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Yiwen Bo(薄轶文) and Rujun Ma(马儒军)
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TOPICAL REVIEW — Multiferroicity and multicaloric effects

Electrocaloric thermal management devices: Toward high-efficiency solid-state refrigeration

Yiwen Bo(薄轶文) and Rujun Ma(马儒军)†

School of Materials Science and Engineering, Nankai University, Tianjin 300350, *China*

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Addressing the urgent demands for intelligent, miniaturized, and efficient thermal management in modern electronics, alongside the energy and environmental constraints, the development of compact and high-performance cooling systems has become imperative. The electrocaloric (EC) effect, which enables reversible entropy and temperature changes in dielectric materials through electric-field-controlled polarization, offers distinct advantages including high efficiency, fast response, and ease of integration. This review outlines the thermodynamic principles and surveys the evolution of EC thermal management devices. Ceramic-based EC devices exhibit strong potential for high-power applications due to their high thermal conductivity and thermal stability, while polymer-based EC devices are suited for wearable and flexible integration because of their mechanical compliance and processability. This review further contrasts the design, actuation, and application profiles of these platforms. Despite notable progress, challenges remain in long-term stability, multi-physics coupling, miniaturized integration, and environmental adaptability. Advances in material understanding, device design, and intelligent system control will position EC technology as a key enabler of efficient, compact, and sustainable next-generation thermal management.

Keywords: electrocaloric effect, thermal management device, coefficient of performance, high-power and wearable refrigeration

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1. Introduction

Vapor-compression refrigeration technology has dominated thermal management applications for nearly two centuries since its appearance in the early 19th century, being widely employed across civil, industrial, and extreme environments (e.g., deep-sea and aerospace applications).[1–3] The coefficient of performance (COP) is defined as the ratio of cooling capacity to the total power input and serves as the key metric for refrigeration efficiency. Conventional residential air conditioning systems typically achieve COP values between 2–5; this relatively low efficiency range contributes to refrigeration and heat pump systems accounting for 20%–25% of global electricity consumption.[4] A critical environmental concern stems from the system's core component, refrigerants, particularly the widely used chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). Leakage of these refrigerants can cause ozone depletion and exacerbate the greenhouse effect.[5] Although research continues on environmentally friendly alternatives, factors such as cost and system compatibility hinder the widespread adoption of fully sustainable refrigerants. When considering both energy consumption during operation and refrigerant leakage impacts, air conditioning and related applications may account for up to 10% of global greenhouse gas emissions. This not only accelerates climate change but also generates significant societal concerns regarding energy sustainability and environmental protection.[6,7]

The ongoing evolution of electronic devices toward miniaturization, integration, and wearability, coupled with the rapid advancement of artificial intelligence (AI) technology, has significantly enhanced the intelligence of applications ranging from in-vehicle electronics to embodied intelligence and manned spaceflight. However, these developments demand increasingly higher computational power from electronic chips, exacerbating heat generation and thermal failure challenges.[8–11] Furthermore, the compact power supplies used in microelectronics and wearable devices face dual limitations: restricted energy capacity and thermal instability, including excessive heat generation or reduced efficiency in cold environments.[12–14] Conventional vapor-compression thermal management systems, reliant on bulky components like compressors and evaporators, suffer from structural complexity, poor scalability, and suboptimal cooling efficiency, rendering them inadequate for the prolonged temperature control needs of modern microelectronics. Consequently, thermal management has emerged as a critical bottleneck in developing high-reliability, stable, intelligent electronic systems, underscoring the urgent need for compact, wearable, and energy-efficient bidirectional thermal regulation solutions (Fig. 1).

†Corresponding author. E-mail: malab@nankai.edu.cn

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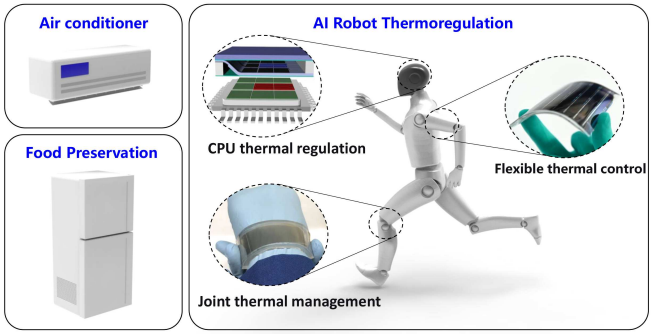


Fig. 1. Thermal management technology in building space temperature control, food preservation, and robotic thermal regulation. Reproduced with permission from Refs. [3,15,16].

