



REVIEW

Advances in Thermoelectric Cooling Applications: A Review

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ABSTRACT: Recently, the thermoelectric cooler (TEC) has become popular as a technology that can provide cooling in a solid state because of its small size, high temperature control accuracy, silent operation, and environmental friendliness. Since the technology does not involve any refrigerants and moving components, it is appropriate for reliable localized cooling compared to vapor compression systems. Nevertheless, there are certain disadvantages associated with low efficiency and poor heat dissipation. This paper is dedicated to the review of recent developments in TEC technology, which concentrates mainly on aspects of performance and design determined by the application. The review will be organized depending on different application areas, such as space cooling of various scales (including automotive systems), combined vapor compression refrigeration, and enclosed cavities. Moreover, new applications of TEC in the field of wearable cooling and clothing thermal management, along with aerospace, microchip cooling in electronics, and battery thermal management, will be reviewed.

KEYWORDS: Thermoelectric cooler (TEC); enclosed-space cooling; peltier effect; diversified applications

1 Introduction

Cooling technologies have been identified as critical elements in both industrial and practical applications [1,2]. Accurate temperature control is required in many industries, such as food storage [3], aerospace engineering [4], medical cold chain logistics [5], wearable electronics [6,7], and home air-conditioning systems [8]. Nevertheless, increasing requirements for temperature control and environmental sustainability have introduced new difficulties for traditional cooling technologies [9]. As a result, the development of cooling technologies with greater reliability and better environmental compatibility has become a primary emphasis of recent technological advancements [2].

The technology of compression refrigeration is currently the most popular technology in industrial applications, air-conditioning systems, and refrigeration systems [10]. For instance, Stirling coolers have been shown to provide substantial cooling power with relatively high efficiency [11]. Although these technologies have several benefits, they are often accompanied by considerable vibration, noise, and refrigerant use, which can lead to operational constraints, specifically in applications where precise temperature control is required. The performance of sensitive devices can thus be affected by the noise, vibration, and refrigerant dependence of these technologies [12,13]. On the other hand, cooling using magnetic technology [14,15] has proved to have some advantages.

Magnetic-Cooling technology offers high cooling performance with a noiseless and eco-friendly system, relatively. However, this technology is still in its budding stage. Its complexity and high production cost are currently the biggest drawbacks to its large-scale commercialization.

Therefore, developing a free of vibration, noiseless, and eco-friendly cooling system represents a big task for researchers [2]. A new technology called thermoelectric cooling technology (TECT) has been developed as an alternative to the aforementioned obstacles [16]. TEC technology has the capability to directly convert electrical energy into a temperature difference. The TEC Cooling system has a simple cooling method with a noiseless and vibration-free system. Moreover, it is eco-friendly, rugged, and easy to operate in varying conditions [16,17]. Therefore, thermoelectric coolers (TECs) are helpful for temperature regulation and can be employed in various applications [18]. In this context, the primary objective of this review is to provide a comprehensive understanding of thermoelectric cooling (TEC) across different spatial scales. Generally, space cooling refers to the cooling of large indoor environments. However, this study also considers TEC applications in smaller, localized spaces. These applications include automotive cabins, Compression-Refrigeration systems, electronic and microchip cooling, and aerospace systems. Moreover, this review gives a brief introduction to some of the TEC integrated systems in other applications like cooling in wearables and batteries. Consequently, this review tries to address the problem associated with large-scale space cooling and small-scale local cooling by introducing the flexibility of TEC to operate in different applications. This makes it possible to have a holistic view of the performance of TEC in large and confined spaces for cooling. From the viewpoint of space cooling, the performance of TEC depends on its capability to reject heat through the hot side. The problem becomes even more severe in the case of enclosed or large spaces that require continuous heat rejection. Consequently, the integration of TEC with radiative cooling is used as a complementary technique for thermal management. It should be noted that radiative cooling provides passive heat rejection without the need for energy consumption, which helps in achieving the aim of space cooling using TEC systems. In particular, a hybrid TEC-radiative cooling system was incorporated into this review since it involves the main purpose of space cooling systems. The organization of this paper can be outlined as follows: first, a review of TEC systems integrated in a vehicle's cabin is introduced. Secondly, the literature related to TECs integrated in compression-refrigeration space cooling systems is comprehensively reviewed. Thirdly, building and space cooling systems with TECs in different scales are discussed. Finally, comparative studies of TEC integration in other systems are reviewed.

Several works from the literature were conducted to find relevant papers on TEC systems and their applications. The official scientific database and websites were utilized to review the previous studies, while theoretical background, thermoelectric fundamentals, and history of TEC systems were provided from other relevant studies. A wide ranges of topics were involved in the current review over the recent sixteen years, including TEC-integrated systems in different scales of space cooling, TECs in electronic cooling, battery thermal management, and radiative-sky cooling. Several parameters and applications related to the TEC systems were investigated through these studies, including hybrid cooling systems, performance, coefficient of performance, cooling capacities, temperature differences, energy consumption, heat rejection techniques, and thermal management applications.

2 Basics of Theoretical Analysis

In 1834, French physicist Jean Charles Athanase Peltier made the discovery of the Peltier effect. It was determined that a closed circuit comprised of two materials absorbs or releases heat at their connections when an electric current travels through them [19,20]. Peltier phenomenon is almost the opposite procedure of the Seebeck effect, where a temperature difference produces an electric potential. In thermoelectric devices, one junction is heated, and the other is cooled, depending on the electric current direction and the materials used. The Peltier effect has immense applications in heating and cooling systems, particularly in the cooling of electronic equipment. When an electric current is passed through two different conductive

materials, an endothermic reaction takes place at one junction and an exothermic reaction at the other junction. The heat absorbed or released is proportional to the electric current and is written as [20]:

$$dQ/dt = \pi abI \quad (1)$$

where

dQ/dt : the absorbed or released heat rate (W)

I : the current intensity (A)

πab : Peltier coefficients (W/A)

The rate of absorbed or released heat is strongly dependent on the electric current intensity. The higher the current, the higher the rate of absorbed or released heat, thereby raising the rate of the heat transfer process and decreasing the time required for cooling or heating. The Peltier coefficient, therefore, defines the amount of heat absorbed or released at the junction for a unit current. The ability of a material to improve heat absorption or release via the Peltier effect is directly proportional to the absolute value of the coefficient.

However, the importance of the factors mentioned above changes depending on the size of the application. For example, in small-sized systems like microchips and wearables, electricity and the Peltier coefficient dominate heat transfer processes. However, in large-sized systems, increased cooling capacity is required to handle the greater amount of cooling load.

The coefficient of performance (COP) is one of the most important parameters used to evaluate the performance of thermoelectric cooling systems. It is defined as the ratio of the cooling capacity (Q_c) to the input electrical power (P_{in}). Since the input power can be determined from the applied voltage and electric current, the performance of the system is directly linked to both electrical and thermal parameters. A higher COP indicates better system performance, as more cooling is achieved with lower energy consumption, while a lower COP reflects reduced efficiency.

The COP of thermoelectric systems is strongly influenced by several operating conditions. Increasing the electric current enhances the temperature difference (ΔT) due to the stronger Peltier effect, which initially leads to an improvement and increase in the coefficient of performance (COP). However, at higher current levels, the generated internal heat (Joule heating) increases, raising the hot-side temperature and consequently causing a reduction in the COP. Therefore, optimizing these parameters is essential to improve the overall efficiency of thermoelectric cooling systems.

$$COP = Q_c/P_{in} \quad (2)$$

here Q_c represents the cooling capacity while P_{in} refers to the electrical power input. The thermoelectric coolers have a cooling capacity dependent on the contribution of Peltier effect, Joule heating, and heat conduction from the module. Therefore, the cooling capacity can be represented as:

$$Q_c = \alpha IT_c - (1/2)I^2R - K(T_h - T_c) \quad (3)$$

where α is the Seebeck coefficient, I is the electric current, T_c is the cold-side temperature, T_h is the hot-side temperature, R is the electrical resistance, and K is the thermal conductance.

It is evident from Eq. (3) that the significance of cooling capacity and heat losses depends upon the scale. In the case of electronic or wearable devices, minimizing Joule heating is of great significance due to the small space available. However, in the case of batteries or vehicles, high cooling capacity is significant.

$$P_{in} = V * I \quad (4)$$

$$COP = Q_c / (V * I) \quad (5)$$

Apart from the description of COP through input electrical power, there is another way in which COP can be explained through thermodynamic properties of the thermoelectric generator. As per the First Law of Thermodynamics, the input power is equivalent to the difference between heat energy rejected by the hot side and absorbed heat energy at the cold side. Hence, COP can be rewritten as:

$$COP = Q_c / (Q_h - Q_c) \quad (6)$$

$$Q_h = \alpha I T_h + (1/2) I^2 R - K(T_h - T_c) \quad (7)$$

Eq. (7) represents the heat rejected at the hot side of the thermoelectric module and can be expressed as a combination of Peltier, Joule, and conduction effects where α is the Seebeck coefficient, I is the electric current, T_h is the hot-side temperature, T_c is the cold-side temperature, R is the electrical resistance, and K is the thermal conductance.

Furthermore, since the hot-side heat can be expressed as the sum of the cooling capacity and the input power as follows:

$$Q_h = Q_c + P_{in} \quad (8)$$

In extensive applications such as space cooling, refrigeration, and hybrid cooling systems, where the coefficient of performance (COP) and power consumption are critical factors, several thermoelectric coolers (TECs) are necessary. Thus, the quantity of modules, power distribution, and thermal dissipation on the hot side significantly influence overall efficiency.

From Fig. 1, it is apparent that the COP value is directly proportional to the value of electric current at low values of electric current due to an increase in cooling capacity, but beyond a certain point, it decreases due to an increase in electric power consumption as reported by Cai et al. [21].

This large variation in COP values (0.13 to 6.1) comes from the fact that there is variation in the operating parameters and configurations, and in performance evaluation procedures of the TEC systems. It was found that the maximum COP can be calculated as:

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

$$ZT = \frac{\alpha^2}{k} \sigma T$$

where Z and σ are figure of merit and electrical conductivity, respectively.

The performance of TEC system is influenced by factors such as temperature differential, current supplied, thermal load, efficiency of heat rejection, and thermal contact resistance. Also, the number of TECs used and their configuration, heat sink design, flow rate of air/coolant, and environmental conditions

may greatly affect the performance of the TEC system. Low COP (Coefficient of Performance) values are usually found with large temperature differentials, poor hot side heat rejection, and high electrical input while high COP values could result from small temperature lift, good heat rejection, or in hybrid systems where COP includes the effect of other cooling systems.

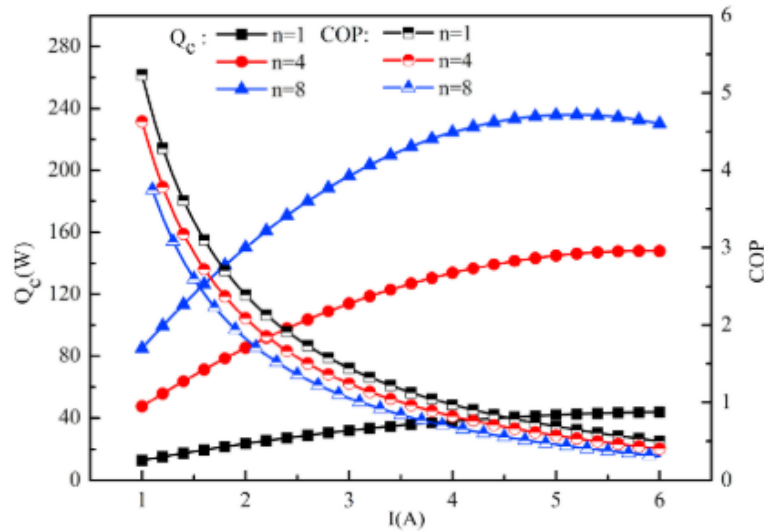


Figure 1: Effect of electric current on the cooling capacity (Q_c) and coefficient of performance (COP) for different numbers of thermoelectric modules ($n = 1, 4$, and 8). Here, n denotes the number of thermoelectric modules used in the system [21].

3 Applications of Thermoelectric Coolers in Vehicles.

The technology of thermoelectric cooling has revealed a certain potential for use in automotive applications; nevertheless, its cooling capacity is still a significant limitation that does not allow the widespread adoption of this technology in conventional vehicle air-conditioning systems. Wan et al. [22] developed a localized auxiliary air-conditioning system using multiple TEC units positioned around the driver as shown in Fig. 2a. A CFD (Computational Fluid Dynamics) model was employed to evaluate the cabin temperature field and thermal comfort, followed by optimization of the temperature near the cold side of the TEC units. Root square mean (RSM) method was used to analyze the sensitivity of the input variables. Results show that temperature is reduced by about (2°C (Celsius)) in the vehicle room. The temperature difference between experimental and numerical ranges between ($0.5\text{--}2^{\circ}\text{C}$ (Celsius)). Results obtained from numerical and optimization models were validated with corresponding findings from experiments.

Beyond conventional cabin temperature regulation, Kim et al. [23] developed thermoelectric cooling (TEC) units capable of supplying cooled air from the rear-seat ceiling. Such units are distinguished by an output of 90.715 W . By integrating energy storage components with TECs and thermoelectric generators, a self-powered cooling solution was realized for the rear-seat headspace. Vehicles parked outdoors are exposed to pronounced temperature fluctuations across seasons, reaching extremely high cabin temperatures during by their compact configuration, ease of installation, and silent, vibration-free operation. As shown in Fig. 2b, the proposed arrangement achieved a rapid temperature reduction within a localized volume equivalent to the size of an adult head, lowering the temperature by 19°C in three minutes. Twelve thermoelectric generators were placed along the vehicle exhaust pipe to enable waste heat recovery and autonomous operation. At a 0.37°C operating temperature, the generators delivered an entire electrical summer and significantly reduced temperatures in winter.

Such extreme thermal conditions increase air-conditioning demand and fuel consumption, while in new energy vehicles (NEVs), air-conditioning operation results in a substantial reduction in available battery power. To address this problem, as can be seen in Fig. 2c, Srivastava et al. [24] suggested a solar powered thermoelectric heating and cooling system. Localized TEC systems seem to perform better than whole-cabin cooling since they allow focusing on those areas where passengers are present and thus need cooling and minimize the required heat load. Thus, Wan et al. [22] improved thermal comfort for the driver, while Kim et al. [23] managed to achieve a 19°C temperature drop in three minutes within the confined space of the rear seat headspace. The solar-powered system of Srivastava et al. [24], however, holds promise for minimizing reliance on battery power of the vehicle. Summaries of the most recent works are listed in Table 1.

