A Review of Thermoelectric And Hybrid Cooling Solutions In Portable Storage: Performance, Applications, And Future Trends

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Abstract- *Thermoelectric cooling (TEC) technology is increasingly recognized as an energy-efficient and eco-friendly substitute for traditional refrigeration methods. Utilizing the Peltier effect, TEC modules are known for their compact size, dependability, and precise temperature regulation, making them ideal for a wide range of uses, from portable cooling gadgets to medical storage solutions. Recent research has concentrated on enhancing TEC performance through advanced modelling, multistage setups, and hybrid cooling techniques. Additionally, the incorporation of control methods, such as PID and model predictive control, has improved the system's stability, efficiency, and adaptability under various operating conditions. New strategies are also investigating the application of machine learning for optimization and adaptive performance. This literature review compiles significant advancements in thermoelectric cooling, focusing on modelling techniques, performance enhancement strategies, and intelligent control methods. It underscores both the potential and current limitations of TECs, paving the way for their wider use in sustainable thermal management solutions.*

Keywords: Thermoelectric cooling, Peltier effect, Portable refrigeration, PID control, Performance optimization, Intelligent control.

I. INTRODUCTION

Food spoilage and inadequate storage are pressing issues that directly affect public health, food security, and global sustainability. According to the Food and Agriculture Organization (FAO), nearly one-third of the food produced globally is lost or wasted, with a significant portion attributed to inefficient storage and preservation systems [1]–[3]. Perishable items, such as dairy products, fruits, vegetables, insulin-based medicines, and vaccines, are particularly vulnerable to fluctuating or inappropriate temperatures during storage and transportation. This challenge is magnified in developing regions, where power shortages, high ambient temperatures, and limited infrastructure reduce the effectiveness of conventional refrigeration.

The causes of food spoilage are also multifaceted. Variations in ambient temperature, microbial growth, and chemical degradation are among the leading contributors to the reduced shelf life. Traditional cooling systems, which are typically based on vapour-compression technology, require compressors, refrigerants, and continuous power, making them unsuitable for portable applications orresource-constrained field. [4].

The impact of inadequate food storage extends beyond mere food wastage. It has socio-economic consequences by affecting farmers, supply chains and consumers. In healthcare, improper storage of temperature-sensitive medications and vaccines can compromise their efficacy and safety, leading to severe public health risks. This underscores the urgent need for compact, reliable, and energy-efficient storage technologies that can address diverse preservation requirements.

In response, researchers and industries have increasingly explored alternative and hybrid cooling methods for data centers. Thermoelectric cooling (TEC), based on the Peltier effect, has emerged as a promising solution owing to its compactness, solid-state operation, and absence of harmful refrigerants [5]. However, limitations such as relatively low efficiency under high thermal loads have driven interest in hybrid systems, where TEC is combined with phase-change materials (PCMs), liquid cooling, or insulation technologies to enhance performance. These integrated approaches show potential for applications ranging from portable food containers to vaccine transportation units.

With advances in materials science, Internet of Things-based monitoring, and energy-efficient design, thermoelectric and hybrid cooling systems are moving closer to practical deployment. This review aims to provide a comprehensive examination of recent developments in portable cooling containers, highlighting their design principles, performance trends, and potential applications in food preservation and healthcare logistics.

II. LITERATURE REVIEW

Food preservation technologies play a pivotal role in maintaining product quality during transportation, particularly for perishable items such as fish, dairy products, and fresh produce. Recent advances in portable solar-powered thermoelectric cooling systems have demonstrated significant utility in this domain, achieving rapid temperature reductions to 5 ± 0.2 °C within three hours and maintaining stability even under continuous loading conditions [6]. Such systems enable on-site preservation and extend usability during off-grid transport, although limitations such as moderate cooling capacity (COP ~0.44) and dependence on ambient conditions remain [6]. Phase-change material (PCM)-based storage has further extended preservation duration, with nanocomposite PCM cold plates sustaining safe yoghurt storage for up to 87 h without active cooling [7]. These technologies not only reduce spoilage during long-distance distribution but also minimize the reliance on conventional compressor-based systems.

