

A Review: Thermoelectric cooler application for portable beverage coolers

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Abstract. A thermoelectric cooler (TEC), based on the Peltier effect, offers a compact, quiet, and environmentally friendly solution for portable cooling. It can be used to preserve perishable food and other temperature-sensitive items in remote areas with limited or no electricity. This review examines experimental and theoretical studies published between 2014 and 2025, with a focus on portable beverage-cooling applications. Recent studies report improvements in thermoelectric materials, heat rejection, and control strategies; however, the reported coefficient of performance (COP) of portable single-stage coolers remains modest, and cooling performance varies strongly with ambient temperature, cooling load, insulation, and heat-sink design.

Keywords: Thermoelectric, coolers, Peltier effect

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INTRODUCTION

Thermoelectric cooling has gained increased attention, particularly in applications where compactness, reliability, and environmental sustainability are of primary concern. Thermoelectric coolers (TECs), which are based on the Peltier effect, operate by moving charge carriers within semiconductor materials to create a temperature gradient. This results in heat transfer from one side of the device to the other (Xia et al., 2021).

Using TECs in portable beverage cooling systems offers many opportunities but also presents engineering challenges. This review focuses on analyzing thermodynamic efficiency, heat transfer performance, cooling dynamics, and design parameter optimization. Key factors under consideration include module configuration, heat sink architecture, electrical matching, and environmental adaptability. Studies have consistently shown that hot-side heat rejection is a major limiting factor in TEC systems. Improvements in heat-sink design, liquid cooling, thermal interfaces, and insulation can therefore improve overall system performance. Material innovation remains a central concern in thermoelectric research. Bismuth telluride (Bi_2Te_3)-based materials currently dominate room-temperature applications due to their favorable thermoelectric figure of merit (ZT). However, ongoing investigations into skutterudites and half-Heusler compounds show promise for higher-temperature and more energy-efficient applications (Xia et al., 2021).

From a systems engineering standpoint, researchers such as Ykrelef et al. (2025) and Kaewsai et al. (2021) have evaluated how module arrangement and control

logic impact cooling performance and power consumption. The integration of photovoltaic (PV) sources (Basri et al., 2018; Suzuki et al., 2025) and phase-change materials (He et al., 2015) has further improved the off-grid functionality of these devices, particularly in remote or mobile settings.

The practical applications of thermoelectric beverage coolers extend beyond convenience to include recreational transportation, vending infrastructure, and medical cold-chain delivery systems (Mirmanto et al., 2019; Muratçobanoğlu & Hepbasli, 2023). This paper compiles and evaluates advances in thermoelectric cooling from a thermal engineering standpoint, emphasizing component-level heat-transfer mechanisms, system-level thermal integration, and performance benchmarking across varied operating conditions.

Furthermore, we examine how module geometry, electrical loading, ambient fluctuations, and real-time control mechanisms influence overall cooling performance. This review integrates findings from experimental, prototype, and simulation-based studies and compares metrics such as internal temperature, pull-down time, coefficient of performance (COP), and energy consumption.

LITERATURE REVIEW

A TEC is composed of p- and n-type semiconductor legs that are electrically connected in series and thermally in parallel. A current of a specified magnitude is employed to produce Peltier cooling on one ceramic surface while rejecting heat on the opposing surface. The TEC schematic is shown in Figure 1.