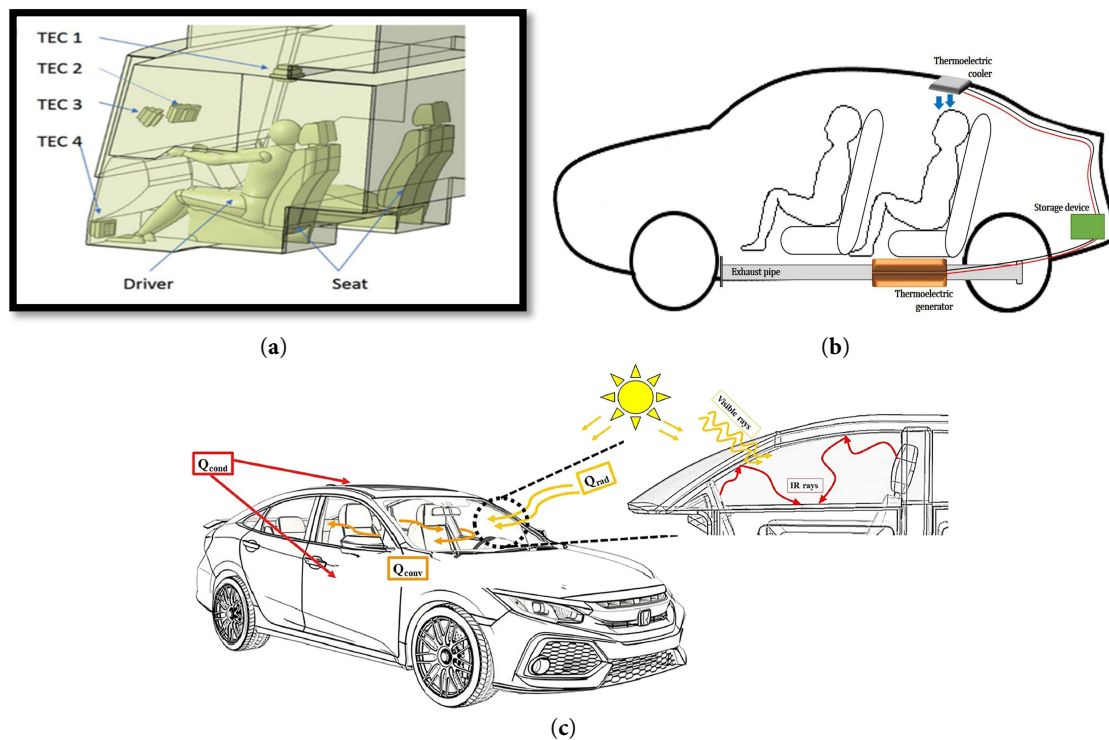


Figure 2: Selected applications of thermoelectric cooling technologies in vehicles (a) Computer-aided design model illustrating the vehicle cabin, driver, and integrated thermoelectric coolers (TECs) [22]. (b) Schematic of the integrated thermoelectric cooler and power generator [23]. (c) The schematic presents a vehicle exposed to summer solar radiation incorporating a solar-assisted thermoelectric system for cabin cooling and heating [24].

Table 1: Summary of recent research on thermoelectric vehicle applications.

Name	Type of Work	Main Object	Main Finding	Significance	Methodological Comparison
Su et al. [25]	Numerical and Experimental	Enhancing the effectiveness cooling under different operating conditions	TEC seats improved thermal comfort by 18.96%	Localized comfort improvement	BCs: thermal boundary conditions with controlled air temperature, forced airflow, pressure outlet, and radiative heat transfer; Numerical: 3D CFD simulation of airflow and heat transfer; Validation: experimental comparison.

Table 1: *Cont.*

Name	Type of Work	Main Object	Main Finding	Significance	Methodological Comparison
Attar [26]	Experimental and Numerical	To design and optimize a zonal thermoelectric cooling system for electric vehicles.	A 12-module system achieved ~1000 W cooling with COP 1.09 and 19.9°C outlet air	High-capacity TEC potential	BCs: ambient conditions, air and liquid inlet temperatures, convective heat transfer at surfaces, and electrical current input; Numerical: analytical thermal model with optimization; Validation: comparison with experimental data.

4 Applications of Thermoelectric Coolers in Compression–Refrigeration System

Refrigeration is a vital technology for food preservation and for cooling a wide range of industrial processes. One of the key challenges currently facing the refrigeration industry is the development of environmentally friendly cooling technologies [27,28]. In the food sector, refrigeration plays an essential role in reducing food waste, extending product shelf life, and improving food quality through better control of production and storage conditions. It also helps in enhancing agricultural productivity by controlling plant vegetative cycles and is an essential component in home kitchens for preserving food freshness and in the healthcare sector for preserving blood, vaccines, and medications [16,29]. Consequently, research and development in the production of cold in research laboratories across the globe are underway to develop innovative and sustainable cold production methods. These emerging technologies include magnetic refrigeration using the magnetocaloric effect, solar refrigeration using solar energy, acoustic refrigeration using sound waves, and thermoelectric cooling, which uses thermoelectric modules (TEMs) working as thermoelectric coolers (TECs) using the Peltier effect to produce temperature differences. All these emerging technologies aim to minimize the environmental effects associated with the use of conventional refrigeration systems by using alternative energy sources and new physical phenomena [30,31]. Fenton et al. [3] reported that the PCM-assisted solar-powered thermoelectric refrigeration system reached the target food-storage temperature of 5°C within 2.22–4.15 h and achieved a COP of 0.69. The addition of water cooling through copper pipes accelerated the cooling process by approximately 3000 s; however, the COP decreased to 0.2 when the energy consumption of the auxiliary thermal bath was included, indicating a trade-off between faster cooling and increased auxiliary energy demand, as illustrated in Fig. 3a. Cuce et al. [32] demonstrated that enhancing hot-side heat rejection using a nanofluid-driven water-to-air heat exchanger significantly improved TEC thermal performance. Among the investigated nanofluids, Al₂O₃–water at 1 wt% provided the best performance, increasing the temperature difference by 55.1% with load and 26% without load, with average COP values of 0.43 and 0.41, respectively, as shown in Fig. 3b. In comparison, Siddique et al. [33] showed that PCM integration provided superior temperature stabilization and reduced continuous energy demand. Their system maintained temperatures below 4°C continuously at an input power of 11.4 W and for 26 h at a minimum power input of 4 W, while the PCM enabled nearly 7 h of passive cooling without energy input. The system also achieved a COP of 0.75 at a temperature difference of 19°C, as presented in Fig. 3c. Compared with the other approaches, Ykrelef et al. [34] achieved the highest reported COP of 0.75 and provided nearly 7 h of passive cooling through PCM integration. Fenton et al. [3] showed that water cooling accelerated the cooling process by approximately 3000 s, but the COP decreased from 0.69 to 0.2 when auxiliary energy consumption was included. Meanwhile, Siddique A. R. M. et al. [33] demonstrated that enhanced hot-side heat rejection using Al₂O₃–water nanofluid increased the temperature difference by

up to 55.1%, although the average COP remained around 0.41–0.43. Table 2 represents a summary of the most recent studies involved.

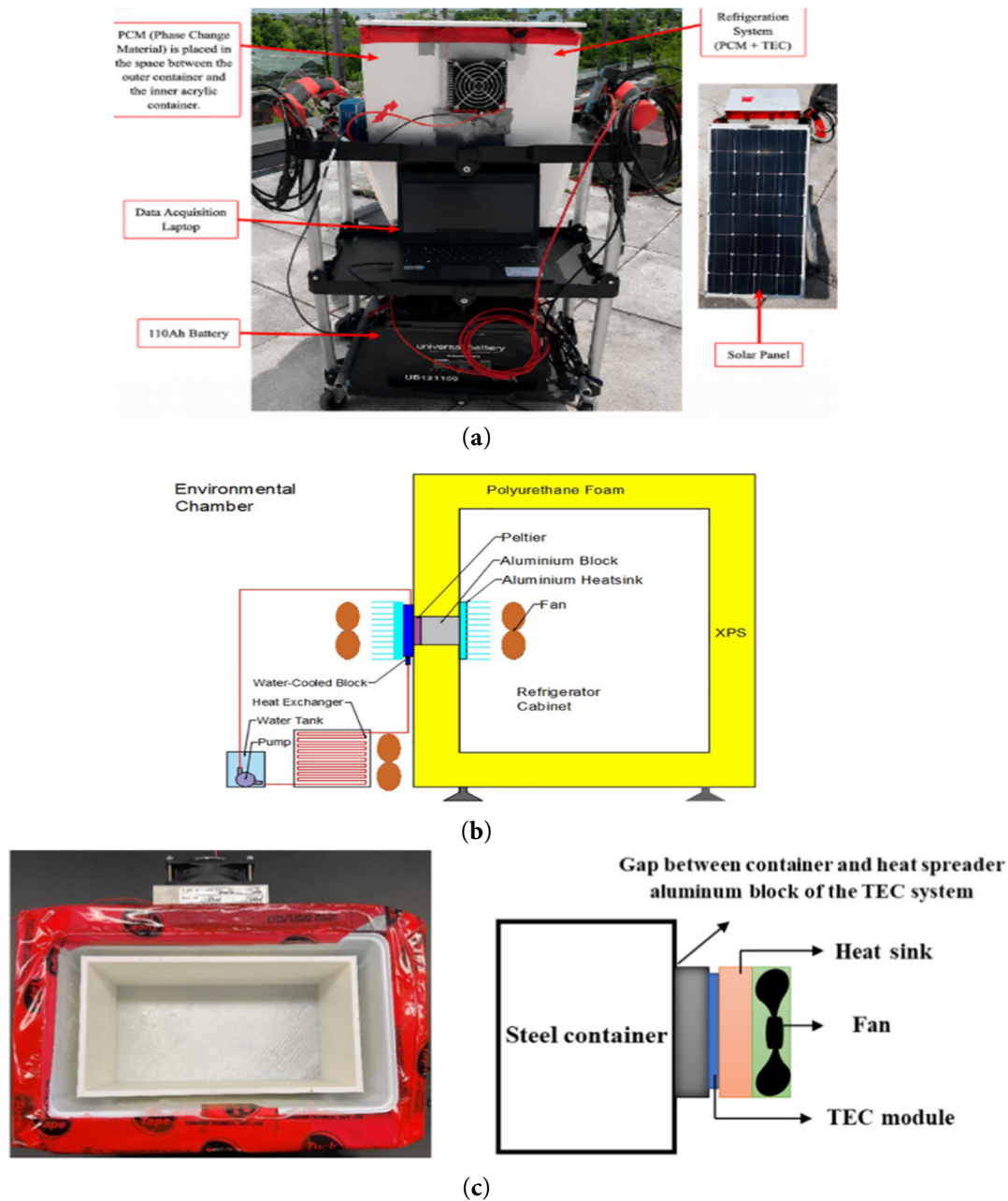


Figure 3: Several studies have investigated the application of thermoelectric coolers (TECs) in Compression-Refrigeration system. (a) novel thermoelectric food storage system incorporating phase change materials [3]. (b) Schematic of the experimental setup for the developed TEC system [32]. (c) A thermoelectric module-integrated food storage container [33].

Table 2: Summary of recent research of Thermoelectric coolers in Compression–Refrigeration system.

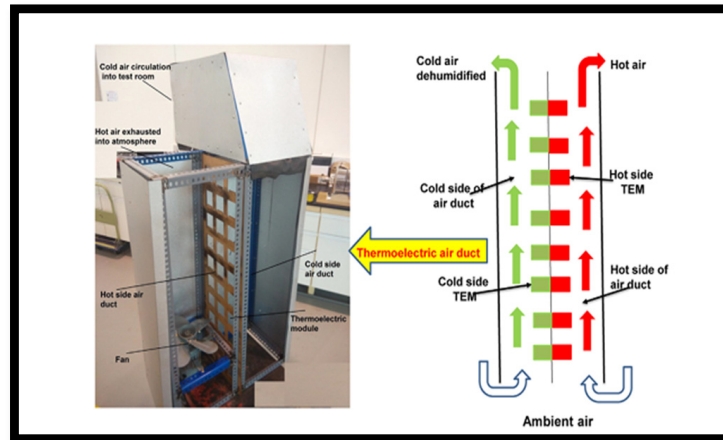
Name	Type of Work	Main Object	Main Finding	Significance	Methodological Comparison
Ykrelef et al. [34]	Experimental and numerical	To design and test a thermoelectric cooler (TEC) prototype operating near room temperature.	The temperature dropped from 19.6°C to 1.6°C, achieving a COP of about 0.9 using series and parallel connections	Efficient TEC cooling near room conditions	BCs: ambient thermal conditions, cold-side temperature control, and humidity effects; Numerical: artificial neural network model; Validation: statistical analysis of experimental data.
Söylemez et al. [35]	Experimental and numerical	To develop and validate a CFD model to predict the cooling time of a TEC-cooled fresh food compartment.	The package cooled from 25 to 10°C in 146.5 min; CFD error was <10% (upper) and 37–71% (lower).	Reliable CFD prediction for TEC cooling	BCs: inlet airflow conditions, ambient temperature, and wall thermal conditions; Numerical: CFD simulation; Validation: comparison with experimental results
Fu et al. [36]	Experimental and numerical	evaluate the performance of a hybrid VCR–thermoelectric refrigeration system for deep freezer applications.	The VCR–TE system reached <−20°C, improved COP to 0.54 (1.5 A), increased Q_c to 71.5 W (~30%), and the best fin height was 30 mm	Hybrid VCR–TEC performance enhancement	BCs: ambient conditions, freezer temperature, airflow, and imposed heat flux; Numerical: CFD simulation; Validation: experimental comparison.
Zhang et al. [37]	Experimental and numerical	Optimize power sharing between TEC and) Vapor Compression Refrigeration) VCR to maximize COP and cooling.	Optimal θ improved TEC–VCR performance: at 100 W, power allocation ratio $\theta = 0.52$ reached −55.23°C and COP = 0.13	Optimized power distribution improves cooling	BCs: ambient conditions, cooling load, and power input distribution; Numerical: mathematical model; Validation: comparison with experimental data.
Elnagga et al. [38]	Experimental and numerical	To optimize a PV-powered thermoelectric mini refrigerator for maximum COP and minimum energy use.	The system can operate effectively on solar power, with an optimized COP of 71.089%	Solar-powered TEC feasibility	BCs: electrical input conditions, ambient temperature, and internal cooling control parameters; Numerical: MATLAB-based model; Validation: experimental comparison.
Gökçek M. and Şahin F. [39]	Experimental	To evaluate the impact of a water-cooled minichannel heat sink on a thermoelectric refrigerator's cooling and COP	To evaluate the impact of a water-cooled minichannel heat sink on a thermoelectric refrigerator's cooling and COP	Heat sink enhancement for TEC performance	BCs: electrical input, water cooling conditions, and ambient temperature; Method: experimental study; Validation: direct experimental measurements.
Bozorgi et al. [40]	Experimental	To evaluate a PCM-based thermoelectric refrigerator for food cooling and its environmental impact	The PCM-based TE refrigerator kept food below 5°C for 7 h without electricity, provided 29.4% weekly cooling time without power, and showed lower environmental impacts in	PCM improves cooling without power	BCs: thermal storage conditions using phase change material and ambient environment; Method: experimental study; Numerical: not included; Validation: experimental performance evaluation.

Table 2: Cont.