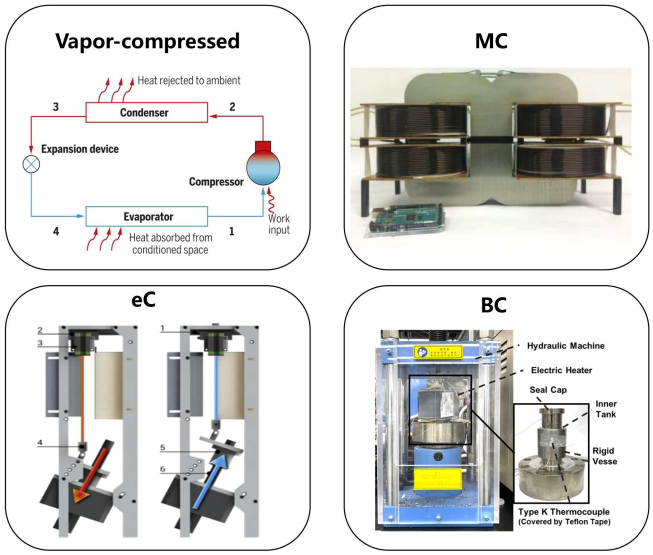


Fig. 2. Research efforts on vapor-comperssed, magnetocaloric (MC), elastocaloric (eC), and barocaloric (BC) thermal management systems. Reproduced with permission from Refs. [23,34,38,39].

In recent decades, significant progress has been made in developing active bidirectional solid-state thermal management technologies. Thermoelectric (TE) technology, as one of the more mature approaches, utilizes the Peltier effect at semiconductor P–N junctions to achieve substantial cooling/heating power density.[17–19] However, its practical application is limited by considerable Joule heating during operation, causing a dramatic decrease in the COP with increasing cooling capacity. Parallel research efforts have explored alternative caloric technologies including magnetocaloric (MC),[20–23] elastocaloric (eC),[24–32] and barocaloric (BC) systems,[33,34] with particular focus on overcoming performance limitations and implementation barriers (Fig. 2). While these technologies have achieved notable breakthroughs in T_{span} and cooling power, their widespread adoption is hindered by intrinsic material constraints and thermodynamic cycle requirements that result in structural complexity, miniaturization difficulties, and reduced energy efficiency. In contrast, the EC effect has emerged as a particularly promising solution, attracting growing research interest due to its unique advantages in solid-state operation and miniaturization potential, leading to remarkable progress in both theoretical understanding and practical implementation.[33,35–37]

2. The fundamental thermodynamic principles of the EC effect

The EC effect is a fundamental thermodynamic phenomenon observed in dielectric materials wherein an applied external electric field induces a modification of the material's internal polarization state, leading to either an isothermal entropy change (ΔS) or an adiabatic temperature change (ΔT).[40–43]

2.1. The fundamental cycle process of the EC effect

As depicted in Figs. 3(a) and 3(b), the complete EC cycle consists of four distinct thermodynamic processes: two adiabatic and two isothermal stages. Specifically, an electrocaloric (EC) material initially at temperature T in an adiabatic environment is subjected to an external electric field that rapidly increases from E to $E_{\max}$ ($E < E_{\max}$). The swift application of the electric field causes the originally randomly oriented dipoles to align abruptly along the field direction. To conserve the total entropy of the system, the material exhibits a temperature increase to $T + \Delta T$. Subsequently, during the heat-release phase, the heated material ($T + \Delta T$) gradually transfers thermal energy to the cooler surroundings until thermal equilibrium is reestablished at T. When the electric field is rapidly reduced from $E_{\max}$ back to E, the dipoles return to a randomized orientation. To maintain total entropy conservation, the material undergoes a corresponding temperature decrease to $T - \Delta T$. Finally, in the heat absorption stage, the cooled material ($T - \Delta T$) absorbs heat from the warmer environment until it returns to its initial temperature T.[7,44,45] This unique mechanism enables direct electric-field control of material entropy and temperature without extra energy conversion. It offers several outstanding advantages, including ultrafast thermal response with temperature change rates theoretically reaching 10^8 K/s under a square-wave voltage, and remarkably high thermodynamic efficiency with a $\text{COP}_{\text{Carnot}}$ between 60% and 80%.[44,46] These outstanding characteristics, combined with the advanced state of modern electronics manufacturing where highly integrated circuit systems have achieved unprecedented levels of miniaturization and widespread commercial availability, position EC temperature control technology as an exceptionally promising solution for next-generation thermal management applications. The technology's inherent compatibility with existing electronic systems, coupled with its superior performance metrics, suggests tremendous potential for rapid industrial adoption and large-scale commercialization across diverse fields ranging from microelectronics cooling to advanced wearable temperature control systems.[15,47,48]

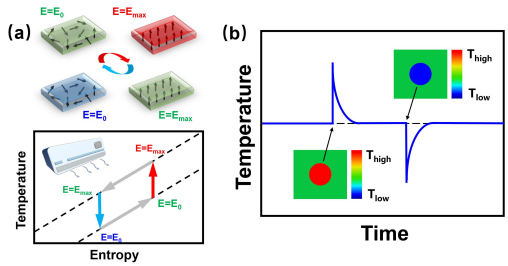


Fig. 3. (a) The basic cycle principle of the EC effect. (b) The schematic diagram temperature–time profile and corresponding infrared thermal images of the EC material during a full heating-cooling cycle.

