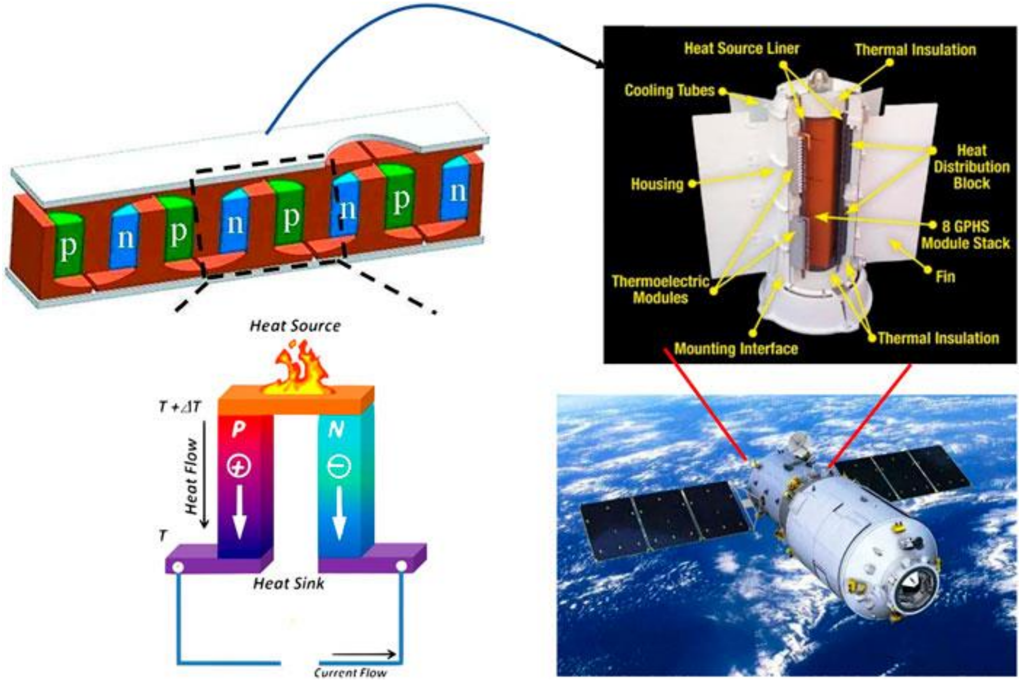
- Waste heat recovery in manufacturing.
- Thermoelectric generators can be used to recover waste heat from industrial processes, such as in power plants, factories, and vehicle engines.
- By converting this waste heat into electricity, thermoelectric generators can improve the overall energy efficiency of these industrial systems and reduce their environmental impact.
- Example applications include waste heat recovery from furnaces, boilers, and exhaust systems in industrial facilities and transportation.

Automotive Sector

- TEGs in exhaust systems and heat recovery.
- Thermoelectric generators are being explored for automotive applications, particularly in the recovery of waste heat from vehicle exhaust systems.
- By capturing the heat from the hot exhaust, thermoelectric generators can generate electricity to power various vehicle systems, such as lighting, infotainment, and battery charging.
- This improves the overall fuel efficiency of the vehicle and reduces its environmental impact by converting otherwise wasted heat into useful electrical energy.

Space Applications

- Radioisotope thermoelectric generators (RTGs).
- In space applications, thermoelectric generators can be used to power spacecraft and satellites by converting the heat generated by radioactive decay of isotopes, such as plutonium-238, into electrical energy.
- These Radioisotope Thermoelectric Generators are a reliable and long-lasting power source for deep space missions, where solar panels may not be feasible.
- Examples include the use of RTGs in the Mars Curiosity rover and various NASA spacecraft, providing a consistent power source for scientific instruments and communication systems.



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Emerging Research Areas

- Hybrid systems and integration with other energy sources.
- Researchers are exploring the integration of thermoelectric generators with other energy harvesting technologies, such as photovoltaics, piezoelectrics, and wind turbines, to create hybrid energy harvesting systems.
- This approach can help overcome the limitations of individual technologies and provide a more comprehensive solution for power generation in a wide range of applications.
- Additionally, there is ongoing research on improving the efficiency and cost-effectiveness of thermoelectric materials and modules, as well as developing innovative system designs and thermal management strategies.

Cost and Scalability

Estimate the power output of a thermoelectric generator given the temperature difference between the hot and cold sides, the geometric dimensions of the TEG, and the material properties of the thermoelectric elements.

Sample calculation: Consider a TEG with a temperature difference of 200°C, a cross-sectional area of 10 cm^2, and a length of 2 cm. Assume the thermoelectric material has a Seebeck coefficient of 200 µV/K, an electrical resistivity of 1 × 10^-5 Ω·m, and a thermal conductivity of 1.5 W/m·K. Calculate the power output of the TEG (Bell, 2008) (Yazawa & Shakouri, 2011).

Efficiency Calculation

Determine the conversion efficiency of a thermoelectric generator given the material's figure of merit and the temperature difference between the hot and cold sides.

Consider a thermoelectric material with a figure of merit, ZT, of 1.0. The hot-side temperature is 600 K, and the cold-side temperature is 300 K. Calculate the maximum theoretical efficiency of a thermoelectric generator using this material.

$$\eta = \frac{P}{Q} = \frac{\Delta T}{T_H}\left(\frac{\sqrt{1+\overline{ZT}}-1}{\sqrt{1+\overline{ZT}}+\frac{T_C}{T_H}}\right)$$

Application-Based Design

Design a small thermoelectric generator to power a wearable health monitoring device using the temperature difference between the human body and the ambient environment.

Example calculation: Assume the body temperature is 37°C and the ambient temperature is 20°C. Design a TEG with a footprint of 5 cm^2 and a thickness of 5 mm to generate sufficient power to run the wearable device.

Application-Based Design

1. To design the TEG, we need to consider the following factors: Temperature difference: $\Delta T = 37°C - 20°C = 17°C$
2. Thermoelectric material properties: Seebeck coefficient, electrical resistivity, thermal conductivity
3. Geometric dimensions: cross-sectional area and length of the thermoelectric elements.
4. Using the power output formula and typical thermoelectric material properties, we can calculate the expected power output for the given temperature difference and device size.

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