Thermoelectric coolers: Systematic Analysis on Principle, Use and Limitations

Guanchen Zhou

XinChang High school, ShaoXing, 312500, China
ZGC18767542704@outlook.com

Abstract. Thermoelectric coolers (TECs), operating through the Peltier effect, are a solid-state means of temperature control with no moving parts, mechanical vibrations, or refrigerant gas. In this paper perform systematic analysis of TEC technology beginning from its historical evolution and basic operational principles. Application areas of importance revealed by the present analysis include the thermal stabilization of optoelectronic devices with minimal noise, fast response and precise temperature control. A systematic comparison with the conventional vapour-compression refrigeration highlights the competitive strengths of the TECs in specific application scenarios, however, yet recognizes the disadvantages of energy consumption, through typically lower coefficient of performance (COP) than CCs, and relative expense in materials and cooling mechanisms. As the goals are stated above, we review the recent advances for high figure of merit (ZT) thermoelectric materials, module-level structure optimization, and system-level integration in this regard. The conclusion is that TECs reside in a complementary role to conventional cooling technologies with high potential to extend to more applications by incorporating superior materials performance and thermal management systems in the future.

Keywords: Thermoelectric cooler; Peltier effect; Solid-state refrigeration; COP; Thermal management

1 Introduction

With the acceleration of the progress of science and technology, accurate and continuous temperature control technology has not only promoted the development of various advanced technologies but also widely exist in our daily life. However, today even the traditional vapor-compression refrigeration is matured and efficient, it has inherent drawbacks, like high working noise, dependency on refrigerants, difficulty of miniaturization, and regular maintenance, making it not suitable for special scenarios in satisfying the requirements [1]. In this context, a solid-state cooling technique, TEC which realizes the converting of electrical energy to thermal energy by exploiting the thermoelectric effect, has been developed and stand out from others owing to specific merits.

In this article, it presents the development history of TECs from the initial finding of the Peltier effect to the today's solid-state cooling, and describes basic working

S. Zhang (ed.), *Proceedings of the 2025 International Conference on Electronics, Electrical and Grid Technology (ICEEGT 2025)*, Advances in Engineering Research 292,
https://doi.org/10.2991/978-94-6463-986-5_91

mechanisms of TECs by focusing on material/semiconductors and heat pumping processes. Additionally, this paper broadened the analysis to a benchmark comparison of TE coolers with common refrigeration systems, where exceptional benefits in terms of smaller size, lower noise level, and enhanced ability to regulate temperature precisely can be exploited, at the expense of the energy performance and price. Moreover, the article discusses the long-standing challenges like relatively small COP and issues from the material points of view, as well as promising options such as design of high ZT materials, innovative system integration and better design of thermal management. To provide this comprehensive view, we strive in this article to link the historical, conceptual, applied, and critical perspective of TEC technology, giving a guidance to potential future applications in small and large-scale systems.

2 Analysis of Theoretical Foundations

2.1 Development History

Thermoelectric cooling chips, composed of semiconductor materials, emerged as a cooling device around 1960. However, their theoretical foundation—the Peltier effect—dates back to the 19th century.

In 1821, German physicist Thomas Seebeck discovered the Seebeck effect, which states that an electromotive force (voltage) is generated in a circuit composed of two different conductors when a temperature difference exists between them. This effect laid the physical foundation for thermoelectric power generation [2].

In 1834, French watchmaker and physicist Jean Peltier discovered the reverse phenomenon—the Peltier effect: when an electric current flows through the junction of two different conductors, the junction either absorbs or releases heat.

However, for nearly a century thereafter, due to the extremely weak Peltier effect observed in metallic materials, this discovery remained at the level of laboratory phenomenon without leading to any practical applications.

Until the mid-twentieth century, however, rapid evolution in semiconductor materials made it finally possible to utilize the Peltier effect, because semiconductors can be doped to obtain both P-type and N-type which have high Seebeck coefficients and electrical conductivity but still lower thermal conductivity compared with metals, thus successful commercial fabrication of high-performance thermoelectric conversion devices became achievable.