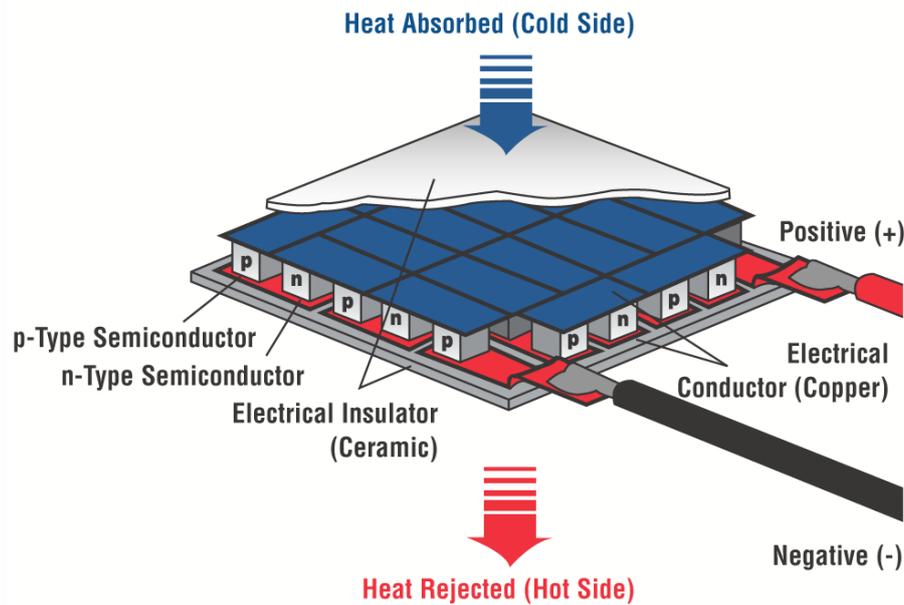


Figure 1. Schematic diagram of the TEC module. Source: Adapted from Aziz et al. (2015)

Depending on the application requirements and the desired temperature gradient, thermoelectric cooling systems can be configured in several distinct arrangements. The most common configurations include single-stage, multi-stage (cascaded), and thermopile assemblies. The efficacy of each of these architectures depends on the achievable temperature differential, cooling capacity, and system efficiency.

The single-stage configuration has been the most widely adopted due to its structural simplicity and compact design. The system consists of a single TEC module comprising multiple thermocouples connected in a series. These systems are well-suited for moderate cooling requirements, typically achieving a temperature differential of 30–40°C. Single-stage modules, such as TEC1-12706, are frequently utilized in beverage coolers, medical mini-fridges, and electronics thermal management systems (Kaewsai et al., 2021; Giri & Nain, 2020).

Conversely, multi-stage TECs, also known as cascaded configurations, are engineered to achieve lower temperatures by stacking modules. Each stage of the process is designed to cool the subsequent stage, thereby enabling temperature reductions exceeding 60 °C (Sharma et al., 2014). These systems are characterized by increased complexity, necessitating precise thermal insulation and active control to circumvent inter-stage inefficiencies. Cascaded modules are frequently used in scientific instrumentation and vaccine storage.

A third approach involves thermopile configurations, in which several TECs are assembled in parallel, mechanically and thermally, to increase the cooling area or distribute thermal loads more evenly.

In larger enclosures, the utilization of thermopile arrays proves advantageous, as it enables the maximization of surface contact without compromising the performance of individual modules (Muratçobanoğlu & Hepbasli, 2023).

Each configuration necessitates meticulous thermal management, particularly on the hot side, to avert heat accumulation that can degrade performance. As demonstrated by studies by Hu et al. (2024) and Abderezzak et al. (2021), micro-channel water blocks and heat-pipe sinks are highly effective at maintaining thermal gradients across TEC stages.

Abderezzak et al. (2021) conducted a thorough thermal evaluation of hybrid cooling systems integrating micro-channel water blocks and copper-based heat pipes with thermoelectric (TEC) assemblies. Their experimental setup demonstrated that when both mechanisms are employed, the temperature difference across the TEC module could be stabilized more effectively, thereby enhancing the overall coefficient of performance (COP) by 20–30% compared to conventional finned heat sinks.

The study further reported that the inclusion of microchannels with a high surface-area-to-volume ratio significantly improved convective heat transfer. Concurrently, the heat pipes enabled expeditious axial heat transfer from the TEC's elevated surface to the ambient environment. The incorporation of dual-mode cooling enhancements has been shown to improve thermal uniformity, reduce hot-spot formation, and extend the cooling unit's operational lifespan. The research affirms that careful thermal interface design is critical for sustaining TEC performance, particularly in high-load or continuous-use scenarios.

METHODOLOGY

This review employs a systematic literature review approach, focusing on research studies published between 2015 and 2025 that address thermoelectric cooling technologies for portable or small-scale beverage cooling systems. The databases searched were Scopus, IEEE Xplore, ScienceDirect, and Google Scholar, using combinations of the keywords "thermoelectric cooler," "portable refrigeration," "beverage cooler," "Peltier module," and "thermal optimization." The selection of studies was based on the inclusion of empirical data, detailed system descriptions, and relevance to thermal engineering objectives, including coefficient of performance (COP), cooling rate, and energy efficiency.