Optimal storage temperatures vary across food categories and directly influence both safety and organoleptic properties. For example, fresh fish and meat typically require storage at 0-4 °C, dairy products at 1-5 °C, and fresh produce within 0-8 °C, depending on respiration rates [8]. Maintaining these narrow ranges is crucial to avoid microbial proliferation, enzymatic degradation, and texture loss. Studies on cold chain logistics for fruits and vegetables emphasize that even minor deviations from target temperatures can significantly reduce shelf life and market value [8]. This underscores the importance of integrating precise temperature monitoring and control mechanisms into portable storage units.

A significant trade-off in mobile food storage systems exists between energy efficiency and preservation quality. Although thermoelectric modules are compact and vibration-free, they often exhibit lower coefficients of performance than vapour compression systems, resulting in higher power demands for equivalent cooling performance [9]. Nevertheless, they offer advantages in terms of maintenance simplicity and adaptability for renewable energy integration, making them suitable for intermittent-use scenarios, such as small-scale deliveries. In contrast, PCM systems excel in passive preservation with minimal energy consumption but require preconditioning and may lack adaptability to fluctuating load demands [7]. Thus, selecting an optimal system requires balancing the operational cost, energy input, and thermal stability of the target goods.

Portable container designs for long-distance delivery increasingly incorporate hybrid solutions that combine active thermoelectric cooling with passive PCM buffering, addressing both short-term thermal spikes and prolonged storage needs [10]. Insulation quality, particularly through vacuum-insulated panels, plays a decisive role in minimizing heat ingress, directly impacting both the hold time and energy consumption [7]. Additionally, ergonomic considerations, such as modular compartmentalization, ease of cleaning, and weight distribution, further influence adoption in both commercial and humanitarian supply chains. The evolution of these designs continues to address the dual demands of maintaining strict temperature tolerances and achieving high portability, a challenge that remains central to innovation in the food cold chain sector [8]-[10].

The performance and autonomy of thermoelectric cooling systems depend heavily on their power sources and energy management strategies. Among the available options, solar photovoltaic (PV) integration is particularly promising. Because thermoelectric modules operate on direct current, PV panels can power them without the need for DC-AC conversion, thereby reducing losses and simplifying the system design [11], [12]. In practice, PV modules are often paired with energy storage to allow cooling to continue at night or during cloudy periods.

System sizing depends on the cooling demand, coefficient of performance (COP) of the TECs, and local solar resources. Studies have shown that solar-powered vaccine storage units can run on as little as 60-80 Wh/day, whereas larger, continuous systems may require several hundred Wh/day [11]. Careful insulation and heat exchanger optimization can significantly reduce energy demand.

Energy storage is typically provided by lithium-ion batteries, which are chosen for their high energy density, deep discharge capability, and long cycle life [13]. A Battery Management System (BMS) ensures safe operation by protecting against overcharging, deep discharge, and overheating. Hybrid approaches using solar energy during the day and battery power at night can minimize battery size and cost while maintaining continuous operation [13].

When combined with well-designed thermal systems, efficient PV arrays, and smart battery management, solar-powered TECs offer a reliable and sustainable cooling solution that is particularly valuable in off-grid, rural, and emergency applications.

