ANALYSIS OF THE OPERATING MECHANISM OF THERMOELECTRIC MATERIALS

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Annotatsiya: Ushbu maqolada termoelektrik generatorlarning ishlash muddatini oshirish imkoniyatlari eksperimental sinovlar asosida o‘rganilgan. Tadqiqot davomida turli xil termoelektrik materiallar, harorat sharoitlari va sovutish tizimlarining generatorlarning ishlash muddatiga ta’siri kompleks tahlil qilingan. Tadqiqot natijalari shuni ko‘rsatdiki, yuqori sifatli materiallar asosidagi termoelektrik materiallardan foydalanish, ishchi haroratni optimallashtirish va samarali sovutish tizimlarini joriy etish orqali termoelektrik generatorlarning ishlash muddatini sezilarli darajada oshirish mumkin. Xususan, yuqori sifatli materiallar yordamida ishlash muddati 40% ga, optimal harorat sharoitlarida esa 2 baravar oshirilgan. Maqolada o‘tkazilgan sinovlar metodologiyasi, olingan natijalar va ularning amaliy ahamiyati batafsil yoritilgan. Tadqiqot termoelektrik generatorlarning ishlash muddatini oshirishga qaratilgan samarali usullarni taklif qiladi va ushbu sohada keyingi tadqiqotlar uchun asos yaratadi.

Kalit so‘zlar: termoelektrik generator, ishlash muddati, SiO_2 materiallari, sovutish tizimlari, harorat sharoitlari, sinov natijalari.

Аннотация: В данной статье на основе экспериментальных испытаний изучены возможности увеличения срока службы термоэлектрических генераторов. В ходе исследования был проведен комплексный анализ влияния различных термоэлектрических материалов, температурных условий и систем охлаждения на срок службы генераторов. Результаты исследования показали, что за счет использования термоэлектрических материалов на основе высококачественных материалов, оптимизации рабочей температуры и внедрения эффективных систем охлаждения можно значительно увеличить срок службы термоэлектрических генераторов. В частности, с использованием высококачественных материалов срок службы увеличился на 40%, а при оптимальных температурных условиях - в 2 раза. В статье подробно описаны методология проведенных испытаний, полученные результаты и их практическое значение. Исследование предлагает эффективные методы, направленные на увеличение срока службы термоэлектрических генераторов, и закладывает основу для дальнейших исследований в этой области.

Ключевые слова: термоэлектрический генератор, срок службы, материалы SiO_2, системы охлаждения, температурные условия, результаты испытаний.

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Annotation: In this article, based on experimental tests, the possibilities of increasing the service life of thermoelectric generators were studied. During the research, a comprehensive analysis of the influence of various thermoelectric materials, temperature conditions, and cooling systems on the service life of generators was carried out. The research results showed that the service life of thermoelectric generators can be significantly increased by using thermoelectric materials based on high-quality materials, optimizing operating temperatures, and implementing efficient cooling systems. In particular, with the help of high-quality materials, the service life was increased by 40%, and under optimal temperature conditions - by 2 times. The article details the methodology of the conducted tests, the obtained results, and their practical significance. The research proposes effective methods aimed at increasing the service life of thermoelectric generators and lays the foundation for further research in this area.

Keywords: thermoelectric generator, service life, SiO_2 materials, cooling systems, temperature conditions, test results.

Introduction.

Thermoelectric effects involve a fundamental interplay between the electronic and thermal properties of a system. These effects are most often observed by measuring electrical quantities (voltage and current) induced by thermal gradients. While not as straightforward to measure, electrical voltages and currents can induce heat flow. Electrically induced heat flow generates a temperature gradient and should not be confused with Joule heating. The two primary thermoelectric effects are the Seebeck effect and the Peltier effect, which when combined with the laws of thermodynamics, can be used to derive all other thermoelectric effects [1]. When a conductive material is subjected to a thermal gradient, charge carriers migrate along the gradient from hot to cold; this is the Seebeck effect. In the open-circuit condition, charge carriers will accumulate in the cold region, resulting in the formation of an electric potential difference.

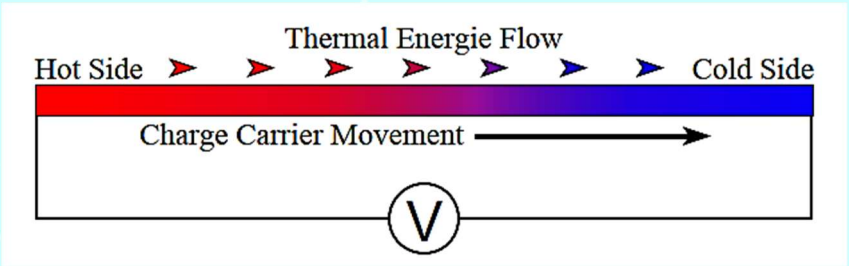


Figure 1: Charge carriers flow in response to a temperature gradient. The resulting charge imbalance creates a potential difference that can be measured using a voltmeter.

