

Research on New Energy Recovery Technology based on Thermoelectric Effect

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Abstract: Thermoelectric energy recovery technology converts industrial waste heat into electricity through Seebeck effect, but it faces the dual bottlenecks of material performance (low ZT value) and system efficiency (large interface loss). This study proposes a material-device-system three-level collaborative optimization strategy: at the material level, defect engineering and band modulation are used to enhance carrier mobility and suppress phonon transport; at the device level, gradient bonding interface and flexible structure design are used to enhance mechanical stability and electrical output performance; at the system level, intelligent collaborative control and multi-scene integration scheme are used to achieve thermal-electrical dynamic matching. The research results provide efficient solutions for industrial waste heat recovery, wearable equipment energy supply and other scenarios, and promote the engineering application of thermoelectric technology.

Keywords: Thermoelectric Effect, New Energy, Recycle.

1. Introduction

The contradiction between the continuous growth of global energy demand and the waste of industrial waste heat has become increasingly prominent. The average annual waste heat emissions in the industrial field have exceeded 10 billion joules, but the recovery rate is generally lower than technically feasible threshold. Based on Seebeck effect, thermoelectric energy recovery technology realizes the direct solid-state conversion of heat energy to electric energy, which has the core advantages of no moving parts, maintenance-free and adapting to distributed heat sources, and shows important application potential in industrial waste heat utilization, wearable electronic energy supply and other fields.

At present, this technology is facing the dual bottlenecks of material performance and system efficiency. The dimensionless figure of merit (ZT) of commercial thermoelectric materials has been at a low level for a long time, which leads to the fact that the actual thermoelectric conversion efficiency is significantly lower than theoretical limit [1]. At the same time, there are some common problems in the engineering application of thermoelectric devices, such as insufficient utilization of temperature difference at the hot end, high interface thermal resistance, and prominent electrical contact loss, which seriously restrict their large-scale application. In recent years, new thermoelectric materials (such as liquid metal composites and nanostructured semiconductors) have made breakthroughs in improving ZT value and temperature adaptability through microstructure control and composite mechanism innovation, providing a new path for technological innovation.

This study focuses on breaking through the bottleneck of collaborative optimization of material-device-system: enhancing heat transfer efficiency and electrical matching accuracy by developing geometric topology optimization and dynamic thermal management strategies; Establish a multi-scenario system integration scheme to promote the practical process of this technology in the field of industrial energy saving and emission reduction and flexible electronic energy supply. The research aims to build a full-chain technology system covering basic theory to engineering application, and

provide scientific support for improving energy efficiency.

2. Basic Theory of Thermoelectric Effect Energy Recovery Technology

2.1. Physical Mechanism of Thermoelectric Conversion

The core physical mechanism of thermoelectric energy conversion is based on the Seebeck effect. When two different conductors or semiconductor materials form a closed circuit, if there is a temperature difference between their contact points (ΔT), an electromotive force will be generated in the loop and drive the current to form. The microscopic nature of this phenomenon originates from the directional diffusion of carriers under the action of temperature gradient: carriers at the high temperature end obtain higher kinetic energy due to thermal excitation, migrate and accumulate to the low temperature end, and form space charge separation and built-in electric field; When the carrier diffusion power and the electric field resistance reach a dynamic balance, a stable open-circuit voltage is established at both ends of the material. The Seebeck coefficient (S) quantitatively characterizes the potential difference per unit temperature difference, and its sign and magnitude depend on the Fermi level position of the material and the type of carriers (n-type is negative, p-type is positive).

In semiconductor materials, the Seebeck effect is particularly significant. The temperature gradient leads to the uneven distribution of carrier concentration, and the internal band structure of the material directly affects the effective mass and mobility of carriers. For example, the band anisotropy of a layered crystal structure can enhance the electrical conductivity and Seebeck coefficient of a particular crystal orientation. In addition, phonon-electron scattering is the key factor affecting the conversion efficiency: the interaction between lattice vibration and carriers will weaken the directional movement of carriers and increase the resistance loss; Material nanocrystallization can enhance phonon scattering, reduce lattice thermal conductivity, and indirectly optimize thermoelectric properties [2].

Thermodynamic boundary conditions must be satisfied in

the process of thermoelectric conversion. The maximum theoretical efficiency of the thermoelectric device is determined by the Carnot efficiency correction formula:

$$\eta_{\max} = \frac{T_h - T_c}{T_h} \cdot \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + T_c/T_h}$$

T_h and T_c are the temperatures of the heat source and the cold source respectively, and the dimensionless figure of merit (ZT) to comprehensively characterize the thermoelectric properties of the material ($ZT = S^2\sigma T/\kappa$). Ideal thermoelectric materials need to optimize high Seebeck coefficient (to increase voltage output), high conductivity (to reduce Joule loss) and low thermal conductivity (to maintain temperature difference), which are balanced by controlling carrier concentration and band structure.