In the 1950s, the research team led by Academician A.F. Ioffe of the Soviet Academy of Sciences made groundbreaking contributions to semiconductor thermoelectric theory, proposing the "ZT value" to evaluate the performance of thermoelectric materials [3].

With the maturation of high-performance thermoelectric materials such as Bismuth Telluride (Bi_2Te_3) and advances in processing techniques, the first commercially viable thermoelectric cooling module was introduced in the 1960s. Since then, TEC technology transitioned from theory to practical application.

2.2 Structure and Working Principle

As a modern device to fabricate the semiconductor cooler, the modern Peltier effect was based on the semiconductor material, and the common Peltier-effect semiconductor cooler module, the structure from the top to the bottom is ceramic substrates, electric-conducting electrodes (copper or copper alloys), and connected series arranged P/N-type semiconductor thermocouples. Ceramic plate surfaces with Al2O3 or AlN are divided into the upper and lower layers of aluminum oxide Al2O3 or AlN in electrical insulation, thermal conduction, and mechanical support. The conductive electrodes are drawn on the ceramics substrates to make the electrical connection. Multiple P-type and N-type semiconductor particles are chained to each other with the conducting electrodes, to make up the entire series circuit [4]. Semiconductor cooler structure is shown in Fig.1.

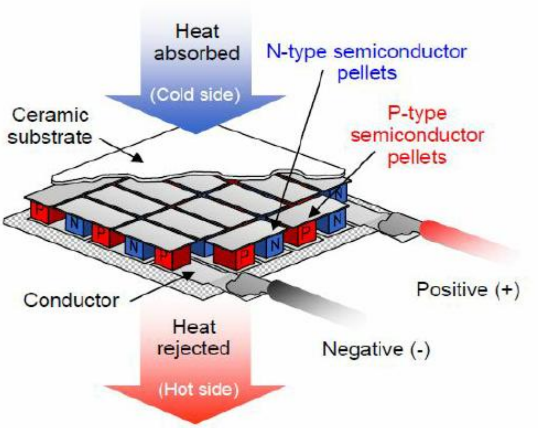

Fig. 1 Semiconductor cooler structure [4]

The so-called Peltier effect refers to the phenomenon wherein, when a direct current passes through a circuit composed of two different semiconductor materials, one end absorbs heat while the other releases heat. Heavily doped N-type and P-type bismuth telluride (Bi_2Te_3) are primarily used as the semiconductor materials in TECs. The bismuth telluride elements are electrically connected in series and thermally in parallel. A TEC comprises several P-type and N-type pairs (groups), which are connected together via electrodes and sandwiched between two ceramic plates. The ceramic plates on each side of the TEC assembly prevent short circuits in the laser diode caused by the TEC circuit.

Controlled temperature of a TEC can go up to 30°C-40°C. Current flowing through the TEC will cause heat to be moved from the hot side to the cold side. Thus, making the side where the heated element faces have a “hot” side, while a "cold" side for the other side. This forms a heating and cooling principle in TECs. In addition to whether the cooling or heating process occurs, what rate the cooling or heating is performed depends on the direction and amount of current that is flowing through the TEC [5].

In practical applications, TECs are typically mounted between a heat sink and the device housing. The cold side is in contact with the laser diode to provide cooling, while the hot side is attached to the heat sink to dissipate heat to the external environment—this represents the most common configuration. In applications requiring high stability of the laser operating temperature, bidirectional temperature control is generally employed: the TEC cools the laser diode at room and high temperatures, while it provides heating in low-temperature environments. When the direction of the current is reversed, the original cold and hot sides of the semiconductor cooler switch roles. Consequently, the side adjacent to the laser diode becomes the hot side, thereby heating the laser diode [6].

3 Applications and Comparative Analysis

3.1 Typical Application Scenarios

TECs are suitable for fields where conventional refrigeration systems cannot meet the requirements.

Electronic Device Cooling. To address the issue with increasing junction temperature from base station power amplifier in 5G communications, an innovative 40 mm $\times$ 40 mm TEC design is integrated on top of the GaN Chip of the base station power amplifier. Together with heat pipe cooling block, it enables 22-degree decrease of chip junction temperature at the thermal load of 80W than the standard air-cooling method in a base station, enhancing the system reliability with 30%. Besides, a nanometer scale hydrophobic surface coating is used for minimizing the condensation corrosion in the contact surface.