The search yielded 50 records. After duplicate removal and title/abstract screening, 22 studies met the inclusion criteria: (1) portable beverage or small-scale cooling application, (2) quantifiable thermal or electrical performance data, and (3) sufficient description of system configuration or thermal design.

A systematic extraction and tabulation of key data points was conducted, encompassing TEC module specifications (type, size, stage), electrical power characteristics (voltage, current), thermal interfacing (heat sink material, fin geometry, active/passive cooling), time to reach target cooling temperatures, and resulting COP values. Where possible, figures were normalized to enable cross-comparison, and performance was evaluated under both steady-state and transient operating conditions. To facilitate comparative analysis, the data were meticulously arranged into a matrix, thereby enabling the differentiation between system configurations, including single-stage, cascaded, and thermopile configurations.

Furthermore, studies proposing advanced optimization methods such as artificial intelligence (AI), fuzzy logic, and evolutionary algorithms were reviewed separately to examine how predictive modeling and adaptive control could enhance cooling performance in dynamic outdoor or mobile environments. The synthesis of data placed a premium on metrics deemed most pertinent to pragmatic implementation, including internal beverage temperature, the coefficient of performance (COP), power consumption per liter of coolant, and the system's response to fluctuating ambient temperatures. The included studies were compared qualitatively by system configuration, heat-rejection strategy, power source, cooling time, achieved temperature, and reported COP.

RESULTS AND DISCUSSION

A comparative analysis of the 22 selected studies reveals several key insights into the thermal

performance and practical feasibility of thermoelectric beverage coolers. The results of the study were grouped based on configuration type, thermal enhancement method, and power source.

System Performance by Configuration

Single-stage TEC systems remain the most common option for portable coolers because they are simple, compact, and easier to integrate. However, their performance is strongly constrained by hot-side heat rejection, insulation quality, and operating conditions.

The architecture, which can be described as cascaded or multi-stage, enhances the achievable temperature differential by thermal series stacking of TEC modules. Given that each additional stage increases electrical resistance and contact losses, practical implementations rarely exceed two or three stages for portable devices. However, these configurations remain attractive for specialized applications, such as vaccine carriers, where sub-zero temperatures take precedence over efficiency considerations.

Multi-module or thermopile arrangements may improve temperature uniformity in larger enclosures by distributing the cooling load over a larger surface area. Their effectiveness, however, depends on module spacing, control strategy, and hot-side heat rejection.

Mainil (2018) developed a portable thermoelectric cooling box with a 22-liter capacity, as illustrated in Figure 2. The fabrication of the cooling box involved integrating nine TEC modules. The portable thermoelectric cooler box (PTECB) has the following dimensions: length x width x height (36.5 cm x 25.5 cm x 26.5 cm). The primary components of PTECB, in addition to TEC, consist of a heat sink (two pieces), a fan (five pieces), a thermoelectric controller, a 12V, 7.2A battery, and a 600VA uninterruptible power supply (UPS). The box temperature achieved at input powers of 50.5W, 72.72W, and 113.64W were 19.98 °C, 19.77 °C, and 18.52 °C, respectively. The temperature achieved in the box was 22.45 °C when the cooling load was 1440 mL and 23.32 °C when the cooling load was 2880 ml.

Effectiveness of Heat-Sink Enhancements

The reviewed works concur that the design of the hot-side heat sink is the dominant bottleneck in TEC assemblies. Shen (2019) conducted a series of wind-tunnel experiments to evaluate 30 aluminum fin geometries. The results of these experiments demonstrated that staggered-fin arrays delivered 18% higher convective coefficients than traditional inline designs at the same volumetric flow rate. Hu (2024) advanced this concept by incorporating an embedded liquid microchannel heat sink, thereby achieving a 27% reduction in thermal resistance in comparison with the optimal air-cooled counterpart.