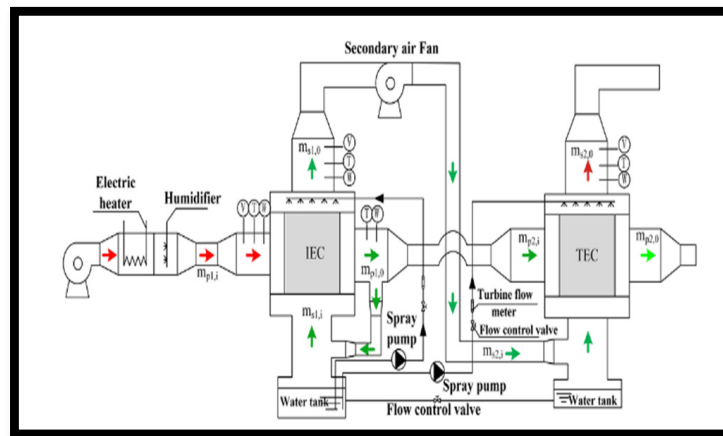
Name	Type of Work	Main Object	Main Finding	Significance	Methodological Comparison
Riffat et al. [41]	Experimental	To evaluate heat pipes and PCM for improving thermoelectric refrigeration.	Encapsulated PCM improved thermoelectric refrigerator performance and provided thermal storage, while heat pipes enhanced heat transfer and reduced reverse heat flow during power failure	PCM and heat pipe enhance TEC efficiency	BCs: heat transfer enhancement conditions using PCM and heat pipes; Method: experimental study; Validation: experimental performance analysis.
Liu et al. [42]	Experimental	To test a 37.8 L two-stage thermoelectric freezer under different conditions.	It reached -14.9°C (25°C ambient), with $\Delta T = 62.1$ K, 53.50 W cooling capacity, and peak COP of 0.237 (TTEM) and 0.153 (freezer).	Two-stage TEC improves freezing performance	BCs: ambient conditions and staged cooling operation; Method: experimental study; Validation: measured performance data.
Rudresha et al. [43]	Numerical	Optimize a Peltier thermoelectric refrigerator design using CFD (ANSYS Fluent).	Sharp-edge geometry gave the best cooling, with $\Delta T \approx 7.5-9.4^{\circ}\text{C}$.	Geometry optimization enhances TEC cooling	BCs: initial thermal conditions, domain definition, and turbulent flow conditions; Numerical: CFD simulation using finite volume method; Validation: comparison with experimental data.
Hu and Shen [44]	Experimental	Evaluate the performance of a thermoelectric freezer system	Achieved $\approx -16^{\circ}\text{C}$, cooling ≈ 75 W, and COP ≈ 0.45 .	ractical feasibility of thermoelectric freezer for residential cooling	BCs: ambient + convection + water cooling + insulation; Method: experimental; Numerical: none; Validation: measured data.

5 Applications of Thermoelectric Coolers in Enclosed Space Cooling

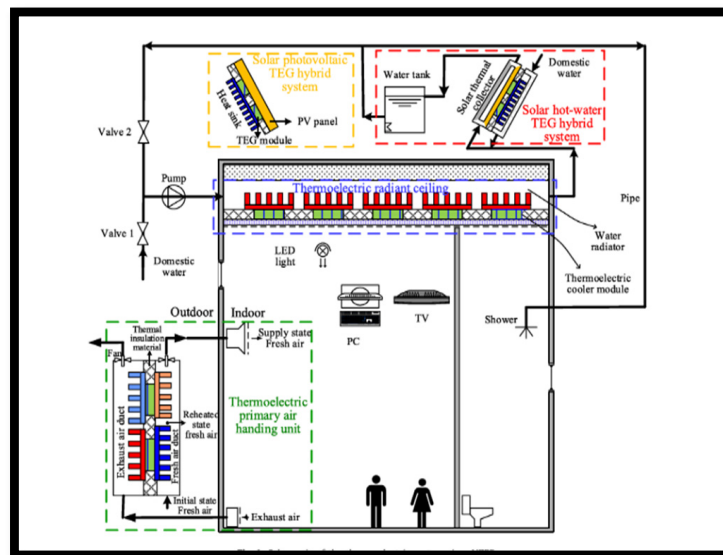
Thermoelectric cooling (TEC) has gained increasing attention for enclosed-space cooling due to its capability to provide localized and controllable thermal regulation within confined volumes. The integration of TEC in enclosed spaces offers a compact and scalable cooling approach, particularly where conventional air-conditioning systems are impractical or inefficient. Irshad et al. designed and configured a novel integration in an air duct combined with a PV wall to cool a closed test room, as shown in Fig. 4a. The proposed system achieved a maximum indoor temperature reduction of 6.8°C, a cooling capacity of 517.24 W, and a COP of 1.15 at optimal operating conditions. The results demonstrated that PV-assisted thermoelectric cooling is a viable, refrigerant-free solution for energy-efficient cooling of enclosed spaces [45]. Duan et al. [46] developed a novel hybrid air-conditioning system integrating indirect evaporative cooling with air-cooled thermoelectric cooling to overcome the efficiency limitations of conventional cooling systems under hot and humid conditions. The proposed system effectively utilizes natural cooling sources while enabling precise control of air temperature and humidity through thermoelectric modules. Experimental and numerical results demonstrated that the system can cool supply air below the dew point temperature while achieving a high coefficient of performance, indicating its strong potential for energy-efficient cooling of enclosed spaces in building applications Fig. 4b. Shen et al. [47] developed and evaluated an integrated thermoelectric cooling and power generation system for application in net zero energy buildings. Thermoelectric radiant ceilings and a thermoelectric primary air handling unit were employed to replace conventional Heating, Ventilation, and Air Conditioning (HVAC) systems for cooling enclosed spaces while maintaining indoor thermal comfort and air quality. Additionally, thermoelectric generators were integrated with photovoltaic and solar hot-water systems to enhance renewable energy production. Case study results demonstrated that the proposed system provided sufficient cooling and heating and increased annual solar energy generation by approximately 34% (about 767 kWh), transforming the building from a non-zero energy building into a plus-energy building as shown in Fig. 4c. Cai et al. [21] proposed an active thermoelectric ventilated (ATEV) system integrated with the building envelope to enhance built space cooling. A network-based thermodynamic model combined with finite-time thermodynamics was developed to evaluate cooling capacity, coefficient of performance (COP), and entropy generation. The system performance was analyzed under different operating currents, numbers of thermoelectric coolers, and heat exchanger configurations (parallel and counter flow). Results showed that the counter-flow configuration achieved higher cooling capacity and better overall thermal performance, while excessive numbers of thermoelectric modules led to reduced efficiency for energy-efficient cooling of enclosed built spaces. Irshad et al. [45] achieved a 6.8°C indoor temperature reduction and a COP of 1.15 using PV-assisted TEC cooling, while Duan et al. [46] improved temperature and humidity control by integrating indirect evaporative and thermoelectric cooling. Shen et al. [47] increased annual solar energy generation by approximately 34%, whereas Zhou Y et al. [48] in Fig. 4d investigated the performance of a novel hybrid regenerative cross flow thermoelectric cooling with indirect evaporative cooling system at different air flow rates. It was found that the maximum performance depends on the optimal flow rate and the length ratio of the wet channel. Number of related works from literature are summarized in Table 3.



(a)



(b)



(c)

Figure 4: Cont.

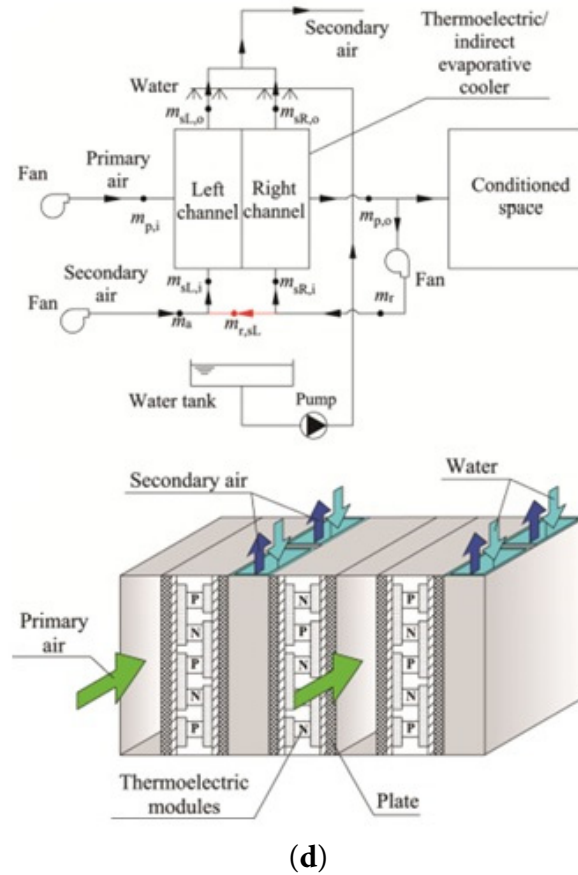


Figure 4: Selected Engineering Applications Thermoelectric in enclosed space cooling. (a) Description of an air duct system integrated with thermoelectric cooling [45]. (b) Schematic illustration of the experimental setup [46]. (c) Conceptual schematic of thermoelectric-based systems within Net Zero Energy Building (NZEB) [47]. (d) Schematic representation of an active thermoelectric ventilation system [48].

Table 3: Summary of recent research on thermoelectric coolers for space cooling applications.

Name	Type of Work	Main Object	Main Finding	Significance	Methodological Comparison
Zhou Y et al. [48]	Numerical	Optimize a TEC-assisted indirect evaporative cooler for building space cooling	Higher COP and dew-point effectiveness than conventional designs, with clear optimal conditions.	Improved IEC–TEC cooling efficiency	BCs: inlet air temperature, humidity, and flow conditions; Numerical: mathematical model; Validation: not reported.
Ji et al. [49]	Numerical	Simulate a TEC heating–cooling system for air sterilization.	Air > 65°C and COP up to 5.4	High-temperature TEC system capability	BCs: inlet velocity, no-slip walls, and pressure outlet; Numerical: CFD simulation; Validation: grid independence test.
Manikandan et al. [50]	Numerical	To improve TEC performance for building cooling using a modified pulse operation.	The pulsed method achieved ~600 W cooling and COP = 1.01, outperforming steady mode (+23.3% cooling, +2.12% COP); rectangular pulse was best	Pulse operation enhances TEC performance	BCs: convective hot side and constant heat flux at cold side; Numerical: 1D transient finite difference model; Validation: comparison with literature and experimental trends.
Tian et al. [51]	Numerical	To design a tube-bundle tubular TEC as a new air cooler	3D simulations showed it can work effectively as an air cooler, and performance depends on thermal + geometric parameters	Tubular TEC effective for air cooling	BCs: internal temperature boundary, insulated outer surface, and electrical input; Numerical: 3D CFD (finite element method); Validation: analytical comparison.
Mansoor et al. [52]	Numerical	To assess the transient performance of a TEC-assisted air-cooling system.	Lower air velocity improved heat flux ratio (HFR) and ΔT ; higher velocity increased heat flux	Airflow optimization improves heat transfer	BCs: air & water inlet (constant velocity & temperature), zero-gradient outlet, TEC hot/cold sides (Th, Tc); Numerical: 3D transient CFD (Open FOAM, FVM); Validation: comparison with experimental & theoretical studies (COP error 3.64–20.3%).
Sun et al. [53]	Numerical	TEC-assisted PCM cold storage unit.	TEC sped up PCM freezing and improved cooling/COP under optimal conditions.	PCM integration improves cooling performance	BCs: zero velocity, adiabatic walls; Numerical: 3D CFD; Validation: experimental comparison ($\approx 6\%$)
Jabbar et al. [54]	Numerical	TEC air-cooling system for space cooling in hot climates.	Validated ($\sim 9\text{--}13\%$ error); higher air velocity reduced ΔT .	Validated TEC performance in hot climates	BCs: inlet velocity and temperature, wall s no-slip, zero-gradient; Numerical: 3D CFD; Validation: literature comparison ($\approx 10\%$)
Zhou et al. [55].	Numerical and theoretical	Analyze a TEC-assisted indirect evaporative cooler	It can cool air below dew point, with optimal TEC/airflow settings giving high COP	Sub-dew point cooling using TEC–IEC	BCs: steady inlet conditions; Numerical: analytical model; Validation: not reported
Liu et al. [56]	Experimental and numerical	Develop a building-integrated a separately-configured SC-TEC for space cooling.	Cooling output $16.66 \rightarrow 18.82 \text{ W/m}^2$ and COP +1.3%.	Building-integrated TEC feasibility	BCs: constant hot-side temperature; Numerical: FEM (COMSOL); Validation: experimental validation

Table 3: *Cont.*

Name	Type of Work	Main Object	Main Finding	Significance	Methodological Comparison
Zhang et al. [57]	Experimental and numerical	To design and test a compact high-performance TEC cooling/heating system.	It achieved high heating (COP_h 2.18, Q_h 1088.8 W) and cooling (Cop 1.18, Q_c 588.8 W).	High-performance TEC for dual operation	BCs: controlled airflow, water temperature, and power input; Numerical: RSM-based model; Validation: experimental comparison with PTC heater
Gillott et al. [58].	Experimental and numerical	Evaluate a small-scale building TEC cooling unit	8 TECs achieved ~220 W cooling with $COP \sim 0.46$; PV becomes viable at $\leq £1.25/W$.	Small-scale TEC viable with PV support	BCs: controlled chamber conditions, temperature difference, and electrical input; Numerical: mathematical model; Validation: laboratory experimental testing
Wang et al. [59]	Experimental and theoretical	Study and test a heat-pipe-assisted TEC cooling system.	cooling improved; higher voltage and a spoiler duct enhanced performance.	Heat pipe enhances TEC cooling efficiency	BCs: hot/cold side temperatures, airflow, and electrical input; Numerical: 1D heat transfer model; Validation: experimental testing.
Zhou et al. [60]	Experimental and numerical	To assess and optimize a two-stage IEC/TDEC cooling system	Achieved comfort by tuning parameters; model accuracy $\pm 10\%$; optimization improved COP.	Optimization improves comfort and COP	BCs: steady-state inlet, no heat loss, and uniform wall conditions; Numerical: finite difference model; Validation: experimental comparison.
Yang et al. [61].	Experimental and numerical	Model and validate a confined-space TEC cooler.	$<10\%$ error; 15 TECs reached $\sim 17^\circ C$.	Reliable TEC cooling in confined spaces	BCs: steady-state, ignore humidity coupling, 1D wall heat transfer, uniform air temperature (lumped); Numerical: thermal resistance network model + analytical equations; Validation: experimental comparison (error $<10\%$).
Saini et al. [62]	Numerical	To model thermoelectric air conditioning and compare graded vs. constant TE materials	Graded materials boost cooling but lower COP; constant materials at low current can reduce power use at equal cooling	Material selection impacts TEC efficiency	BCs: steady-state, uniform T_c & T_h , constant fluid properties, negligible radiation & contact resistance Numerical: analytical model (CPM) + 1D FEM (graded materials); Validation: literature comparison (no; direct experiment).
Ahmed et al. [63]	Experimental and numerical	Evaluate a PV-PCM-TEC building cooling system	PV power ≈ 857 W, indoor temperature reduction $\approx 17.5^\circ C$, max $COP \approx 6.1$).	PV-PCM-TEC system enhances building cooling	BCs: transient heat transfer; Numerical: Runge-Kutta model; Validation: experimental comparison.
He et al. [64]	Numerical	Optimize a TEC window frame for building	Uniform power improves performance; COP rises with more active cells and higher airflow (up to a limit)	Design optimization improves TEC window performance	BCs: inlet/outlet + adiabatic; Numerical: CFD + model; Validation: cross-validation

Table 3: Cont.