Multiple TECs are working in parallel in the industrial laser cooler and each TEC is provided with independent overcurrent protection circuit. When temperature gap of one TEC lower than the setting value about 80%, the redundant modules can be automatically switched on, achieving wavelength stability of laser system even under the high temperature of 45°C. The fluctuation of beam quality M^2 factor is within ±0.02 [7].

Biomedical and Analytical Instruments. TECs have been a key enabling technology for precise and fast temperature cycling, or continuous sample storage at low temperatures of PCR instruments, DNA sequencers, or small-scale refrigerators used as portable biochemical analyzers. The reversibility of TECs via the change in direction of the electrical current enables almost instantaneous switching between heating and cooling modes, thus the full cycles in thermal timescales much shorter than what typical compressor-based heat pumps can provide. The additional benefits of the solid-state operation leading to low vibration and low electrical noise eliminate another constraint to sensitive biochemical processes. In medical refrigeration and in portable analyzers, TECs are able to offer stable low temperature environments without refrigerant gases, they are therefore eco-friendly and usable in point of care diagnostics. Due to their small dimensions, they are suitable for miniaturization of the diagnostic devices without loss of thermal performance. Because of the fast responsivity, the fine temperature control, and the reliable operation, TEC is a precious component of many current-day biomedical instrumentation where temperature control has a direct implication on the result of the diagnosis [8].

Human Body Cooling Systems. A high performance 21 W personal cooling system on the base of TEC technology has been introduced. The system creatively designs the high-density copper fin heat exchanger on the hot side to enhance the cooling performance and the integrated aluminum fin liquid cooling module on the cold side to enlarge heat absorbing ability. The significant contribution is the physical isolation between the TEC hot and cold sides which not only reduce significantly the thermal short circuit losses with good structure integrity and stability. Our light 160-grams core module realizes a cooling coefficient of performance (COP) of 0.8 and continuous working for 4 hours on one battery charge, suitable for long term personal application.

The proposed high-level solution can utilize the cooled liquid as the refrigeration fluid. The cooled liquid is pumped out from the refrigeration unit and can flow out as a closed loop to transfer the heat energy to a dedicated liquid cooled undershirt so that the personal body temperature can be self-regulated. A self-sealing quick-link coupling is incorporated between the refrigeration unit and undershirt which holds the unit with a tight secure fit to improve user-friendliness as well as increase the safety of the cooling system. This novel concept not just allows for immediate possible use, but opens up a very solid technical base for a variety of cooling scenarios from medical treatment and clothing for industry workers to outdoor activities and sport and performance optimization [9].

3.2 Comparison with Traditional Compression Refrigeration

TECs and compression refrigeration systems exhibit a complementary rather than competitive relationship. Compression refrigeration is suitable for macro-scale applications requiring high energy efficiency and large cooling capacities.

In contrast, TECs dominate specialized fields demanding precise temperature control, miniaturization, high reliability, and silent operation. Their value lies not in energy efficiency but in their irreplaceable functional characteristics.

4 Challenges and optimization

4.1 Challenges

Although they have obvious advantages, the thermoelectric cooling technology must solve the key problems existing internally for a broader application range, especially in the mass large-capacity refrigeration field.

The biggest problem of thermoelectric cooling technology is that the cooling efficiency (COP value) is relatively poor. Now the widely used bismuth telluride materials in large commercial TEC are limited to very small room temperature ZT of about 1.0, and the theoretical maximum COP can only be several times smaller than that of compression system. In addition, the electric power used by the TEC is several times that used by compression type for the same cooling, and the waste heat is also larger, so that the heat dissipation amount should be several times the size and cost of compression system [10].

Meanwhile, the cost should not be ignored. The high-performance thermoelectric materials contain rare elements such as bismuth and tellurium, and the complicated preparation (such as zone melting) make the material cost is very high. What's more, in order to dissipate the heat generated by the system, the thermoelectric system generally uses high performance heat sinks (or liquid cooling), which will cause the total volume and cost of the system to increase.