Figure 2. Portable Thermoelectric Cooler Box. Source: Adapted from Mainil et al. (2018)

Hybrid approaches that integrate passive heat-pipe elements with active microchannels further enhance thermal conductance. Abderezzak's (2021) research demonstrated that a flat-plate evaporator heat pipe coupled to a copper micro-channel cold plate homogenized temperature along the hot side, thereby minimizing localised hotspots that are known to degrade semiconductor junction reliability. Infrared imaging revealed a maximum temperature difference of 1.3°C across the heated ceramic surface, which is approximately one quarter of the temperature difference measured on the baseline finned sink.

It is important to note that the enhancement of heat sink performance cannot be attributed exclusively to material or geometry. Interface optimization, including the use of high-conductivity thermal pads or thermal paste, can reduce contact resistance and improve heat transfer across the module-heat-sink interface. During the course of the endurance testing, the degradation of the thermal interface material (TIM) emerged as a failure mode, thereby underscoring the importance of selecting materials that are resistant to mechanical creep and thermal cycling.

Dynamic airflow control represents another promising direction. Ykrelef (2025) embedded pulse-width-modulated (PWM) fan drivers linked to predictive AI algorithms, enabling fan speed to ramp proactively ahead of anticipated load spikes. Compared with fixed-speed operation, adaptive airflow achieved equivalent cooling performance with 12% lower average power draw and reduced acoustic emissions, thereby improving user acceptance in consumer appliances.

Lastly, phase-change materials (PCMs) introduced between the heat sink and outer enclosure deliver a

thermal buffer that dampens ambient transients. Simolowo (2016) reported that integrating a paraffin-wax PCM maintained beverage temperatures below 10°C for an additional 45 min after power loss—critical for ensuring quality during transport. Nevertheless, designers must account for the added mass and latent-heat saturation over repeated cycles.

Collectively, these studies indicate that incremental improvements in heat-sink architecture, surface treatment, and control strategies synergistically elevate system efficiency. A modular design ethos—allowing upgrade of heat-sink elements without redesigning the TEC core—could accelerate commercial adoption.

Energy Source and Power Consumption

Basri et al. (2018) demonstrated a vehicle-mounted portable thermoelectric soft-drink cooler powered by photovoltaic input, and fuzzy control reduced the time to reach 15°C to 30 min. PV-assisted TEC systems may further benefit from MPPT and efficient power electronics, but quantitative efficiency claims should be reported only when supported by a verified source.

AC-powered systems provide stable input power, whereas DC or PV-powered systems offer portability and off-grid capability. Performance comparisons between these power modes should therefore be presented only under matched thermal and electrical test conditions.

Control algorithms such as fuzzy logic and predictive control can reduce unnecessary power draw by adjusting current input and fan speed to match thermal load. However, reported energy savings should be compared only when the studies use comparable box volume, ambient temperature, and cooling load.

Energy consumption per unit of cooling capacity remains a critical metric for evaluating the practicality

of off-grid applications. The lowest figures corresponded to systems combining high-conductivity heat sinks with adaptive power control, reinforcing the holistic nature of efficiency optimization.

In essence, the integration of energy-efficient power electronics, predictive control, and hybrid storage emerges as the most viable pathway to enhancing operational autonomy while mitigating climate-dependent variability.

Overall Observations

In general, portable thermoelectric coolers for beverages exhibit a high degree of adaptability and the capacity to achieve functional cooling objectives while maintaining a compact form factor. The salient trade-offs that have been identified pertain to the efficiency versus cost, the cooling depth versus speed, and the simplicity versus adaptability. Current research suggests that improved control strategies, thermal storage, and more effective heat-rejection systems are promising directions for further optimization.

The review demonstrates that while individual innovations, such as new materials or control algorithms, offer incremental gains, a systems-level integration approach is essential for achieving commercially viable performance in off-grid and mobile cooling markets.

CONCLUSION

The reviewed studies show that TECs are attractive for portable beverage cooling because they are compact,

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low-noise, and compatible with DC or solar power. However, system performance depends strongly on heat rejection, insulation, operating conditions, and control strategy, so comparisons across studies should be interpreted cautiously.

However, the practical implementation of TEC beverage coolers is hindered by challenges related to heat dissipation, energy storage, and climate variability. The extant literature supports the conclusion that a system-level optimization approach is essential for achieving meaningful performance gains. Future work should emphasize standardized test protocols, verified comparative data, and clearer reporting of ambient conditions, load, and power consumption to support practical design decisions.

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