Name	Type of Work	Main Object	Main Finding	Significance	Methodological Comparison
Zhao et al. [65]	Experimental	To test a TEC-PCM prototype for space cooling.	It achieved temperature difference (ΔT) $\approx 7^\circ\text{C}$, COP ≈ 0.87 (max 1.22), and $\sim 33.5\%$ energy saving.	TEC-PCM improves energy efficiency	BCs: temp + current control; Numerical: model; Experimental: prototype; Validation: Experimental vs. model
Irshad et al. [66]	Experimental and numerical	To assess a TEC air-duct cooling system for buildings	It reduced temperature ($1.2\text{--}5.3^\circ\text{C}$) and humidity ($5\text{--}31\%$), with COP $0.39\text{--}0.68$ and $\sim 38.8\%$ energy	TEC duct cooling reduces temperature and humidity	BCs: ambient conditions, input current $2\text{--}7\text{ A}$, airflow control; Numerical: TRNSYS simulation model; Validation: experimental comparison (error $<0.6^\circ\text{C}$)
Ibáñez-Puy et al. [67]	Theoretical	To design a Peltier-based active façade for buildings.	A theoretical façade module integrating Peltier cells was proposed for efficient heating/cooling.	Facade-integrated TEC enhances building efficiency	BCs: voltage + ΔT ; Experimental: real prototype; Validation: theoretical comparison.
Piantanida [68]	Experimental	To test a PV-powered TEC façade	Indoor temperature improved by $\sim 3\text{--}4\text{ K}$.	PV-powered TEC improves indoor conditions	Numerical none
Han et al. [69]	Experimental and Numerical	Optimize and test a thermoelectric ventilator for building heat recovery.	Max COP = 4.78 (summer) and 4.16 (winter), with main losses in the TEC modules.	Optimized TEC ventilation boosts performance	BCs: inlet fresh/exhaust air temperatures, airflow rate, working current; Numerical: mathematical model + simulation program; Experimental: ventilator testing; Validation: simulation vs. experiment (deviation $\approx 2.65\%$).
Harren Lewiset al. [70]	Numerical	Optimize a TEC-based active window to reduce building heat gain	The Active Thermal Insulator (ATI) window can outperform normal windows, and TEC selection is key.	ATI window reduces building heat gain	BCs: indoor/outdoor temperature, solar radiation, PV power; Numerical: optimization + mathematical model (MATLAB); Validation: no experimental (optimization-based study).
Cheng et al. [71]	Experimental	Develop and test a solar-powered TEC cooling module for building space cooling.	Higher water flow improved cooling, achieving up to 16.2°C air temperature reduction in the model house.	Solar TEC enhances space cooling performance	Numerical: none
He et al. [72]	Experimental and Theoretical	To evaluate a PV/T-driven thermoelectric system for room cooling/heating	Room temperature reached 17°C , COP > 0.45 , water heated by $\sim 9^\circ\text{C}$, and thermal efficiency was 12.06%	PVT-TEC system enhances thermal efficiency	BCs: solar irradiance, ambient temperature, electrical input (current/voltage); Numerical: model mathematical Validation: simulation vs. experiment (good agreement, error $\approx 1\text{--}2^\circ\text{C}$)

Table 3: Cont.

Name	Type of Work	Main Object	Main Finding	Significance	Methodological Comparison
Xu et al. [73]	Experimental and Theoretical	To test a PV-powered thermoelectric window for space heating/cooling.	Experiments validated the model and confirmed the window can control heat flow through the envelope	TEC window controls building heat flow	BCs: outdoor/indoor temperature, solar radiation, applied voltage (≈ 20 V); Numerical: transient heat transfer model; Experimental: prototype window testing; Validation: experimental vs. simulation comparison
Luo et al. [74]	Experimental and numerical	To assess a PV-thermoelectric wall Building Integrated Photovoltaic + Thermoelectric wall system (BIPVTE)	Reduced annual heating/cooling load, with up to 172% higher energy savings	BIPV-TEC reduces building energy demand	BCs: indoor/outdoor temperature, air duct temperature, current; Numerical: dynamic heat transfer + ANN model; Validation: experimental comparison.
Luo et al. [75]	Numerical	To model and assess a Building Integrated Photovoltaic + Thermoelectric) BIPVTE (wall for reducing building heat gain	The Building Integrated Photovoltaic + Thermoelectric) BIPVTE (wall reduced daily heat gain by $\sim 70\%$ compared with a conventional wall.	BIPV-TEC wall reduces heat gain	BCs: thermal + solar + airflow; Numerical: coupled model (PV + state-space + TE); Validation: experimental
Lu et al. [76]	Numerical	To model and optimize a thermoelectric radiant panel for space cooling/heating.	Validated results identified optimal panel/insulation thickness and uniform TEM placement for best performance	Optimized design improves TEC performance	BCs: indoor/outdoor + solar + airflow; Numerical: dynamic model (state-space); Validation: experimental comparison.
Liu et al. [77]	Experimental	Evaluate a solar TEC air conditioner that also supplies hot water	Achieved COP up to 4.51; 2.59 (cooling) and 3.01 (heating) in water-source mode.	Solar TEC achieves high COP	BCs: ambient temperature, indoor air temperature, water tank conditions, and convective heat transfer (air + water cooling). Numerical: mathematical heat transfer model of thermoelectric system. Validation: comparison between simulation and experimental results.
Liu et al. [78]	Experimental	Test a PV-driven TEC radiant wall for building cooling/heating.	Inner wall surface was $3\text{--}8^\circ\text{C}$ cooler; reduced load and identified optimal TEC settings.	PV-TEC reduces building thermal load	BCs: solar radiation, ambient temperature, indoor temperature, airflow channel, and thermal insulation boundaries. Numerical: PV + thermoelectric theoretical/analytical modeling. Validation: experimental measurements under real operating conditions.

Table 3: *Cont.*

Name	Type of Work	Main Object	Main Finding	Significance	Methodological Comparison
Liu et al. [79]	Experimental	To test a solar-powered TEC cooled ceiling with displacement ventilation for building cooling	Performance improved by voltage control; cooling heat flux > 60 W/m ² (COP 0.9) and heating heat flux > 110 W/m ² (COP 1.9).	Voltage control enhances TEC performance	BCs: ambient temperature, indoor temperature, airflow convection, and radiant heat transfer. Numerical: heat transfer equations for thermoelectric modules (analytical model). Validation: experimental testing and measured performance data.
Al-Nimr et al. [80]	Numerical	Assess a dual-mode TEC/TEG solar system for buildings.	redicted performance, energy savings, and payback period under Mediterranean climate.	Solar TEC enhances energy savings	BCs: ambient temperature, solar radiation, hot/cold junction temperatures, and airflow conditions; Numerical: MATLAB/SIMULINK model using heat balance equations for cooling/heating and power generation modes; Validation: no direct experimental validation (simulation-based study).
Van Dessel et al. [81]	Numerical	A TEC-integrated double glazing for building space heating/cooling.	Effective for heating; cooling needs further optimization.	TEC glazing supports building thermal control	BCs: surface thermal boundaries (indoor/outdoor), radiation and convection inside air cavity, and material interfaces; Numerical: finite element model (FEM) for steady-state heat transfer analysis; Validation: experimental validation through temperature comparison between model and measurements.
Abdalla et al. [82]	Experimental and numerical	To assess TEC as a pre-cooling method to improve air conditioning efficiency	TEC achieved higher COP (2.8 vs. 1.56) with optimal performance at 308 K, but higher exergy losses.	TEC can enhance HVAC efficiency and offers a promising sustainable cooling solution.	BCs: inlet velocity/temp + pressure outlet + insulated walls + isothermal TEC; Numerical: CFD; Validation: exp vs. CFD (error < 7%).
Lu et al. [83]	Numerical	To evaluate the performance of a thermoelectric-integrated heat exchanger for enhancing air cooling.	TEC integration significantly improved cooling capacity, achieving up to ~35–49% enhancement compared to the conventional system.	TEC technology shows strong potential to improve cooling efficiency in confined and high-temperature environments.	BCs: inlet velocity/temp + pressure outlet + insulated walls + TE current + water cooling BC; Numerical: 3D CFD Validation: exp + literature; Results: cooling ↑ up to ~50%, optimum current 6 A.

6 Thermoelectric Usage in Other Applications

Recently, there has been increasing awareness that thermoelectric cooling, which is also referred to as the Peltier effect, can be a highly promising alternative cooling solution due to the fact that it is state-of-the-art, compact, silent, and capable of providing precision temperature control. While vapor compression cooling devices involve using refrigerants and having mechanical parts, TEC cooling devices are devoid of both, which makes them very appealing, especially for highly reliable, miniaturized, and environmentally friendly uses. Consequently, much research and development effort has gone into TEC cooling solutions for different purposes, such as wearable devices and smart textiles for local cooling, electronics and high-power devices for hotspot cooling, space applications for thermal stability in harsh conditions, and lithium-ion battery systems for improved temperature uniformity and safety.

6.1 Wearable Device Applications

Thermoelectric coolers (TECs) are very significant in wearable technology, since they help in providing localized cooling effectively, thereby making the device more comfortable and efficient. Through TECs, there can be proper temperature control, which cannot be achieved through other cooling technologies. This is especially important as localized cooling not only saves energy but also prolongs battery life. Moreover, the compact and flexible nature of TECs enables effortless integration with a wide range of wearable device designs, thus promoting personalized thermal management.

However, it is important to keep the body at a comfortable temperature for health reasons. However, traditional thermal management systems involve air-conditioning systems that cool the entire enclosed space. Although efficient, these systems consume a lot of energy and often involve the use of environmentally hazardous refrigerants. To overcome this, Hong et al. [6] proposed a wearable flexible thermoelectric device (Fig. 5a) that can be used for individualized cooling when placed directly on the body. The device consumes low power and does not emit any environmental pollutants. Tests indicated that it could provide a cooling rate of more than 10°C and a relatively high COP ($\text{COP} > 1.5$). Such devices could greatly decrease the demand for cooling systems by providing individualized cooling that is locally based. However, wearable TEC systems face challenges in regulating body temperature due to the high thermal resistance of human skin and surrounding air, both of which have low thermal conductivity. To resolve this issue, Kishore et al. [7] investigated the influence of thermal resistance associated with heat sources and heat sinks, as well as the thermoelectric materials thermophysical properties, on overall device performance. An optimized device configuration was developed, demonstrating the capability of the thermoelectric cooler to reduce skin temperature by up to 8.2°C below ambient conditions Fig. 5b. Additionally, compared to traditional commercial thermoelectric modules, the improved design produced a material volume-based cooling efficiency that was almost 500% higher. In flexible thermoelectric cooler (TEC) design, compressive strength plays a vital role, particularly due to the inherent brittleness of Bi_2Te_3 -based materials, which can restrict practical applications. To address this limitation, A composite filler made of silica aerogel, hollow glass microspheres, and polydimethylsiloxane (PDMS) was presented by Gao et al. [84]. The proposed composite exhibits ultra-low thermal conductivity, thereby increasing the gradient of temperature across the encapsulation layer.

Moreover, its honeycomb-like architecture further suppresses heat transfer while simultaneously enhancing the compressive robustness of flexible TECs. By combining hexagonal boron nitride with PDMS to create a radiative cooling film, effective thermal-side heat dissipation was accomplished in addition to encapsulation enhancement. The structural configuration and microstructural features of the composite material are illustrated in Fig. 5c. A pin-fin flexible encapsulation layer was suggested by Wei et al. [85] to

improve the performance of wearable thermoelectric coolers (TECs). As illustrated in Fig. 5d, when used on a stationary human body, the device achieved a power density of $6.63 \mu\text{W cm}^{-2}$. The flexible pin–fin layer was created by curing a liquid metal–elastomer at a temperature of 20°C . Although demonstrated on wearable systems, the proposed flexible pin–fin structure highlights a promising heat-dissipation strategy that can be extended to thermoelectric applications in automotive environments, particularly for localized cooling and low-power energy harvesting. A comparison of these studies shows that Hong et al. [6] achieved a cooling rate exceeding 10°C with a COP above 1.5, whereas Kishore et al. [7] reduced skin temperature by up to 8.2°C and improved volume-based cooling efficiency by nearly 500%. While Gao et al. [84] aimed at improving the mechanical strength and inhibiting heat transfer via a low thermal conductivity encapsulation, Wei et al. [85] used a flexible pin fin structure and demonstrated a power density of $6.63 \mu\text{W cm}^{-2}$.

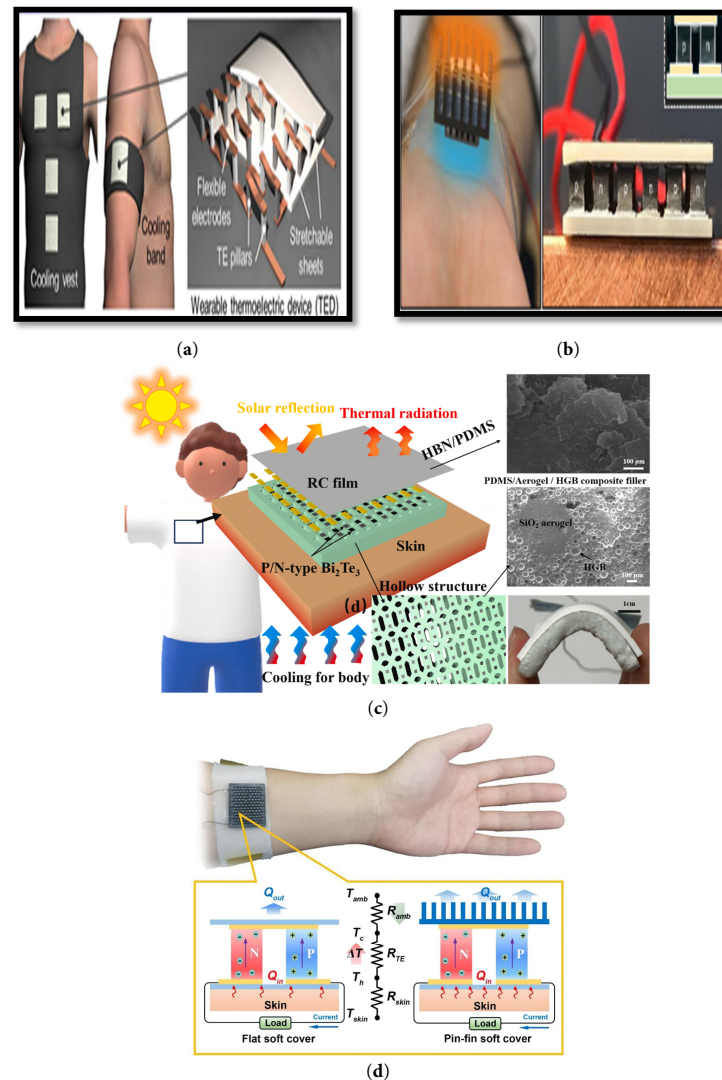


Figure 5: Application of thermoelectric coolers (TECs) in wearable electronic devices. (a) A wearable thermoelectric device designed for personalized human comfort cooling [6]. (b) Personal cooling achieved using wearable thermoelectric modules [7]. (c) A honeycomb-structured wearable TEC fabricated from multifunctional elastomer composites integrated with radiative cooling films [84]. (d) A newly developed wearable TEC featuring a soft protective cover [85].

