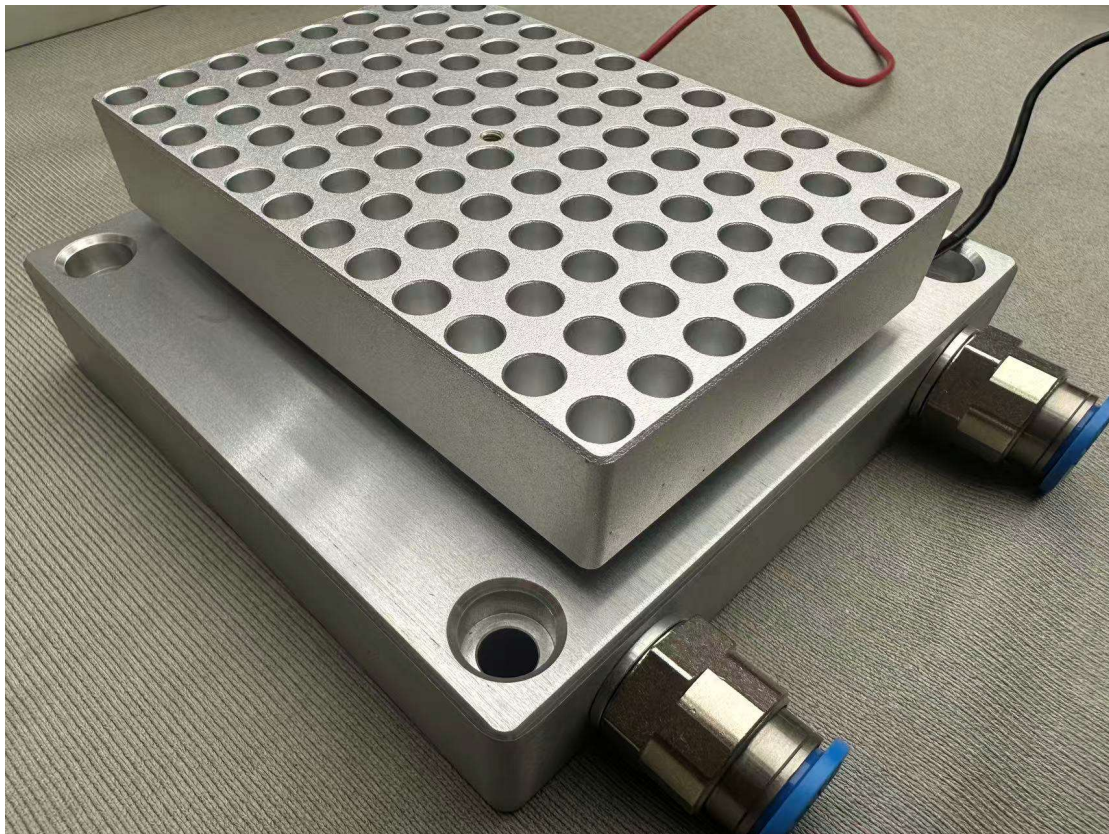


Thermal Improvement of Thermoelectric Coolers in Extreme High-Temperature Environments: High-Temperature Resistant Heat Dissipation Structure Design



1. Abstract

High temperature Thermoelectric Cooler cooling has always been a critical technical challenge for semiconductor refrigeration equipment deployed in extreme conditions such as outdoor exposure, high-temperature workshops, and enclosed cabinets. Traditional Thermoelectric Cooler systems designed for room-temperature

environments suffer from severe cooling efficiency decline, uncontrolled hot-end heat accumulation, and accelerated thermal fatigue aging when operating long-term above 50°C. Based on years of field commissioning, mass production experience, and repeated testing of outdoor high-temperature projects, ZICOTEC concludes that most TEC failures in high-temperature environments stem from mismatched heat dissipation structures, insufficient thermal insulation, and unreasonable power control strategies rather than defective chips. Starting from practical engineering pain points, this paper summarizes the actual performance attenuation rules of Thermoelectric Coolers under high-temperature conditions. A complete and mass-producible high-temperature thermal improvement solution is established covering high-temperature resistant material selection, zoned cold-hot thermal insulation design, and dynamic power regulation strategies. Verified by actual tests, the optimized structure effectively suppresses high-temperature performance attenuation and significantly improves the stability and service life of outdoor high-temperature refrigeration equipment. This research provides practical design guidelines for upgrading and developing industrial semiconductor refrigeration devices for extreme thermal environments.