4.2 Future optimization

In order to solve these problems, industry and research are exploring 3 levels of optimization.

Material Innovation: Establishment of material research priorities: Considering a variety of new, higher performance bulk materials including tin selenide (SnSe), cobaltite’s and skutterudites; and further understand lowdimensional nanostructured materials, hybrid two dimensional semiconductors and topological insulators. The materials community is trying to solve (i) metal and semiconductor thin films, superlattices, quantum dots, nanowires etc., to drastically reduce lattice thermal conductivity via phonon boundary scattering in order to enhance ZT value; (ii) organic materials, in terms of flexibility and bio-compatible so as to offer novel alternatives for localization of heating in wearable electronic devices [11].

Structural Design and System Integration Optimization: At the device level, the segmented design is adopted, and the thermoelectric materials used in the section which can work in an appropriate temperature range are as much as possible, so as to get the optimal average ZT value at the whole temperature difference. And at the system level, the optimization of heat dissipation efficiency of hot-end. By using some high-efficiency coolants, the temperature of hot-end will be reduced effectively, so that the overall performance of TECs will be improved. Effective circuit design and control strategy also brings the better energy efficiency for specific working conditions.

Process and Cost control: Another approach to develop new idea of material preparation and process to reduce cost, improve material utilization and even achieve more complex device structure to promote TECs entry into other larger market.

5 Conclusion

In summary, TECs are a solid-state heat pump technology based on the Peltier effect. Compression refrigeration system and TECs have a clear complementary coexistence relationship, and each of them will occupy the applicable range.

At present, low energy conversion efficiency and high cost are still the main limiting factors for TECs to expand applications into high-power and universal ones. Its future development will largely depend on the revolutionary advance in thermoelectric materials. TECs will continue to develop in the future with the development of new materials, new structures, and new system integration schemes, which will further improve the performance of TECs. In addition, the process and cost will also be further improved, and TECs will explore the market.

References

1. Lloveras, P., Tamarit, J.L.: Advances and obstacles in pressure-driven solid-state cooling: A review of barocaloric materials. MRS Energy & Sustainability 8(1), 3–15 (2021).
2. Li, C., Luo, Y., Li, W., et al.: The on-chip thermoelectric cooler: advances, applications and challenges. Chip 3(2), 100096 (2024).
3. Nimmagadda, L.A., Mahmud, R., Sinha, S.: Materials and devices for on-chip and off-chip peltier cooling: A review. IEEE Transactions on Components, Packaging and Manufacturing Technology 11(8), 1267–1281 (2021).
4. Górecki, K., Posobkiewicz, K.: Cooling systems of power semiconductor devices—A review. Energies 15(13), 4566 (2022).
5. Chen, W.Y., Shi, X.L., Zou, J., et al.: Thermoelectric coolers: progress, challenges, and opportunities. Small Methods 6(2), 2101235 (2022).
6. Liu, M., Coppola, A., Alvi, M., et al.: Comprehensive review and state of development of double-sided cooled package technology for automotive power modules. IEEE Open Journal of Power Electronics 3, 271–289 (2022).
7. Joshi, S.N., Zhou, F., Liu, Y., et al.: A review of select patented technologies for cooling of high heat flux power semiconductor devices. IEEE Transactions on Power Electronics 38(6), 6790–6794 (2023).
8. Kulkarni, M.B., Goel, S.: Recent advancements in integrated microthermofluidic systems for biochemical and biomedical applications – a review. Sensors and Actuators A: Physical 341, 113590 (2022).
9. Wenfang, S., Xinze, X., Yaqi, L., et al.: Investigation on a new semiconductor cooling garment for reducing heat stress of outdoor workers performing moderate activities in a hot and humid environment. Energy and Buildings 312, 114174 (2024).
10. Yan, Y., Zheng, Y., Sun, H., et al.: Review of issues and solutions in high-power semiconductor laser packaging technology. Frontiers in Physics 9, 669591 (2021).
11. Chang, K.H., Tsai, C.C., Wang, C.H., et al.: Optimizing the energy efficiency of chiller systems in the semiconductor industry through big data analytics and an empirical study. Journal of Manufacturing Systems 60, 652–661 (2021).