6.2 Applications in Garments

Ongoing global climate change has led to a marked increase in the frequency, intensity, and duration of summer heatwaves, resulting in a growing incidence of heat-related illnesses and associated mortality. Personal cooling systems that can control skin temperature in a thermally comfortable range provide a promising method for alleviating heat stress. Nevertheless, modern cooling clothing is often restricted by its bulky design and poor controllability of cooling capacity. As a result, creating cooling garments that are wearable, lightweight, and ecological has become crucial. Zhang et al. [86,87] have been conducting research on the design of liquid cooling garments (LCGs) using thermoelectric cooling technology (TECT). Controlling the temperature of inlet water makes the garments able to fulfill the human body cooling demands under a wide range of ambient conditions and exercise levels. The design of the LCG is shown in Fig. 6a. The experimental results show a clear dependence of cooling capacity (CC) on exercise intensity, with a huge difference in the coefficient of performance (COP) among activities such as jogging, sitting, and walking. These results can offer important information for designing cooling garments that can effectively decrease relative humidity and temperature in the microclimate zone, even with high ambient temperatures of up to 40°C, consequently enhancing overall thermal comfort [88]. An LCG that was further improved for the thermal flow field in car cabins was proposed by Zhang and He [87]. The system employs a thermoelectric cooler (TEC) as the active cooling component, with a maximum COP of 0.68, as shown in Fig. 6b. The LCG has low power consumption, with a peak power demand of only 0.15 kWh, which has huge potential in efficient and wearable thermal management. Experimental work was conducted under hot summer conditions inside stationary vehicles. The experimental outcome showed an average temperature drop of about 3°C for the drivers wearing the LCG compared to those without cooling, at ambient temperatures of 37 to 42°C. The experimental outcome proved the effectiveness of the proposed LCG for human body temperature regulation in vehicular environments. The experimental outcome proved the effectiveness of the LCG for human body temperature regulation. Xu et al. [89] created a TEC-assisted ventilated cooling vest to increase individual thermal comfort in warm, hot indoor conditions. The structural arrangement of the vest is shown in Fig. 6c. The thermoelectric cooling unit consists of a 3D-printed shell, in which a TEC module is embedded. The shell is designed with a single air inlet and two air outlets for easy airflow passage. Forced convection is provided by a fan that blows air through the cooling system. The cooled air is then delivered to the vest through PVC tubing. To ensure efficient heat dissipation, a heat exchanger cooled by water is placed on the upper part of the shell, in which a compact pump and cooling tower are used to maintain a constant water temperature. Owing to its compact and integrated design, the system enables efficient regulation of body temperature. Experimental evaluations conducted in hot indoor environments demonstrated that the ventilated vest successfully suppressed the rise in skin temperature and achieved a slight reduction in skin temperature to improve both the wearability and cooling effectiveness of cooling garments. A portable thermoelectric cooling garment was created by Xu et al. [89], as depicted in Fig. 6d. Metabolic heat released by the human body is dissipated through capillary structures and subsequently dissipated via the integrated refrigeration system. The coolant is cycled through embedded pipes to restore residual cooling capacity and enhance the system's overall thermal stability. Experimental evaluations demonstrated that the system achieved a cooling capacity of 340.4 W and a minimum water temperature of 15.7°C. Under an electrical input power of 100 W and an ambient temperature of 30°C. A comparison of these studies shows that Zhang M. et al. [86] found LCG performance to be strongly dependent on exercise intensity, whereas Zhang and He et al. [87] achieved a maximum COP of 0.68 and an average temperature reduction of about 3°C in stationary vehicles. Wang et al. [88] improved thermal comfort using a TEC-assisted ventilated vest with water-cooled heat rejection, while Xu et al. [89] achieved

a cooling capacity of 340.4 W at an electrical input power of 100 W. Overall, the approaches differed mainly in cooling mechanism, operating environment, and targeted thermal demand.

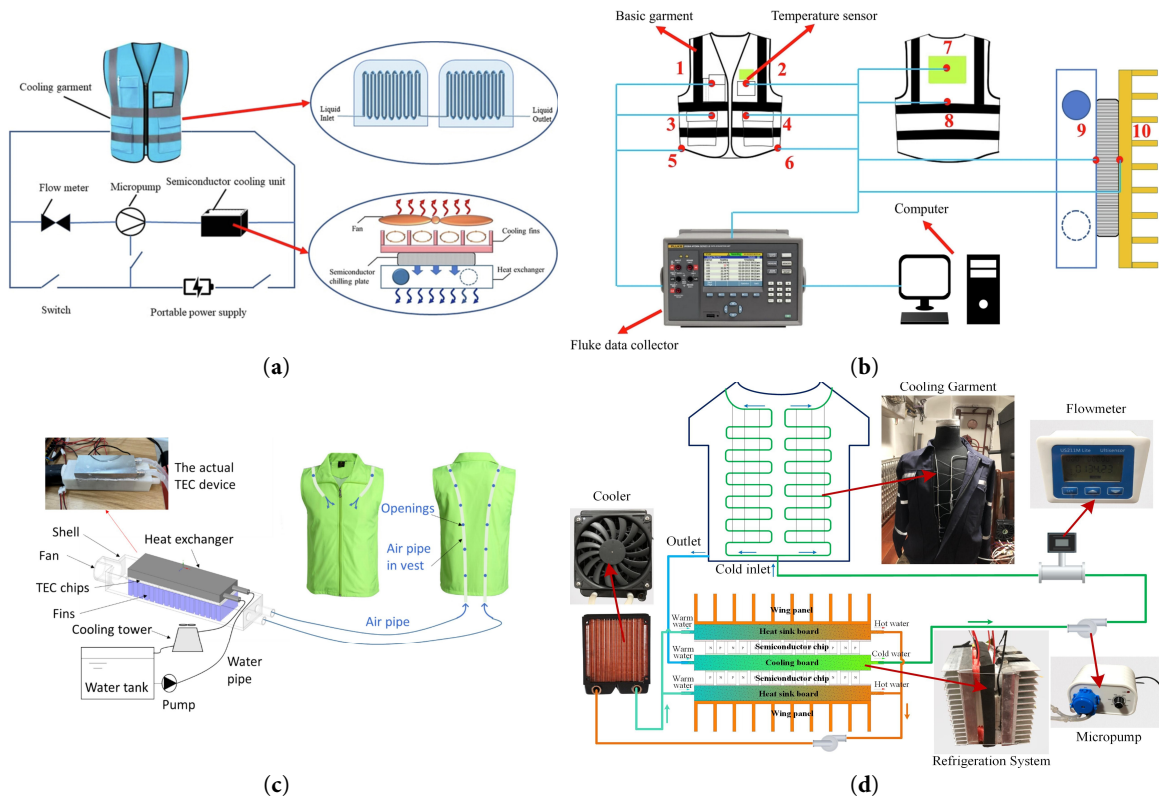


Figure 6: Selected studies on cooling garments for human thermal comfort. (a) A novel liquid cooling garment (LCG) design [86]. (b) Experimental configuration and evaluation criteria for thermal comfort assessment [88]. (c) Schematic illustration and prototype image of a TEC-based air-cooled garment [89]. (d) A thermoelectric cooling garment incorporating a cold-fluid circulation system [90].

6.3 Microchips Applications

Due to the quick development of semiconductor technology and the fabrication of microfluidic chips, the integration density of transistors in central processing units (CPUs) has rapidly increased over the past few decades, leading to a dramatic increase in operating temperatures. The dependability and lifetime of CPUs are seriously threatened by high temperatures and high heat flux density [91]. Thermoelectric coolers (TECs) have received much attention in the field of chip-level thermal management owing to their rapid response time, high, reliability, scalability, flexibility, and absence of moving parts.

The direct integration of TECs onto or within chips enables efficient and localized temperature regulation. To enhance cooling effectiveness, the hot side of a TEC is commonly coupled with a high-performance heat exchanger, like a microchannel heat sink. However, high fabrication expenses and greater parasitic contact thermal resistance at the TEC interface frequently limit conventional microchannel heat sinks. Teardrop-shaped microchannel heat sinks have emerged as a promising alternative, particularly for millimeter-scale applications. Liu et al. numerically investigated nine-millimeter-scale channel cross-sectional geometries, with particular emphasis on economically manufacturable teardrop-shaped designs [91]. The optimized teardrop configuration achieved a thermal–fluid performance evaluation criterion approximately 1.8 times higher than that of conventional rectangular channels. By integrating the millimeter-scale channels directly

into the TEC substrate, parasitic contact thermal resistance was significantly reduced, as illustrated in Fig. 7a. Under this configuration, the cold-side temperature of the TEC was reduced to 18.6°C, corresponding to temperature reductions of 3.5°C and 4.4°C compared with teardrop-shaped and traditional block heat sinks, respectively, under identical operating conditions. Furthermore, it was demonstrated that a prototype thermoelectric cooling system for high-power field-effect transistors could maintain a steady-state temperature of 51.3°C at a heat flux density of 75 kW m⁻². This temperature was 2°C lower than that of systems using traditional block heat sinks and 1.4°C lower than those using teardrop-shaped millimeter channels, highlighting the effectiveness of millimeter-scale teardrop microchannel heat sinks in improving the performance of TEC cooling. Polymerase chain reaction process stabilization using a computerized microfluidic temperature control system developed by Ji et al. [92]. As shown in Fig. 7b, the system is made up of a thermal control board, a thermoelectric cooling module, and graphical user interface software, which enables the simultaneous regulation of temperatures and droplet observation on the chip. In an effort to improve thermal regulation, PID (fuzzy proportional-integral-derivative) control was utilized, and the distribution of temperatures for various reagents was analyzed using numerical simulations. The use of fuzzy PID control improved thermal stability by 67.8% and shortened processing time by 1195 s. Sun et al. proposed a dual thermoelectric–liquid hybrid cooling system for CPU thermal management [93], as shown in Fig. 7c. It was referred to this system as a dual-hybrid system because it comprises an internal TEC coupled directly to the CPU and a liquid cooling loop assisted by an external TEC. The internal TEC rapidly extracts heat from the CPU hotspot, while stainless steel pipes on the hot side facilitate efficient heat dissipation through water circulation. The cooling medium's internal heat accumulation is suppressed by the external TEC [94].

Results from experiments indicated that, with a cooling medium inlet temperature of 27°C, the average CPU temperature was maintained at 41.8°C, well below the safe operating limit of 50°C. These findings demonstrate the effectiveness of dual thermoelectric–liquid hybrid configurations for high-performance CPU cooling applications. As seen in Fig. 7d, Liu et al. suggested a TEC-based temperature control system for a double-emulsion droplet microfluidic device [94]. In order to achieve consistent gradient temperature management on the microfluidic chip, the system included a separate thermal control unit and looked into several approaches. By accounting for the operational characteristics of the TEC [95] and implementing an adaptive fuzzy proportional–integral–derivative (PID) control scheme, continuous gradient temperature control was successfully realized. Compared with conventional PID control, the adaptive fuzzy PID approach exhibited enhanced stability by effectively suppressing temperature overshoot, deviation, and oscillatory behavior. Accurate small-gradient temperature regulation from 10°C to 15°C, 20°C to 25°C, and large-gradient transitions from 20°C to 0°C and back to 20°C were shown by experimental validation. While small-gradient circumstances restricted the highest temperature variation to 0.192°C and the steady-state error to $\pm 0.07^\circ\text{C}$, large-gradient control resulted in a maximum deviation of 0.309°C and a steady-state error of $\pm 0.1^\circ\text{C}$. Also, a comparison of these studies shows that Liu et al. [91] improved TEC heat dissipation through optimized millimeter-scale channels, achieving a thermal–fluid performance approximately 1.8 times higher than conventional rectangular channels. Ji et al. [92] enhanced thermal stability by 67.8% using fuzzy PID control, while Sun et al. [93] maintained the average CPU temperature at 41.8°C through dual thermoelectric–liquid cooling. In contrast, Liu et al. [94] demonstrated precise gradient temperature regulation with steady-state errors as low as $\pm 0.07^\circ\text{C}$ using adaptive fuzzy PID control. Table 4 summarizes the number of works involved from the literature.

Table 4: Summary of recent research on thermoelectric cooling for microchips.

Name	Type of Work	Main Object	Main Finding	Significance	Methodological Comparison
Liao et al. [96]	Experimental	Develop a heat pipe + TEC CPU transient cooler.	The proposed system dissipated >400 W, kept the heat source temperature below 75°C at full load, and improved transient/startup cooling when the TEC was activated	Heat pipe-TEC enhances transient cooling	BCs: heat source + forced convection + conduction + contact resistance + hybrid cooling modes; Numerical: analytical heat transfer model + thermal resistance network; Validation: experimental measurements.
Xie et al. [97]	Experimental	To test active temperature control of a dual-Compensation Chamber (CC) loop heat pipe using TECs	Stable control ($\pm 0.2^\circ\text{C}$) with low power (<3.8 W), better at 14°C and horizontal. Method 2 was fastest (≤ 168 s), while Method 1 may fail in heating.	Precise temperature control with low power	BCs: heat load + water cooling + convection + conduction + insulation + orientation effect; Numerical: energy balance and physical thermal analysis (no CFD); Validation: experimental temperature measurements.
Chang et al. [98]	Experimental	Evaluate a thermoelectric air-cooling module for electronics.	Best at 6–7 A (20–100 W), better at low loads, sometimes worse than an air heat sink	TEC effective at low electronic loads	BCs: heat load + air cooling + convection + conduction + heat spreading; Numerical: thermal network model (analytical); Validation: comparison with experimental measurements.
Huang et al. [99]	Experimental	Assess a thermoelectric water-cooling device for electronics.	Optimum at 7 A; performance worsens as load increases (20–100 W); improvement is effective for loads <57 W.	Optimal performance at specific operating range	BCs: heat source + water cooling channels + air heat exchanger + convection + conduction; Numerical: thermal network model (analytical); Validation: experimental temperature measurements.
Krishna et al. [100]	Experimental	Improve TEC performance using PCM-filled heat sinks.	Higher voltage increased temperatures, higher air velocity reduced them, and the square-pocket heat sink fully filled with PCM gave the best cooling compared with no PCM.	PCM heat sink improves TEC cooling	BCs: TEC + heat sink + PCM + forced convection + phase change heat storage; Numerical: no numerical model (experimental + thermal relations); Validation: experimental measurements with uncertainty analysis.
SunX. et al. [101]	Numerical	Develop and evaluate a TEC cooling system integrated with a gravity-assisted heat pipe for electronics cooling.	Cooling capacity increased by 64.8% and power consumption decreased by 39.3% compared with a conventional TEC air heat sink system.	Gravity heat pipe enhances TEC efficiency	BCs: CPU heat + liquid cooling + dual TEC; Numerical: analytical system model; Validation: experimental measurements.

Table 4: Cont.