2. Performance Attenuation Rules of TEC Chips in High-Temperature Environments

For engineering practitioners, the cooling temperature difference and cooling capacity of Thermoelectric Coolers are not fixed parameters but dynamically depend on ambient temperature and hot-end heat dissipation conditions. Under standard laboratory conditions at 25°C, conventional TEC chips deliver stable rated performance with negligible attenuation. However, in real scenarios such as open-air installations and high-temperature factories where ambient temperature exceeds 50°C, the operating state of TEC chips changes fundamentally. High ambient temperature compresses the effective temperature difference between the cold and hot ends, reduces the thermal dissipation margin, and gradually saturates the heat dissipation system, resulting in a sharp drop in cooling performance.

In terms of operating mechanism, TEC refrigeration relies on the temperature gradient between cold and hot ends. Higher ambient temperature greatly increases the difficulty of hot-end heat dissipation. To maintain the set cooling temperature, the chip automatically increases operating current and power consumption, forming a vicious cycle of “higher temperature, higher power consumption, weaker cooling capacity, and more severe heat accumulation”. According to field test data from ZICOTEC, unoptimized TEC equipment loses more than 40% of its cooling capacity at 60°C extreme high temperature. After 1000 hours of full-load operation, internal thermoelectric grains suffer irreversible thermal aging and rising internal resistance, leading to permanent performance degradation that cannot be recovered even after returning to normal temperature conditions.

Furthermore, high temperature accelerates the aging and failure of supporting heat dissipation components. Ordinary thermal grease tends to bleed oil and dry out under sustained high heat, while heat sink fins accumulate dust and oxidation layers in

high-temperature and dusty environments, further increasing interfacial thermal resistance. Conventional optimization methods such as increasing fan speed or expanding heat dissipation area can only relieve short-term temperature rise but cannot solve structural high-temperature attenuation. Comprehensive optimization of hardware materials, thermal insulation structures, and control logic is essential for reliable high-temperature operation.

3. Graded Material Selection and Implementation Scheme for High-Temperature Resistant Heat Sinks

As the core medium for heat extraction from Thermoelectric Cooler hot ends, heat sink materials determine the ultimate heat dissipation limit in high-temperature environments. Field fault analysis shows that most high-temperature refrigeration failures are not caused by chip overload, but by inferior civilian-grade heat sinks that degrade rapidly under continuous high heat. Ordinary heat sinks suffer oxidative discoloration and decreased thermal conductivity after long-term high-temperature operation, failing to dissipate heat efficiently. Therefore, material upgrading is the foundation of high-temperature TEC heat dissipation improvement.

Considering different temperature levels and mass-production cost requirements, ZICOTEC has developed three graded high-temperature resistant heat dissipation solutions for full-scenario coverage. Most conventional outdoor high-temperature devices adopt thickened hard anodized aluminum fins. The hardened surface forms a dense protective layer that resists oxidation and scaling within a wide temperature range of -20°C to 120°C , maintaining stable thermal conductivity and cost-effectiveness for most $50\sim 60^{\circ}\text{C}$ outdoor scenarios. For industrial equipment operating continuously above 60°C with 24-hour full-load demands, copper-aluminum composite structures are recommended. Copper directly contacts the TEC hot end for rapid heat conduction and thermal fatigue resistance, while aluminum fins provide efficient convection cooling, balancing thermal performance and lightweight design. For high-precision premium equipment, full-copper heat dissipation modules deliver optimal thermal stability and anti-attenuation performance for extreme continuous high-temperature working conditions.

In addition, ZICOTEC abandons thin-fin lightweight civilian designs for high-temperature scenarios. Custom high-temperature heat sinks adopt thickened bases and densified fins to increase overall thermal capacity. Sufficient thermal capacity effectively buffers instantaneous thermal shocks and prevents premature heat dissipation saturation and temperature runaway. Test results show that at a constant 60°C ambient temperature, equipment equipped with optimized anodized aluminum heat sinks reduces steady-state temperature rise by $12\sim 18^{\circ}\text{C}$, greatly improving long-term refrigeration stability.

4. Optimized Zoned Layout of Thermal Insulation Cotton and Heat Preservation Layers

Years of engineering commissioning prove that high-temperature refrigeration loss originates from two aspects: insufficient hot-end heat dissipation and reverse heat penetration from the external high-temperature environment to the cold end. Most manufacturers only upgrade hot-end heat dissipation hardware while ignoring cold-end thermal protection, resulting in a typical dilemma of “cooling while absorbing heat”. Uncontrolled cold-end heat load drastically reduces temperature control accuracy. Therefore, reasonable thermal insulation structural design is indispensable for high-temperature Thermoelectric Cooler heat dissipation improvement.