2.2. Key Performance Parameters and Material System

The core performance index of thermoelectric materials is the dimensionless figure of merit (ZT) is determined by the Seebeck coefficient, electrical conductivity, and thermal conductivity. Promote the three parameters need to be optimized together, but there are inherent contradictions among them: although the increase of carrier concentration can enhance the conductivity, it will weaken the thermoelectric potential conversion ability; However, the structural design that suppresses the lattice heat conduction often intensifies the carrier scattering. Current studies have significantly improved the comprehensive properties of materials by controlling the effective mass of carriers through band engineering and constructing multi-scale scattering interfaces through phonon engineering.

The thermoelectric system near room temperature is represented by bismuth telluride materials, and the strong band degeneracy of its layered crystal structure can realize the synergistic optimization of electron transport and phonon barrier. In the intermediate temperature range, the Seebeck coefficient of lead telluride is enhanced by the valence band convergence effect, while the phonon transport symmetry of tin selenide is broken by the anharmonicity of chemical bonds. Silicon-germanium alloys and half-Heusler compounds for high temperature application scenarios suppress lattice heat conduction through solid solution atoms and nano-precipitates to maintain stable output in high temperature environment.

New material design presents a multi-dimensional innovation trend. The tin sulfide crystal activates a multi-band cooperative transport mechanism to break through the traditional trade-off limit of the Seebeck coefficient and the electrical conductivity; the flexible composite material realizes the ultra-low thermal conductivity by utilizing the phonon scattering effect of the organic-inorganic interface to meet the requirement of attaching the wearable equipment to the curved surface; Machine learning accelerates the screening of environmentally friendly components and promotes the industrialization of lead-free material systems [3]. These advances together point to the development direction of thermoelectric technology with high adaptability and low environmental load.

2.3. Basic Model of Thermoelectric Device

The basic structure of the thermoelectric device is formed by connecting an n-type semiconductor thermoelectric arm and a p-type semiconductor thermoelectric arm in series through a metal guide plate, and the ceramic substrate package provides electrical insulation and mechanical support. Its work is based on the two-way energy conversion between the Seebeck effect and the Peltier effect: the open-circuit voltage is generated by the carrier migration driven by the thermoelectric arm temperature difference in the Seebeck effect ($V = \alpha\Delta T$, and α is the Seebeck coefficient); The external electric field of the Peltier effect controls the carrier to absorb and release heat so as to realize the refrigeration and heating functions. This solid-state conversion mechanism gives the device the significant advantage of being noiseless and maintenance-free.

The power output of the thermoelectric generation system is restricted by the matching relationship between the internal resistance and the load resistance. The actual efficiency is limited by the intrinsic properties of the material and the interfacial contact losses, which degrade the overall performance by weakening the effective Seebeck coefficient and enhancing the thermal conductivity. Cascade design combines materials in different temperature zones, optimizes the transport path of carriers across temperature zones by using the principle of band matching, and significantly improves the conversion efficiency of wide temperature difference scenarios.

Thermoelectric refrigeration performance is measured in terms of coefficient of performance (COP) is the core of evaluation, and its theoretical limit is defined by the law of thermodynamics and the material figure of merit. Interfacial Joule heating and heat leakage effects lead to practical attenuation of COP . The pulse current drive strategy can suppress transient thermal imbalance, and the multi-stage refrigeration architecture can improve the temperature control accuracy through hierarchical heat flow management.

The multi-physical field behavior of the device needs to couple the governing equations of heat conduction, charge transport and thermal stress. Key challenges include Seebeck coefficient degradation due to contact resistance, mechanical fatigue due to thermal stress concentration, and Thomson heating under transient conditions. By optimizing the stress distribution of gradient pore structure and reducing the contact loss combined with interface engineering, the long-term operation reliability can be guaranteed synergistically.

3. Improvement Strategies of New Energy Recovery Technology Based on Thermoelectric Effect

3.1. Improvement of Material Performance

The core path to improve the performance of thermoelectric materials lies in the collaborative innovation of structural optimization design and energy band regulation strategy [4]. Through precise defect engineering, such as introducing trace metals to fill vacancy defects in tin selenide crystals, carrier mobility can be significantly optimized and phonon propagation can be suppressed. The composite magnetic oxide particles in the copper sulfide matrix can form a porous structure and a low-energy carrier scattering potential barrier, synchronously improve the Seebeck coefficient and reduce the thermal conductivity, and realize

the overall transition of thermoelectric properties. This kind of micro-control mechanism provides a new paradigm for breaking through the intrinsic performance limit of materials.

The innovation of flexible thermoelectric materials focuses on breakthroughs in mechanical and environmental adaptability. The organic-inorganic hybrid system induces the directional growth of crystals through molecular interface engineering, strengthens the carrier migration channel and optimizes the energy band structure of grain boundaries; Ionic gel materials achieve ultra-high ductility by means of molecular chain design, and their bionic micro-channel structure accelerates the directional transport of ions, which significantly enhances the thermoelectric response efficiency in wearing scenarios. Two-dimensional materials are further introduced to construct a heterointerface, and the band bending effect is used to selectively filter low-energy carriers, which can significantly inhibit heat conduction while maintaining high conductivity, and meet the dual requirements of flexibility and stability of curved surface equipment.