Name	Type of Work	Main Object	Main Finding	Significance	Methodological Comparison
Dutt et al. [102]	Experimental and Numerical	Improve μ TEC cooling performance by optimizing contact resistance, geometry, and on-chip packaging.	Net cooling reached 10.8 K (no packaging) and 9.6 K (with packaging), with slight response-time increase and reliability over 85 million cycles.	Design optimization improves TEC reliability	BCs: micro-scale conduction + contact resistance; Numerical: FEM (COMSOL); Validation: thermorefectance experiment.
Xu et al. [103]	Experimental and Numerical	Improve TEC performance by enhancing the hot-side heat sink using a double EFHP finned design.	At 6 A, thermal resistance dropped 19%, cooling capacity rose 8.3%, and COP increased 9.46% versus an aluminum heat sink.	Enhanced heat sink improves TEC performance	BCs: TEC + heat sink + fan + heat pipe; Numerical: CFD + thermal model; Validation: experimental comparison.
Gutiérrez et al. [104]	Numerical	Optimize TEC thermocouple topology under power/stress limits for cooling	Achieved reliable, manufacturable designs that lower temperature and guide TEC	Optimized TEC design improves manufacturability	BCs: heat load + voltage + power constraint; Numerical: Finite Element Method (FEM) + topology optimization; Validation: analytical comparison.
Gutiérrez et al. [105]	Numerical	Optimize TEC cooling under fixed power	Achieved $\sim 10^{\circ}\text{C}$ lower temperature with $\sim 60\%$ less semiconductor material	Material reduction with improved cooling	BCs: thermo-electrical + mechanical + environmental losses; Numerical: Multiphysics FEM + optimization; Validation: analytical/literature comparison.
Zhang et al. [106]	Experimental and Numerical	Analyze TEC cooling for high-power processors.	Optimal current/configuration improved cooling, confirmed by experiments.	Optimization enhances high-power TEC cooling	BCs: processor heat + heat sink + ambient; Numerical: analytical thermal model; Validation: experimental + literature comparison.
Cai et al. [107]	Numerical	Optimize a TEC CPU cooler for minimum temperature and power	Multi-objective gives the best trade-off; optimum depends on weighting.	Multi-objective optimization improves TEC design	BCs: CPU heat + air cooling + convection; Numerical: analytical + heat exchanger model; Validation: performance analysis.
Lee et al. [108]	Numerical	To simulate a thermoelectric micro-cooler and evaluate key design effects.	Better cooling was achieved with thicker elements, more TE pairs, and smaller cross-section area	Design parameters strongly affect TEC performance	BCs: micro-scale conduction + interface resistance; Numerical: FEM (COMSOL); Validation: analytical comparison.

Table 4: Cont.

Name	Type of Work	Main Object	Main Finding	Significance	Methodological Comparison
Chein et al. [109]	Numerical	To evaluate TEC performance for electronic cooling	Max cooling ≈ 207 W, junction temperature $\approx 88^\circ\text{C}$, and hot-side thermal resistance $\approx 0.054^\circ\text{C/W}$.	EC suitable for electronic cooling applications	BCs: chip heat + TEC + microchannel heat sink + convection/conduction; Numerical: analytical thermal model + energy balance + heat sink model; Validation: comparison with literature (no experiment).
Su et al. [110]	Experimental	To enhance cooling performance by integrating thermoelectric cooling (TEC) with ion wind and comparing it with a standalone TEC system.	The coupled system improved COP by $\sim 7.9\%$ and increased temperature reduction by $\sim 6.7\%$, with performance decreasing at high power due to Joule heating.	Demonstrates that hybrid TEC systems significantly improve efficiency and are effective for electronic cooling applications.	BCs: heat source + TEC + water cooling + ion wind convection; Numerical: experimental + energy balance + heat transfer correlations; Validation: experimental measurements + uncertainty analysis.

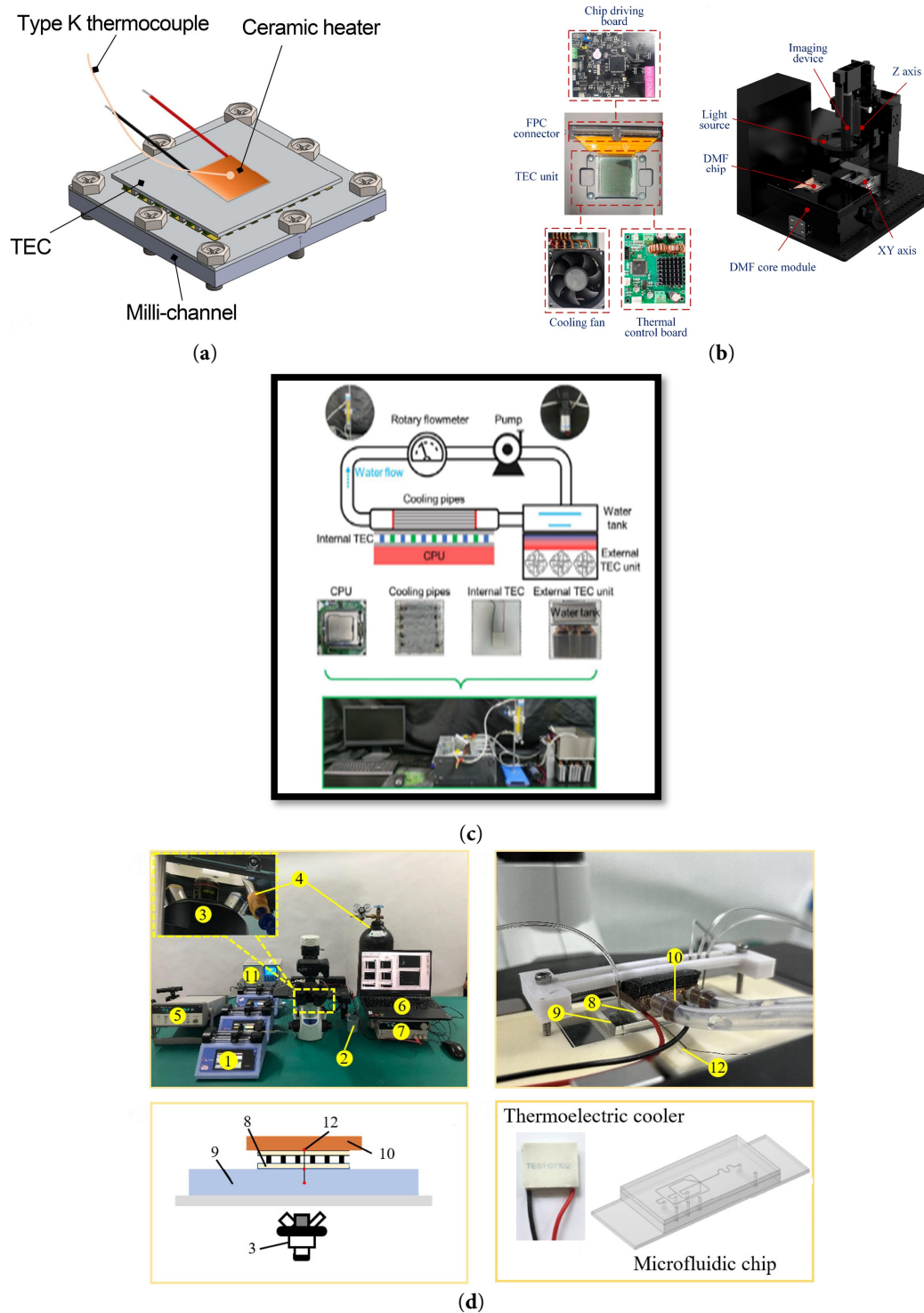


Figure 7: Recent advances in thermoelectric cooling (TEC) applications for chip-level thermal management. (a) A TEC integrated with a teardrop-shaped microchannel heat sink for cooling field-effect transistors [91]. (b) A digital microfluidic temperature control device designed to stabilize the polymerase chain reaction [92]. (c) A schematic depiction of a dual thermoelectric-liquid hybrid cooling system for controlling CPU temperature [93]. (d) A TEC-based temperature regulation system designed for microfluidic chip applications [94].

6.4 Aerospace Applications

TECT is crucial in the aerospace sector due to its role in thermal management in such cases. The technology enhances system performance while ensuring that high power density devices used in spacecraft and high-performance airplanes do not become unstable [95]. TECT is needed due to the operating conditions in aerospace environments that have extreme temperatures. The technology offers an efficient way to manage the temperatures of important electronic parts to prevent overheating damage. In their work, Caroff et al. [5] have presented an optimization algorithm for controlling TECs with regard to high-performance aviation processors such as those used in helicopter systems, as shown in Fig. 8a. In their approach, they concentrate on tuning the thermal resistance of TECs to strike a balance between cooling and energy consumption. Thus, the optimized TEC system is able to maintain the temperature of important parts like FPGA at around 100°C even under tough operating conditions. This shows a great improvement in thermal management since temperatures can reach 120°C without the use of TEC. A novel technique that combines thermoelectric heat pumps with microchannel cooling plates was presented by Xu et al. [111]. As seen in Fig. 8b, this design improves the cooling control of lithium-ion battery packs used in space stations. The cooling plates can now dynamically modify their cooling capacity thanks to the new system. The influence of thermal loads and electrical currents on the transient thermal performance of the heat pumps was evaluated using a lumped model. In addition, three control methods, namely PID control, fuzzy PID control, and BP-PID control, were compared to optimize current control, thus improving temperature homogeneity in the cooling plates. Experimental results showed that the use of heat pumps reduced temperature variations to as low as 1.8 K. Of the three control methods, fuzzy PID control and BP-PID control performed better than the conventional PID control method in terms of overshoot, speed, and accuracy.

Infrared detectors, particularly those in the short-wave infrared band, require very specific cooling conditions, as they are best operated below 210 K. To overcome this limitation, as shown in Fig. 8c, Zhou et al. [112] introduced a novel cooling system that combines multi-stage thermoelectric coolers (TECs) with short-wave infrared detectors in a vacuum dewar box. The cooling system also includes a microchannel heat sink, which is an efficient cooling technology for highly integrated electronic components. The cooling performance of the short-wave infrared detector, TECs, and microchannel heat sink hybrid was analyzed using the finite element method. A comparison of these studies shows that Caroff et al. [5] optimized TEC thermal resistance to maintain critical aviation processors at approximately 100°C under severe conditions, compared with temperatures up to 120°C without TECs. Xu et al. [111] reduced temperature variations in space-station lithium-ion battery cooling plates to 1.8 K, with fuzzy PID and BP-PID outperforming conventional PID control. In contrast, Zhou et al. [112] focused on achieving the stringent sub-210 K cooling requirements of short-wave infrared detectors using multi-stage TECs integrated with a microchannel heat sink.

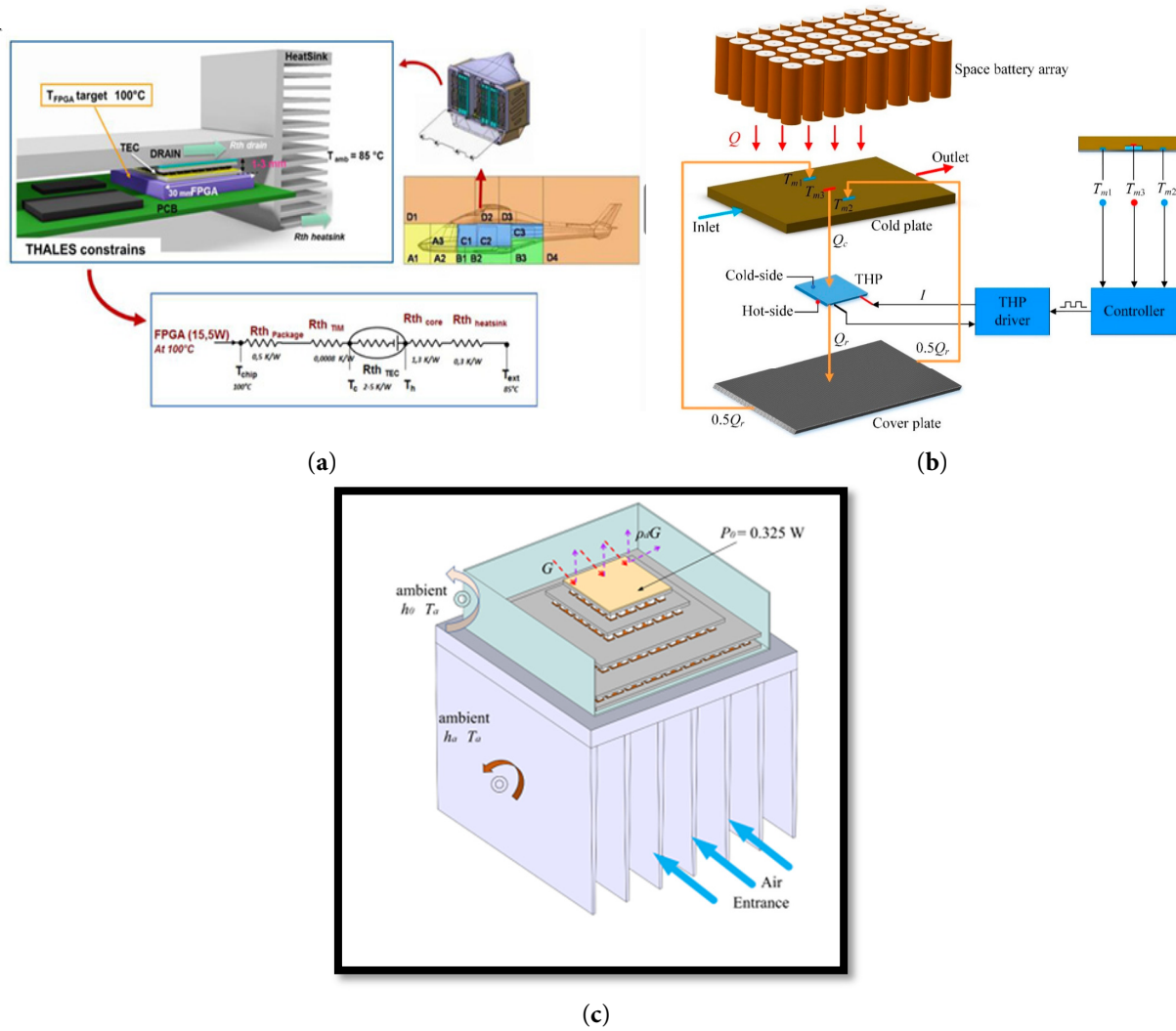


Figure 8: Research progress on thermoelectric cooler (TEC) technologies in aerospace applications. (a) Physical implementation of TECs in helicopter-borne high-performance processors, along with the associated thermal modeling framework [5]. (b) Microchannel cooling plates and integrated thermoelectric cooling devices are used in space stations to control the temperature of lithium-ion battery arrays [111]. (c) Design and implementation of multi-stage TEC systems for the cooling of infrared detectors [112].