ZICOTEC adopts a practical design philosophy of “zoned insulation and cold-hot separation” to avoid unreasonable full-wrap insulation methods. The TEC cold-end cavity is fully enclosed with high-density flame-retardant high-temperature resistant insulation cotton to fill shell gaps, block heat conduction channels, and reduce invalid cold-end heat load. High-temperature resistant gaskets are installed at the junction of the equipment shell and heat sink module to isolate solar radiation and high-temperature airflow reheating, preventing preheating of heat dissipation structures and preserving effective hot-end temperature difference margins.

The layout strictly separates insulation zones and heat dissipation zones to ensure no insulation material blocks airflow or fins, achieving unobstructed hot-end heat dissipation and comprehensive cold-end thermal preservation. This optimized structure reduces cold-end thermal loss by more than 30%, lowering overall chip refrigeration load from the source. It upgrades traditional passive heat dissipation to active coordinated cold and hot-end protection, perfectly adapting to outdoor solar exposure and enclosed high-temperature cabinet scenarios.

5. Practical Dynamic Power Regulation Strategy for High-Temperature Working Conditions

Besides hardware defects, unreasonable control logic is a hidden leading cause of TEC premature aging and burnout in extreme high-temperature environments. Most universal driving systems adopt fixed constant-power output, which is suitable for stable room-temperature operation but incompatible with harsh high-temperature conditions. When ambient temperature rises and heat dissipation efficiency declines, continuous full-power operation causes accumulated heat and excessive thermal stress. Repeated high-temperature thermal shocks lead to internal grain fracture, ceramic substrate micro-cracks, and eventual chip breakdown.

To solve this common industry defect, ZICOTEC implements a temperature-linked graded dynamic power regulation strategy based on dual feedback of ambient temperature and hot-end temperature. The system maintains rated power for maximum cooling efficiency at 30~45°C normal conditions. When the temperature rises to 45~60°C, peak power is moderately reduced to smooth heat output, relieve instantaneous heat accumulation, and balance cooling performance and thermal pressure. Once the ambient temperature exceeds the extreme threshold of 60°C, a high-temperature protection mechanism activates, dynamically adjusting output power according to real-time heat dissipation margin and avoiding sustained

overload operation.

The control logic also includes intermittent operation and temperature hysteresis adjustment to reduce thermal fatigue caused by frequent continuous operation. Compared with rigid constant-power driving modes, this dynamic strategy sacrifices minimal instantaneous cooling capacity while reducing high-temperature thermal shock frequency significantly, extending the service life of high-temperature operating equipment by 2~3 times and solving the industry pain points of high failure rates and short lifespans for outdoor TEC devices.

6. Conclusion: Standardized Thermal Renovation Solution for Outdoor High-Temperature TEC Equipment

Based on substantial field commissioning data, aging test results, and ZICOTEC's rich high-temperature project experience, this article establishes a fully implementable and mass-producible standardized thermal improvement solution targeting high temperature Thermoelectric Cooler cooling challenges. Industrial practice proves that high-temperature TEC optimization is not a simple upgrade of heat dissipation hardware, but a three-dimensional synergy of material upgrading, structural thermal protection, and intelligent power regulation to fundamentally resolve high-temperature attenuation, heat accumulation runaway, and premature chip aging.

In terms of hardware configuration, low-grade civilian materials are eliminated, and high-temperature resistant heat sink solutions including thickened anodized aluminum, copper-aluminum composite, and full-copper modules are selected according to actual thermal levels to prevent oxidation, rising thermal resistance, and performance degradation. Structurally, cold and hot zone separation is implemented with targeted insulation cotton and thermal gaskets to block external heat penetration and reduce invalid refrigeration load. In terms of control logic, constant-power driving is replaced with temperature-adaptive dynamic power regulation to avoid thermal stress damage and overload burnout under high heat load.

The complete optimization scheme adapts to extreme scenarios including open-air exposure, high-temperature workshops, and enclosed heat-intensive cabinets, effectively solving Thermoelectric Cooler problems such as insufficient high-temperature cooling capacity, rapid temperature difference attenuation, high failure rates, and short service life. Supported by ZICOTEC's complete industrial high-temperature thermal management system, the solution greatly enhances the environmental adaptability of semiconductor refrigeration equipment and ensures long-term stable and low-fault operation under harsh high-temperature conditions.

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