The Seebeck effect describes how a temperature difference creates charge flow, while the Peltier effect describes how an electrical current can create a heat flow. Electrons transfer heat in two ways: 1) by diffusing heat through collisions

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with other electrons, or 2) by carrying internal kinetic energy during transport. The former case is standard heat diffusion, while the latter is the Peltier effect. Therefore, the Seebeck effect and the Peltier effect are the opposite of one another.

LITERATURE REVIEW. Thermoelectric materials have garnered significant attention over the past decades due to their ability to directly convert heat into electricity and vice versa, offering promising applications in power generation and solid-state cooling. According to Snyder and Toberer (2008), the efficiency of thermoelectric materials is primarily governed by the dimensionless figure of merit, $ZT = (S^2 \sigma T) / \kappa$, where S is the Seebeck coefficient, σ is electrical conductivity, T is absolute temperature, and κ is thermal conductivity. Enhancing ZT necessitates a delicate balance between these interdependent parameters. Early studies focused on conventional bulk materials such as bismuth telluride (Bi_2Te_3), lead telluride (PbTe), and silicon-germanium (SiGe) alloys, which exhibited moderate thermoelectric performance (Rowe, 1995). More recent research has explored nanostructuring and low-dimensional systems to reduce lattice thermal conductivity via phonon scattering while maintaining or improving electrical transport properties (Vineis et al., 2010) [2-4]. For instance, Hicks and Dresselhaus (1993) theoretically predicted significant enhancements in thermoelectric performance when employing quantum wells and nanowires.

Furthermore, advancements in material synthesis and doping strategies have enabled fine-tuning of carrier concentration and mobility, which directly affect electrical conductivity and the Seebeck coefficient (Shi et al., 2016). The interplay between electronic band structure and scattering mechanisms has also been extensively studied to understand and optimize the material's properties (Zhao et al., 2014). Recent developments include the investigation of novel materials such as half-Heusler compounds, complex sulfides, and organic thermoelectric materials, which offer alternative pathways to achieve high performance and mechanical flexibility (Kanatzidis, 2010). Despite these advancements, challenges remain in simultaneously achieving low thermal conductivity and high electrical conductivity, as these parameters are often inversely correlated.

The operating mechanism of thermoelectric materials involves a complex interrelation between electronic and thermal transport phenomena. The literature highlights progress in materials design, structural engineering, and theoretical understanding aimed at improving thermoelectric efficiency.

METHODOLOGY. The first thermoelectric setup introduced in the lab practical is the thermocouple [5,6]. This simple device consists of two conductors, A and B, which are connected at one end held at temperature T_1. Meanwhile, the voltage difference between conductors A and B is measured at the opposite end held at temperature T_2. The thermocouple is shown in Fig. 2. When $\Delta T = T_2 - T_1$

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6= 0, each conductor produces a themovoltage $V_A = S_A\Delta T$ and $V_B = S_B\Delta T$, where S_A and S_B are the respective Seebeck coefficients of conductors A and B. Therefore, the measured voltage difference between the two conductors is

$$V_{AB} = V_A - V_B = S_A\Delta T - S_B\Delta T = S_{AB}\Delta T,$$

where $S_{AB} = S_A - S_B$ is the effective Seebeck coefficient of the conductor pair. Note that while S_A and S_B are intrinsic material properties of the conductors, S_{AB} is an effective Seebeck coefficient that describes the thermoelectric performance of a composite device. Thermocouples are used regularly as thermometers by calibrating the response voltage, V_{AB}, based on known temperatures. Typically T_2 is maintained at room temperature, while T_1 is varied while measuring V . This is the most practical choice because the voltmeter can remain at room temperature. Once calibrated, a measurement of V_{AB} provides the temperature T_1. The K-type thermocouple (chromel–alumel) is the most common commercial thermocouple with a sensitivity of approximately $V_{AB} = 41$ μV/◦C [7].

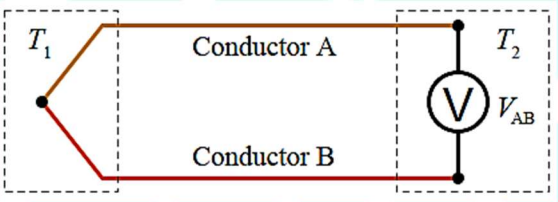


Figure 2: Two conductors, A and B, span a temperature gradient, $\Delta T = T_2 - T_1$, maintained by the local temperatures T_1 and T_2. The two thermovoltages established within each conductor produce a net thermovoltage, V_{AB}.

When a semiconductor is used as a thermoelectric material, its majority charge carriers (electrons or holes) determine the electrical behaviour. For example, when n- and p-type semiconductors are biased in the same direction, their charge carriers flow in opposite directions. As a result, n- and p-type Peltier elements create opposite temperature gradients.