6.5 Applications of Thermoelectric Coolers in Battery Systems

Battery Heat generation occurs within battery cells during the charging and discharging process as a result of electrochemical reactions. Improper thermal management of this generated heat causes faster degradation, lower efficiency and safety failure. In this context, thermoelectric cooling (TEC) technology, which uses Peltier effect, is considered an innovative method to advance the thermal management of batteries. TEC technology is a solid-state cooling method that doesn't need any moving parts. It has several benefits, including small size, quick response time, and precise temperature control through regulated electric current. Also, thermoelectric modules can be designed with heat sinks, liquid cooling systems, or even heat transfer structures for effective dissipation of heat from the battery cells and to maintain uniform temperature within battery packs. In this way, the TECs help in increasing thermal stability, reducing thermal stresses, and maintaining overall reliability and safety of the battery systems. Hani Sait [113]

developed a numerical model to cool down a lithium-ion battery cell with a thermoelectric cooler (TEC) integrated with a pin-fin heat sink and alumina nanofluid channel. The effect of different pin-fin shapes was considered under different Reynold numbers (300–600) to evaluate the battery temperature and pressure drop. Results showed that triangular pin-fins achieved the lowest battery temperature, while oval pin-fins produced the minimum pressure drop, as shown in Fig. 9a. Wiriyasart et al. [114] investigated heat transfer enhancement in a compact thermoelectric cooling module using water, TiO_2 nanofluid, and Fe_3O_4 ferrofluid as coolants under a constant heat load representing a battery pack. The results indicated that nanofluid and ferrofluid cooling improved heat transfer performance and enhanced the Peltier effect in comparison with water. Higher temperature difference across the TEC and reduced thermal resistance on the hot side were also reported. However, an increase in pressure drop was observed, highlighting a trade-off between thermal improvement and pumping requirement, as shown in Fig. 9b. Alghassab [115] studied a hybrid battery thermal management system using thermoelectric cooling (TEC) and phase change material (PCM). The system reduced battery temperature by about 9–14% under different heat loads, showing improved cooling performance for lithium-ion batteries as illustrated in Fig. 9c. Zhao et al. [116] proposed a thermoelectric cooler (TEC)-assisted liquid-cooled BTMS (Battery Thermal Management System) for aircraft. The results showed that the system effectively maintained battery temperature at ambient temperatures up to 45°C, improving thermal performance in comparison with a conventional liquid cooled system. However, these improvements were achieved at the expense of increased BTMS weight, higher power consumption, and reduced battery lifespan, highlighting the trade-off between thermal management performance and system efficiency as demonstrated in Fig. 9d. Wiriyasart et al. [114] improved heat transfer using nanofluid and ferrofluid coolants but at the cost of increased pressure drop, while Alghassab [115] reduced battery temperature by about 9–14% through TEC–PCM integration. Zhao et al. [116] maintained effective battery cooling up to 45°C ambient temperature in spite of increased system weight and power consumption. Numerous researches in this field are summarized in Table 5.

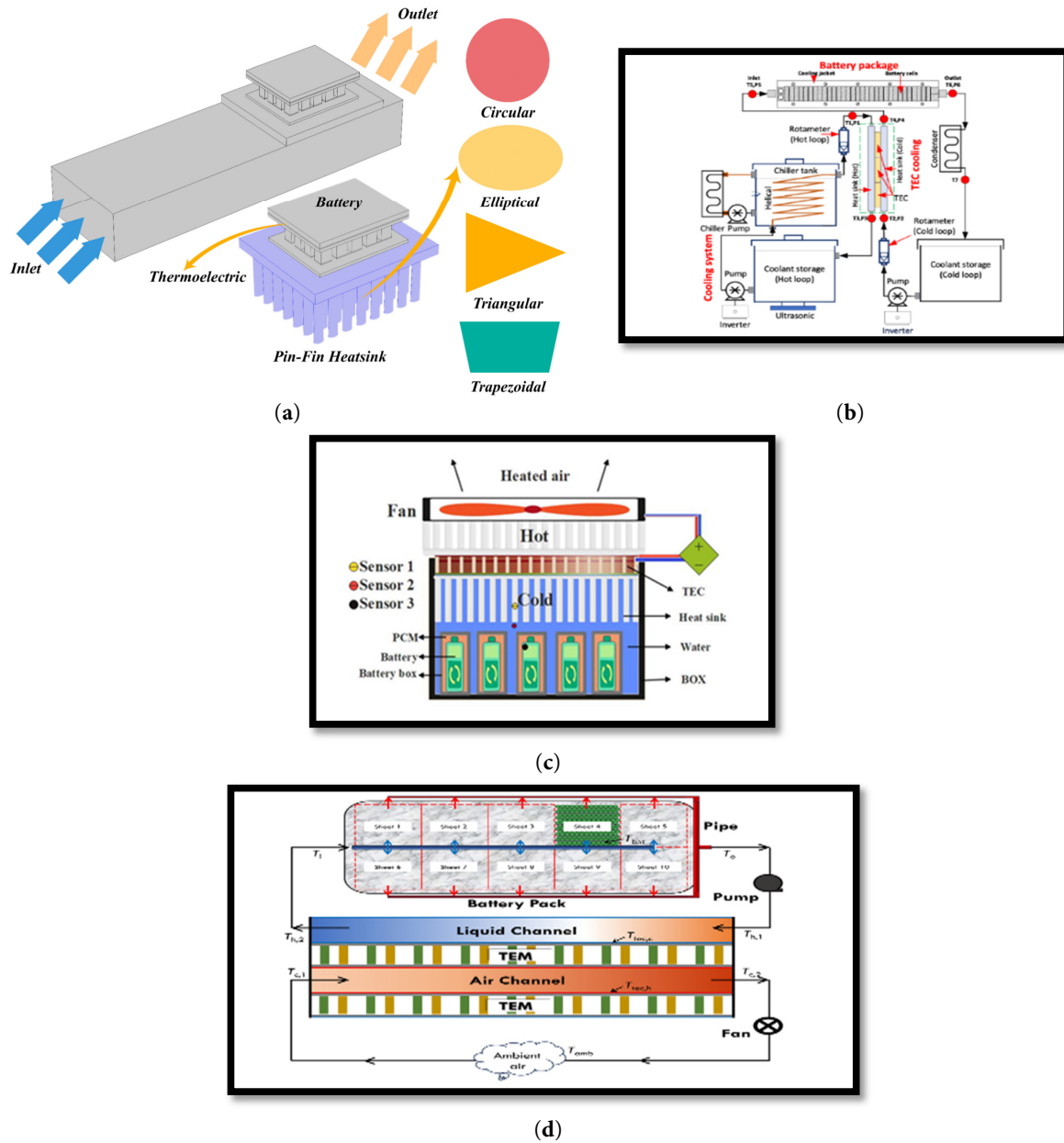


Figure 9: Selected applications of thermoelectric cooling technologies in batteries. (a) A schematic diagram of the battery integrated with a thermoelectric module [113]. (b) Schematic illustration of the proposed thermoelectric cooling system [114]. (c) the laboratory model of a thermoelectric cooling system for battery thermal management [115]. (d) Schematic of the TEC-Based BTMS [116].

Table 5: Summary of recent research on thermoelectric cooling for batteries.

Name	Type of Work	Main Object	Main Finding	Significance	Methodological Comparison
Pakrouh et al. [117]	Experimental	To test a TEC–PCM liquid cooling Battery Thermal Management System.	PCM improved cooling; best case (3TEC/2PCM) reached 37.8°C and COP = 3.23.	TEC–PCM improves battery thermal management	BCs: Battery + TEC + PCM + liquid cooling (conduction + convection + heat storage). Numerical: None. Validation: Experimental measurements.
Pan et al. [118]	Experimental	to test a TEC-based battery preheating BTMS for low temperatures.	Best mode heated the pack from −5°C to 5°C in 824 s with 91.2 W total power.	TEC effective for battery preheating	BCs: TEC battery preheating under low temperature (conduction + ambient interaction). Numerical: None. Validation: Experimental measurements.
Luo et al. [119]	Numerical	To study a hybrid TEC–CPCM–liquid cooling BTMS under extreme conditions.	Best cooling at EG 12%, 3 A, 0.05 m/s; preheating to 293.15 K needed 2240–5600 s at 4–5 A	Hybrid TEC–CPCM improves battery cooling	BCs: TEC + PCM for heat storage and recovery. Numerical: Thermal model (energy balance). Validation: Theoretical comparison.
Zhao et al. [120]	Numerical	Enhance Li-ion battery cooling using PCM + TEC + vibration.	TEC lowered peak temperature by 6.97 K; best at 1.5 A. Vibration reduced peak rise up to 42.32% (best at 70 Hz).	PCM–TEC reduces battery peak temperature	BCs: Battery + PCM + heat pipe + TEC (conduction + convection + phase change). Numerical: CFD multiphysics model. Validation: Literature comparison.
Luo et al. [121]	Numerical	Rapid battery cooling + PCM heat recovery using TEC.	Best: 12% Ethylene Glycol (EG) PCM, 4 A → 361.94 J/kg·s recovery.	PCM enhances heat recovery in TEC systems	BCs: Battery system with TEC + PCM + liquid cooling, including conduction in battery/PCM and convective heat removal. Numerical: CFD thermal model with phase change. Validation: Comparison with reference/literature data.
Luo et al. [122]	Theoretical	Model a TEC-based BTMS for Li-ion batteries and assess key operating effects	TEC lowers battery temperature; performance depends on charging rate, cooling current, and heat transfer conditions	Operating conditions affect TEC battery cooling	BCs: TEC-based battery system under varying operating conditions (charging, cooling, heat transfer). Numerical: Analytical (theoretical) model. Validation: Theoretical analysis and model-based evaluation.
Wu et al. [123]	Numerical	Model a PCM–HP–TEC hybrid BTMS for Li-ion batteries	Hybrid system performed best; HPs/TEC current/Expanded Graphite EG reduce peak temperature, but excessive values can harm uniform it	Hybrid PCM–HP–TEC improves thermal control	BCs: Hybrid system (PCM + heat pipe + TEC), involving conduction, convection, and phase change heat transfer. Numerical: CFD multiphysics model. Validation: Comparison with literature/reference results.

Table 5: *Cont.*

Name	Type of Work	Main Object	Main Finding	Significance	Methodological Comparison
Luo et al. [124]	Numerical	Assess a TEC-based hybrid BTMS (air + water cooling) for batteries	The system enhanced cooling vs. conventional methods; optimal at $h = 50 \text{ W/m}^2\cdot\text{K}$, water = 0.11 m/s , $I = 5 \text{ A}$, giving $T_{\text{max}} = 302.27 \text{ K}$ and $\Delta T = 3.63 \text{ K}$.	Hybrid cooling enhances BTMS performance	BCs: Battery system with TEC + hybrid air and water cooling, including forced convection and conduction. Numerical: CFD thermal model. Validation: Performance comparison with conventional cooling systems.
Pakrouh et al. [125]	Experimental	To develop a hybrid battery cooling system using TEC, PCM, and liquid cooling to improve thermal control and performance.	The best performance was achieved with 3TEC, reducing battery temperature to $\sim 35^\circ\text{C}$ with the highest system efficiency.	Hybrid TEC–PCM–liquid enhances battery cooling	BCs: Battery system with TEC + PCM + liquid cooling, involving heat conduction within the battery and PCM, and convective heat removal through the coolant. Numerical: Not included (experimental study). Validation: Direct experimental measurements and performance comparison between configurations.
Cui et al. [126]	Experimental and Numerical	Develop a precise TEC-based thermal regulation strategy for lithium-ion batteries.	The proposed method was effective, more accurate than the traditional method, and kept the control error below 0.5°C .	Precise TEC control improves battery safety	BCs: TEC-based battery system with controlled heat transfer, including conduction within the battery and convective cooling to maintain stable temperature. Numerical: Numerical thermal model integrated with control strategy. Validation: Comparison with conventional control methods showing improved accuracy.

7 Thermoelectrical Cooling Assisted by Radiative Cooling

This section focuses on the integrated use of radiative cooling (RC) in conjunction with thermoelectric cooling (TEC) systems. However, in place of individualized cooling methods, the RC-TEC combination takes advantage of the advantages that passive and active cooling have to offer, thereby compensating for the disadvantages of each cooling method used alone. In these hybrid designs, RC has two separate applications, which offer unique contributions to the optimization of TEC. For example, Zhao et al. [127] developed an RC-TEC system incorporating a metamaterial film with high infrared emissivity (0.93) and solar reflectivity (96%) as shown in Fig. 10a. The system demonstrated a COP of 1.87 annually in Los Angeles and COP values of 0.96 to 1.49 in Phoenix, Denver, and Miami, highlighting its significant potential for use in temperate regions. Kwan et al. [128] introduced a novel approach where RC plays a two-fold role: to increase the total cooling effect and decrease the temperature on the hot side of the thermoelectric cooler (TEC). As shown in Fig. 10b, the system was able to achieve a cooling effect of 40 W/m^2 with a 10 K temperature difference. This result was possible by optimizing the input power of TEC and enlarging the radiative cooling area on the hot side. Lv et al. [129] evaluated a hybrid PV-RC-TEC configuration Fig. 10c under Wuhan conditions. The system delivered a cooling power density of 93.48 W/m^2 with a COP of 0.64, and it outperformed a conventional commercial air-conditioning unit by 20.8% when tested in a 16 m^2 residential space. Separating the hot and cold sides of a TEC can significantly expand its functionality, enabling simultaneous space cooling and water heating. As demonstrated by Yang et al. [130] in Fig. 10d, a nine-module PV-RC-STEC system achieved a cooling COP of 3.69 and a heating COP of 2.53, with performance further enhanced by increasing the RC-to-PV area ratio. A comparison of these studies shows that Yang et al. [130] achieved the highest reported cooling COP of 3.69 through the PV-RC-STEC configuration, while Zhao et al. [127] obtained an annual COP of 1.87 in Los Angeles but lower values of 0.96–1.49 in other climates. Lv et al. [129] achieved a higher cooling power density of 93.48 W/m^2 than the 40 W/m^2 reported by Kwan et al. [128], although the systems operated under different configurations and conditions. Overall, the results highlight the strong influence of system integration, climate, and radiative cooling area on hybrid RC-TEC performance.