III. STUDIES AND FINDINGS

In multi-zone portable refrigerators, several TECs are assigned to separate compartments and linked via heat exchangers, shifting the control focus from "single set-point tracking" to a coordinated thermal management approach that considers inter-zone interactions and shared power constraints. Physics-based equivalent circuit models of TECs (comprising a Seebeck source, internal resistance, and thermal conductance) are fundamental to controller design, as they facilitate the co-simulation of power electronics and heat-transfer dynamics for each module and zone [14]. Recent advancements in bidirectional MATLAB/Simulink libraries have made it feasible to encapsulate TEC/TEG operations in a single block with temperature-dependent parameters at the system level, allowing supervisory algorithms to effortlessly switch modules between cooling and heating (e.g., for defogging or hot-side heat recovery) and to forecast COP–current trade-offs under varying ΔT requirements per zone [15]. Case studies on two-stage/parallel multi-module architectures indicate that adjusting the current distribution across stages or legs (including inhomogeneous electrical/thermal properties) enhances cooling capacity and COP, directly informing current-sharing strategies across zones with different loads [16]. On the control front, low-level PWM actuation with PID temperature loops remains a reliable baseline; experiments demonstrate that a well-tuned PID reduces overshoot and settling time while maintaining TEC power within limits in embedded (Arduino/DSP) implementations [18], [19]. For fleets of modules and zones, higher-level controllers incorporate constraint handling and prediction: MPC coordinates set points and duty cycles across modules to minimize energy consumption while adhering to temperature limits and battery/PV power budgets, an approach validated in mobile/robotic cooling scenarios and easily transferable to multi-compartment boxes [21]. Emerging machine–learning–assisted optimizers operate above PID/MPC to adaptively select currents and duty cycles that maximize global objectives (e.g., weighted COP across zones or time-of-use–aware energy cost), demonstrating near-global optimal operation in simulations/experiments and providing a data-driven method to manage uncertain cross-coupling between compartments [20]. At the application level, multi-space portable boxes explicitly model inter-compartment energy coupling and implement coordinated control to maintain different set points simultaneously (e.g., produce vs. dairy), reporting tighter temperature uniformity and improved energy efficiency under real usage profiles as useful templates for long-haul food logistics with heterogeneous payloads [17].

IV. CHALLENGES & CONSTRAINS

Although thermoelectric food preservation systems offer certain benefits, they encounter notable obstacles due to their lower efficiency when compared to traditional vapour-compression refrigeration. The naturally low COP of thermoelectric modules leads to increased electrical energy usage, which restricts their scalability for large-scale cold storage applications [4], [14]. Effective heat dissipation on the hot side is a major concern, as poor thermal management can significantly impair cooling performance and reduce the system's lifespan [16]. Additionally, cost and material constraints present challenges, as high-performance thermoelectric materials and sophisticated control hardware add to system complexity and manufacturing costs [3], [7]. In portable systems, reliance on batteries introduces further limitations, such as restricted backup duration, degradation over time, and the necessity for robust battery management systems [9], [13]. Furthermore, achieving consistent temperature distribution and adhering to strict cold-chain requirements for perishable foods under varying environmental conditions remains a technical challenge [8], [10].

V. FUTURE SCOPE

The future potential of thermoelectric food preservation systems is centered on enhancing energy efficiency, implementing intelligent control, and expanding their use in off-grid and portable scenarios. The development of advanced thermoelectric materials and multi-stage cooling setups promises improved coefficients of performance (COP) and reduced power usage, making these systems more suitable for extended food storage durations [3], [14], [16]. By integrating with renewable energy sources like solar power, these systems are anticipated to become more prevalent in rural and remote areas, thereby supporting decentralized cold-chain infrastructure for items such as fruits, vegetables, and vaccines [6], [11], [12]. Another exciting avenue is the adoption of smart control methods, including PID, model predictive control (MPC), and machine-learning-assisted optimization, to boost temperature stability and adaptive cooling capabilities [18]–[21]. These intelligent systems can dynamically modify operating parameters based on factors like load conditions, ambient temperature, and battery status, which helps minimize energy waste and maintain food quality. Furthermore, modular and multi-compartment thermoelectric storage designs can facilitate the simultaneous preservation of various food types at different temperature settings [17].

VI. CONCLUSION

This survey reviews key advancements in thermoelectric cooling (TEC), including modelling, optimization, and control strategies. Early research concentrated on accurate module modelling and performance prediction [14], [15], followed by structural and material-level improvements, such as multi-stage cooling [16],[17]. Control-based studies have shown that PID and Arduino-assisted methods enhance cooling stability and energy efficiency [18], [19]. More recent studies have emphasized the role of intelligent approaches, including machine learning and model predictive control, in achieving adaptive, application-oriented performance [20], [21]. Although promising, challenges remain regarding scalability, energy efficiency under varying loads, and long-term reliability. Future research should focus on hybrid control strategies, IoT-enabled monitoring, and sustainable designs for real-world applications, such as healthcare, food preservation, and rescue robotics. Overall, TEC continues to evolve as a compact, efficient, and sustainable cooling solution with significant potential for future applications.

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