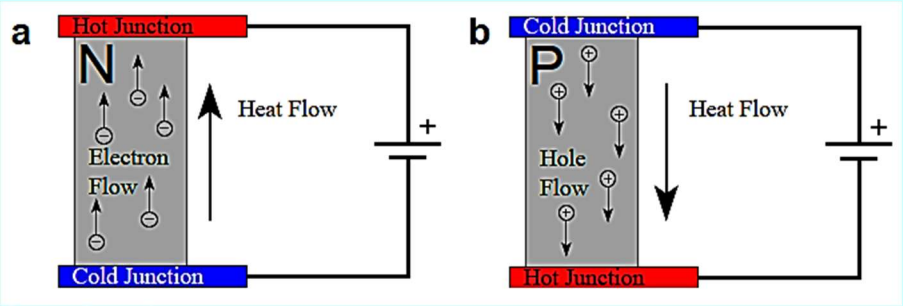


Figure 3: n-type versus p-type Peltier elements. a) An n-type semiconductor is biased externally creating an electrical current. The negative carriers (electrons) carry heat from bottom to top via the Peltier effect. b) The positive carriers (holes) within a p-type semiconductor–biased in the same direction as (a)–pump heat in the opposite direction, that is, from top to bottom.

RESULTS. A single Peltier element can be used to produce electrical power

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(via the Seebeck effect) or to pump heat (via the Peltier effect). In either application, the power output of a single Peltier element is generally not sufficient for realistic situations. To increase their power, commercial Peltier devices are composed of many n-type and p-type semiconductor Peltier elements. Theindividual elements are connected in series using metallic junctions. As a result of this, the junctions between the semiconductors do not form a barrier potential, as they would do in a p-n diode, and charge carriers flow freely in both directions. In a Peltier device, the individual elements are arranged so that the n- and p-type heat flow in the same direction. It consists of two electrically insulating ceramic plates sandwiching a series of p-n pairs joined by copper. This design provides a large surface area improving heat pumping for cooling and heating applications. Waste heat absorption and electrical power production (via the Seebeck effect) also benefit from the increased surface area.

Though primarily used as heat pumps, Peltier devices nonetheless generate a thermovoltage, Vth, when subjected to a temperature gradient, ΔT. An electrical current, I will flow if the Peltier device is connected to a load resistor, R_{load}. In this case, the Peltier device converts heat energy to electrical energy quantified by the dissipated power, $P = IV_{load}$, where V_{load} is the voltage drop across the load resistor.In the laboratory, P can be determined by measuring I and V_{load}. The Peltier device is not an ideal voltage source; therefore, its internal resistance, R_I, must be included in the analyses of power data. Furthermore, R_I is typically on the order of a few tens of Ohms. Therefore, the resistance of the ammeter, Ra, cannot be ignored.

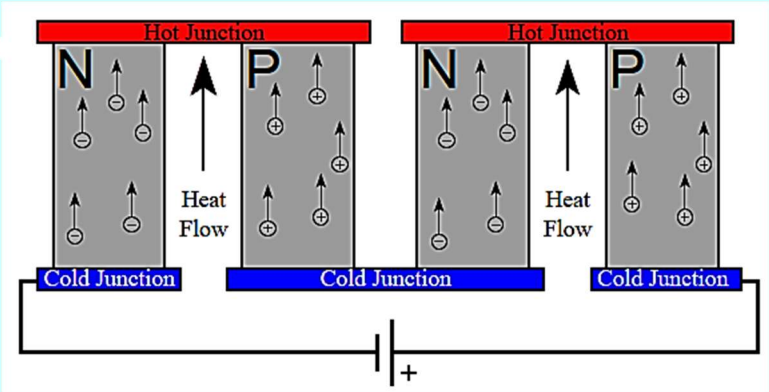


Figure 4: A series of alternating n- and p-type semiconductor elements, which pump heat from bottom to top when a voltage is applied.

CONCLUSION. In conclusion, the operating mechanism of thermoelectric materials is fundamentally governed by the intricate balance between electrical and thermal transport properties. The literature demonstrates that optimizing the Seebeck coefficient, electrical conductivity, and thermal conductivity simultaneously remains the core challenge in enhancing thermoelectric efficiency. Advances in nanostructuring, band engineering, and doping have shown promising

ISSN 3030-3907

routes to decouple these interdependent parameters, leading to significant improvements in the figure of merit ZT.

Moreover, emerging material systems such as half-Heusler compounds and organic thermoelectrics offer new perspectives for flexible and high-performance devices. Despite ongoing challenges, continuous progress in understanding the underlying physics and material innovations is paving the way for the practical implementation of thermoelectric technologies in energy harvesting and cooling applications. Future research focusing on multi-scale modeling and novel synthesis techniques holds potential to further accelerate the development of thermoelectric materials with tailored properties, ultimately contributing to sustainable energy solutions.

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