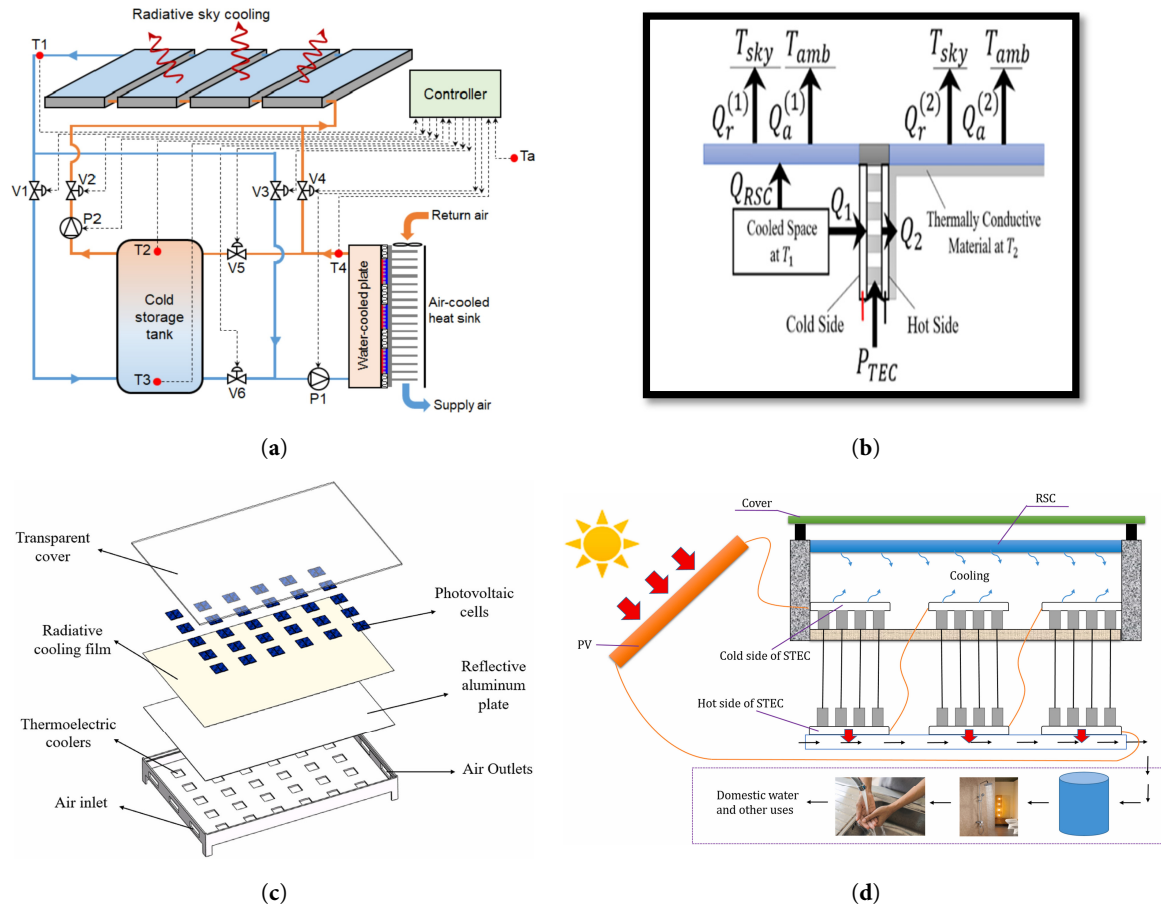


Figure 10: Radiative cooling–Assisted Thermoelectrical Cooling (a) Schematic illustration of an RC–TEC cooling system developed for building applications [127]. (b) Hybrid dual-function configuration in which radiative cooling is utilized for both auxiliary cooling enhancement and thermal regulation of the TEC hot side [128]. (c) Exploded-view representation of the integrated PV–RC–TEC system, highlighting the arrangement of its main components [129]. (d) Operational schematic of a split thermoelectric cooling system combined with photovoltaic power generation and radiative cooling [130].

Table 6 represents a quantitative comparison of different studies from the literature that involve the subject of TEC-based cooling technology.

Table 6: Quantitative comparisons of representative TEC-based cooling studies.

System Mass	Input Power (W)	Hot-Side Heat-Rejection	Temperature Lift (ΔT , °C)	Cooling Capacity (W)	COP	Operating Conditions	Application	Ref.
NR	≈ 360 W	Water/air heat exchanger	$\approx 15.5^\circ\text{C}$	NR	0.58 (maximum)	Water–air configuration; conditions-controlled air and water flow conditions	Automotive air conditioning	Li H. et al. [131]
NR	NR	Heat pipes with	NR	15.54	0.89	Two TEMs; TEM1 = 4 V and TEM2 = 4 V at maximum COP	Ferris wheel cabin air conditioning	Mohamed ES [132]
NR	NR	Aluminum heat sinks with forced-air tangential fans	9	NR	0.78–0.75	Cooling mode; 7.2 V; grids open; fans at 100%; 16 Peltier	Building and conditioning	Ibañez-Puy et [133]
NR	NR	Water-cooled TEC rejected heat transferred by cooling water to the wet channels of the RIEC	5.6–1.7	700–500	≈ 2.5 –9; >10 under favorable climate conditions cells	T-in = 30 – 40°C ; RH = 30–70%; Vin = 0.75–1.25 m/s; I = 0.5–1 A; n = 8 or 12	Building air conditioning and data-center cooling	Zhou et al. [134]

8 Economic Feasibility and Lifetime and Sustainability of Thermoelectric Cooling Systems

The economic feasibility of thermoelectric cooling systems (TECs) is commonly evaluated using key economic indicators that relate system cost, performance, and lifetime. One of the most important parameters is depreciation, which represents the reduction in system value over time and it is expressed as:

$$\text{Depreciation} = (\text{Initial Cost} - \text{Salvage Value}) / \text{Lifetime}$$

This equation shows that the system lifetime plays a significant role in distributing the initial cost over the operational period Palte et al. [135].

In addition, Buchalik and Nowak [136] introduced an economic indicator known as the economic total cooling capacity (ETCC), which evaluates the cooling performance of the system relative to its total cost over a defined operational period. This indicator provides a more practical assessment compared to the coefficient of performance (COP), as it considers both economic and thermal aspects of the system. As shown in Fig. 11, ETCC is strongly affected by operating conditions such as electricity cost and ambient temperature, where increasing these parameters leads to a noticeable decrease in economic performance.

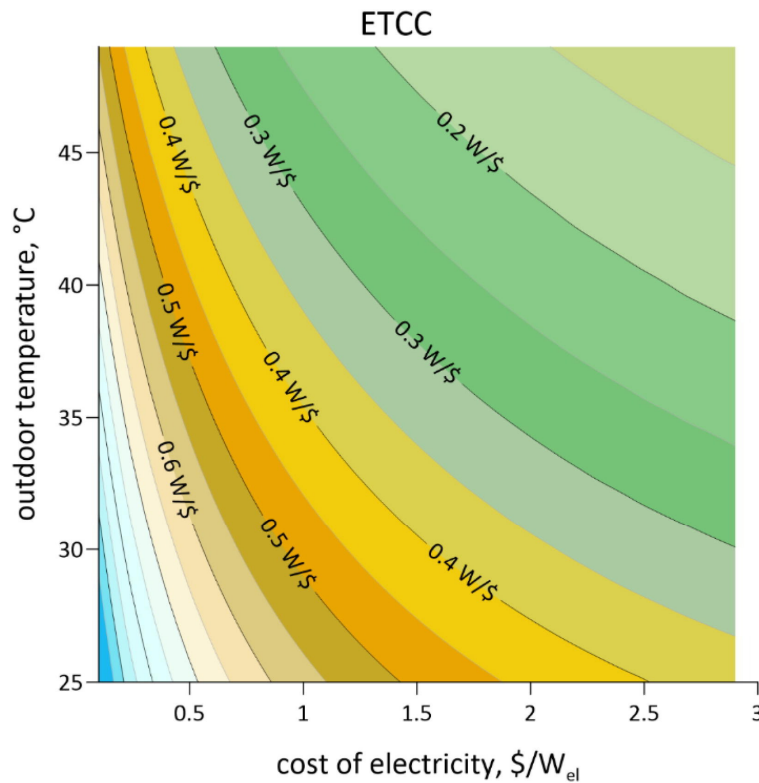


Figure 11: Economic total cooling capacity (ETCC) as a function of electricity cost and outdoor temperature for a constant indoor temperature of 25°C. The figure indicates that, for a given electricity cost, an increase in outdoor temperature results in a decrease in ETCC, reflecting a reduction in the economic performance of the thermoelectric cooling system [136].

Regarding the lifetime of thermoelectric cooling systems, Buchalik and Nowak [136] considered an operational lifetime of 2400 h (equivalent to five years of operation) in their economic analysis of a thermoelectric-air-conditioning system. Furthermore, Palte et al. [135] reported that the designed service

life of a thermoelectric cooling chamber is approximately 30 years, while the associated photovoltaic components have expected lifetimes of 20 years for the solar panels and 10 years for the charge controller. These findings indicate that thermoelectric cooling systems can achieve reliable long-term operation under appropriate operating conditions and effective thermal management.

Regarding the environmental impact, Buchalik and Nowak [136] highlighted that thermoelectric cooling systems are environmentally friendly because they do not require harmful refrigerants such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which contribute to ozone depletion and global warming. In addition to this, they also stated that environmentally friendly heat transfer fluids like water can be utilized in these systems. Also, Palte et al. [135] stated that the combination of TEC and photovoltaics (PV) can decrease the overall energy consumption and emissions of greenhouse gases.

In relation to recycling, the thermoelectric modules may be recycled for the retrieval of valuable materials like bismuth, tellurium, copper, aluminum, and ceramics, by which the negative effects of mining and producing these materials are reduced. However, for effective recycling, separation and retrieval procedures are required since thermoelectric modules contain different materials that are bonded together.

The recycling of thermoelectric modules has recently been considered very important due to its contribution to sustainable development and increased resource efficiency. The significance of material recovery from devices at the end of their life span in order to enhance sustainability and efficiency of resource use has been highlighted in recent research. Thermoelectric modules, especially those using bismuth telluride (Bi_2Te_3) include critical metals such as tellurium, bismuth, antimony, and selenium that can be recovered via modern recycling methods. Material recycling leads to a reduction in the volume of electronic waste, decreased need for primary raw materials, and minimized environmental burden connected with mining and production. Thus, the development of closed-loop recycling technologies is an aspect of resource preservation and the circular economy [137].

However, from a sustainability point of view, the use of thermoelectric coolers is beneficial since there is no use of refrigerants and low emission levels in this cooling technology. However, other issues such as material sustainability and recycling continue to be a challenge. The semiconductor materials used in the thermoelectric modules require recycling techniques that can be quite difficult to achieve. Therefore, there should be efforts to improve recycling methods and use green materials. Future research should therefore focus on increasing material recyclability and minimizing environmental impacts throughout the system lifecycle, including manufacturing and disposal stages.

9 Energy Saving and Carbon Emission Reduction

Thermoelectric cooling (TEC) systems have attracted considerable attention as environmentally friendly cooling technologies because they operate without refrigerants, thereby eliminating direct greenhouse gas emissions associated with refrigerant leakage in conventional vapor-compression refrigeration (VCR) systems. In addition, TEC devices are characterized by their solid-state structure, quiet operation, high reliability, and low maintenance requirements (Twaha et al. [138]; Pourkiaei et al. [139]). Although conventional vapor-compression air-conditioning systems generally achieve COP values of approximately 2.6–3.0, thermoelectric air-conditioning systems typically exhibit COP values of about 0.38–0.45. Nevertheless, integrating TEC modules with conventional cooling systems, heat exchangers, or waste heat recovery technologies can improve the overall system energy efficiency, enhance energy utilization, and minimize the refrigerant-related environmental impacts, as stated by Pourkiaei et al. [139].

According to Twaha et al. [138], approximately 30% of industrial thermal energy is discharged as waste heat and can potentially be recovered using thermoelectric technology. In addition, nearly 40% of

the fuel energy in gasoline vehicles is rejected through the exhaust system, while about 30% is dissipated through the cooling system, demonstrating the significant potential of thermoelectric technologies for improving energy utilization. Furthermore, continued development of thermoelectric systems could reduce vehicle fuel consumption by up to 10% through efficient waste heat recovery, as reported by Twaha et al. [138]. From an environmental perspective, the absence of refrigerants makes TEC systems particularly attractive for reducing carbon emissions. The environmental performance of these devices may be further improved by employing them with renewable energy or in hybrid cooling systems. In addition, according to several life cycle assessments, sustainable materials and proper recycling techniques may help decrease the environmental impact of thermoelectric devices, as illustrated by Jamil and Holden [140]. Nevertheless, despite having lower COP values than those of conventional systems, TEC devices present themselves as an alternative due to their potential to get rid of refrigerants, capture waste heat, and combine with traditional cooling technology.

10 Challenges and Future Perspectives of Thermoelectric Cooling Systems

In spite of various benefits of thermoelectric cooling (TEC), there are a number of technical and practical limitations that prevent extensive use of this method. According to He et al. [141], low efficiency of energy conversion and high cost of thermoelectric materials are the main obstacles in terms of commercial application of TEC technology. From recent studies, it was noted that the figure of merit (ZT) parameter is a crucial factor in increasing the performance of thermoelectric coolers. Furthermore, the increase of operating current in TEC systems can lead to the rise of the value of Joule heating and electrical power consumption, and as a result, a decrease of coefficient of performance (COP). Hot-side heat accumulation is another important practical limitation, since insufficient heat removal can cause an increase in hot-side temperature and temperature difference between the sides of the thermoelectric module. Thus, cooling performance is affected negatively. Pourkiaei et al. [139] noted that TEC performance is significantly affected by properties of thermoelectric materials and the heat dissipation process of the hot side. In practical TEC systems, efficient heat dissipation usually needs additional elements, such as a heat sink, fan, liquid cooling loop, or heat exchanger, which adds complexity, extra power consumption, size and price of the system. Finally, scaling of TEC technology from local cooling to large-scale cooling is rather complicated, because increasing the number of modules does not necessarily improve the cooling performance, especially in the case of significant thermal resistance, electrical losses and uneven heat distribution. More recently, Mousavi et al. [142] emphasized the necessity to develop thermal management techniques, scalability, techno-economic and life-cycle analysis, hybridization with other renewable technologies and intelligent controls like machine learning and Internet of Things. Thus, the future development of TEC technology should pay more attention to high-ZT and low cost of thermoelectric materials, efficient heat-rejection systems, reduction of parasitic power consumption, improvement of long-term reliability and adaptive controls.

11 Conclusion

The application of TEC in vehicle cooling, refrigeration/freezers, and space cooling has great prospects, especially when there is a need for miniaturization, precision temperature control, and environmentally friendly operation. The use of TEC is viable in automotive battery and electronics cooling. (TEC) is applicable in the cooling of small food refrigerators and freezers due to precise temperature control, noiseless operation, and absence of refrigerant, despite being an inefficient technique for specific uses. However, in space cooling, TEC is less favorable as a stand-alone technique but has high effectiveness when it is used with hybrid HVAC systems. Generally, TEC is ideal for localized and supplementary

cooling technology, and much more research is needed to improve materials and energy efficiency. This review highlights the impressive achievements realized through the application of thermoelectric cooling technology in numerous fields such as automotive thermal management, wearable/garments technologies, microelectronic devices, and aerospace applications. The findings show that thermoelectric cooling has gone beyond its conventional application because of innovations that improve performance, flexibility, and system integration. All these improvements support the scientific significance of TEC technologies and their enormous capacity for future improvement and applications. TEC provides precise temperature control in battery thermal management and is most efficient when it is used as a supplementary cooling technique. Moreover, the use of TEC with radiative cooling is a powerful approach for improving thermal efficiency because radiative cooling reduces thermal load in TEC and increases the efficiency of the hybrid system.

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Availability of Data and Materials: Data will be available on request.

Ethics Approval: Not Applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

TEC	Thermoelectric cooler
COP	Coefficient of performance
PCM	Phase change material
I	Current (A)
T	Temperature
BTMS	Battery Thermal Management System
p	Power (w)
PV	photovoltaic panel
Q _c	cooling production (w)
C _h	heating production (w)
HP	heat pipe
h	heat transfer coefficient
ΔT	Temperature difference
EBC	Electrical Power Consumption
TEM	thermoelectric modules
CFD	Computational fluid dynamics
V	Voltage
VCR	Vapor Compression Refrigeration
CPU	Central Processing Unit
BCs	Boundary Conditions
DO	Discrete Ordinates
HVAC	Heating, Ventilation, and Air Conditioning

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