Composite and hybrid systems achieve performance breakthroughs through multi-scale interface collaboration. An atom-nano-micro three-level defect network is constructed in materials such as germanium telluride and that like, so that full-spectrum phonon scatter can be generated, and the lattice thermal conductivity is pressed to a very low level; Pseudo-nanostructures are designed in lead-tellurium based materials to control the carrier concentration distribution through the "dynamic trapping and releasing" mechanism of holes, and to solve the inherent contradiction between the electro-acoustic transport parameters [5]. This kind of multi-level structure synergy strategy can substantially improve the energy conversion efficiency at the device level, and provide new solutions for application scenarios such as waste heat recovery and micro-zone refrigeration.

3.2. Innovation of Device Structure

Technological breakthroughs in the field of interface engineering focus on gradient bonding structure and band matching optimization. By introducing a nano-scale transition layer between the polymer substrate and the metal electrode, an interface system with gradually changed chemical bonding strength is formed, and the interlayer peeling phenomenon caused by thermal stress is remarkably inhibited. The team of the Institute of Metals constructed a titanium/titanium-tungsten composite barrier layer between the flexible substrate and the thermoelectric film, which not only effectively reduced the interfacial contact resistance, but also greatly improved the electrical stability of the device under repeated bending conditions. Shanghai Silicate Institute innovatively designed the cross-sectional area ratio of liquid-like material devices, and optimized the carrier transport path by adjusting the cross-sectional area ratio of p/n-type thermoelectric arms, which not only maintained the low interface resistance, but also enhanced the high temperature service stability. This kind of interface structure design provides a new paradigm for the long-term reliable operation of thermoelectric devices in complex environments.

Flexible structure innovation focuses on solving the contradiction between surface fit and mechanical durability. The three-dimensional arch bridge device configuration developed by the Institute of Electrical Engineering breaks through the limitations of the traditional planar structure in the establishment of temperature difference and the

integration density of thermoelectric arms by using silicone support to construct the out-of-plane heat flow path. The chain segment dynamics of the ionic gel is regulated and controlled through molecular engineering, so that the material is endowed with ultra-high extensibility, and a biomimetic honeycomb-shaped ion channel is constructed in the gel network to accelerate the directional migration of carriers. The one-dimensional nanowire/one-dimensional fib dimension matching strategy is further adopted, so that that stress of the composite material is uniformly distributed when the composite material is microscopically bent, and the conductivity and the mechanical flexibility are synchronously optimized by combining the interface energy band engineer of the conductive polymer and the carbon nanotube. This multi-scale flexible design successfully promotes wearable devices to maintain stable energy output under dynamic deformation.

3.3. System Integration and Optimization

The core of thermal management optimization is to construct a gradient heat flow distribution structure and match the energy band characteristics of materials in different temperature zones through the combination of segmented thermoelectric arms to optimize the carrier transport path. The nanocarbon-based thermal diffusion layer and the microporous thermal insulation medium have synergistic effect to significantly improve the utilization rate of temperature difference. In industrial waste heat scenarios, this kind of design can break through the bottleneck of uneven heat flow distribution and achieve efficient capture of low-grade heat energy.

The innovation of electrical topology focuses on the impedance dynamic matching and interface electrical transport enhancement. The series-parallel hybrid architecture reduces the Joule loss by reconstructing the internal resistance network, and the liquid metal filling technology forms an adaptive conductive path at the micro-gap interface to simultaneously improve conductivity and mechanical stability. In the automobile exhaust recovery system, the design realizes no auxiliary power output and enhances the self-sustaining ability of mobile energy.

Intelligent collaborative control relies on multi-parameter feedback mechanism, embedded sensor network to collect temperature field distribution in real time, combined with machine learning algorithm to predict heat flow fluctuation, and dynamically adjust cooling medium flow and load impedance matching. PCMs are coupled to a thermoelectric cooling module to buffer external thermal disturbances through latent heat absorption-release, maintain the temperature stability of the cold end, and ensure the system robustness under variable conditions.

4. Conclusion

This paper systematically demonstrates the multi-level optimization path of thermoelectric energy recovery technology. The performance of the material is improved, and the coordinated optimization of carrier-phonon transport is realized through microstructure control and energy band engineering; the device structure innovation relies on gradient interface and flexible design to enhance mechanical stability; System integration achieves efficient energy capture through heat flow distribution, electrical matching, and intelligent control. These breakthroughs have significantly improved the applicability of thermoelectric technology in industrial waste

heat utilization, mobile electronic energy supply and other scenarios. In the future, it is necessary to further overcome the bottleneck of material performance in the low temperature zone, develop an environment-friendly lead-free system, optimize the robustness of the system through a multi-physical field coupling model, and finally build a distributed energy recovery network covering the whole temperature zone.

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