2.2. Thermodynamic basis and key material parameters

Currently, the most commonly used thermodynamic descriptions rely on Landau–Devonshire theory and Maxwell's relations, both of which are subject to specific applicability conditions. Landau–Devonshire theory relates the Gibbs free energy of a thermodynamic system to its order parameter (typically polarization intensity and dielectric permittivity) and describes its evolution under the influence of external fields. In contrast, Maxwell's relations provide a direct link between the pyroelectric coefficient $(\partial P/\partial T)$ and the ΔS induced by an electric field, offering a thermodynamic route to quantify the EC response. Although originating from different perspectives, these two theoretical frameworks complement each other and form an essential foundation for understanding EC mechanisms at the level of fundamental thermodynamic equations.

2.2.1. Landau–Devonshire theory for quantitative modeling

The Landau–Devonshire phenomenological theory provides a powerful framework for quantitatively modeling and predicting the EC effect in ferroelectric materials.[49,50] The Gibbs free energy density G is expanded as a function of electric displacement D:

$$G = \frac{1}{2}\alpha D^2 + \frac{1}{4}\xi D^4 + \frac{1}{6}\zeta D^6, \tag{1}$$

where $\alpha = \beta(T - T_c)$, β, ξ and ζ are temperature-independent coefficients.

Since

$$(\partial G/\partial T)_D = -\Delta S,$$
$$\Delta S = -\frac{1}{2}\beta D^2, \tag{2}$$
$$\Delta T = -\frac{T\Delta S}{c_E}, \tag{3}$$

where c_E is the specific heat capacity at the corresponding temperature T.

Therefore, the ΔT can be obtained from the following formula:

$$\Delta T = -\frac{1}{2c_E}\beta T D^2. \tag{4}$$

2.2.2. Maxwell's relations

For polar materials, a direct link is established through the Maxwell relation,[51] derived from the combined first and second laws of thermodynamics:

$$\Delta S = \int_{E_1}^{E_2} \left(\frac{\partial D}{\partial T}\right)_E \mathrm{d}E, \tag{5}$$
$$\Delta T = -\int_{E_1}^{E_2} \frac{T(E)}{C_E(T)} \left(\frac{\partial D}{\partial T}\right)_E \mathrm{d}E, \tag{6}$$

where C_E is the heat capacity, $D = \varepsilon E + P$, P denotes the polarization, and ε is the vacuum permittivity ($\varepsilon = 8.85 \times 10^{-12}$ F/m). These expressions highlight that achieving a large ΔS and a significant ΔT requires the material to exhibit a high $(\partial D/\partial T)_E$ value across a broad range of both electric field and temperature.

2.3. Requirements for EC materials in thermal management systems

The practical implementation of EC materials in thermal management systems involves fundamental operational challenges inherent to the basic principle of the EC effect. During operation, the cyclic application and removal of the electric field inherently induces continuous temperature fluctuations and necessitates heat exchange with the environment. Effective solid-state thermal management using EC effects requires spatial separation of the heating and cooling processes, essentially enabling controlled heat transport. This operational principle shares fundamental similarities with other caloric technologies (eC, BC, MC) and conventional vapor-compression systems.[36] All these approaches rely on a refrigerant that reversibly absorbs and releases heat under the variation of an external field (stress, pressure, or magnetic fields) to enable controlled heat transfer. The heat transport mechanism can be achieved either through a heat transport medium (e.g., gases or liquids) or the direct motion of the material itself. To optimize the performance of EC materials for such applications, a deep understanding of their microstructure is essential. In the most commonly used EC materials for coolers, relaxor ferroelectrics, polar nanodomains (PNDs) serve as the core structural units, and their dynamic behavior critically governs both the operating temperature range and the magnitude of the ΔS in the EC effect.[52–54] Defect engineering can broaden the effective EC temperature range by introducing local compositional and strain inhomogeneity, which distributes the activation energies for PND switching and suppresses sharp phase transitions. Simultaneously, the reversible field-driven reconfiguration of PNDs enhances the temperature-dependent polarization change, thereby increasing ΔS through both the Maxwell relation and contributions from configurational entropy. These synergistic mechanisms enable defect-modulated relaxor ferroelectrics to achieve a wider operational temperature range and superior EC performance. Furthermore, strategies such

as grain size design,[55,56] entropy engineering,[54,57] and multiphase compounding[40,58–60] have been demonstrated to improve both EC performance and thermal conductivity effectively. Ultimately, the practical performance of EC thermal management systems is determined by a complex interplay between the intrinsic EC properties of the materials and engineering factors, including material selection precisely tailored to target operating environments, meticulously designed thermodynamic cycles, and optimally configured system architectures.[44]

3. Thermal management devices based on the EC effect

Transforming these operating principles into functional EC thermal management systems critically depends on device design and engineering implementation. Effective system architectures can efficiently utilize the EC effect to enable controllable heat pumping or precise temperature regulation. Building on the previously discussed heat transfer strategies, diverse device configurations have been developed, each exhibiting unique operational mechanisms and application potential.

Research on the EC effect has progressively advanced toward practical thermal management, spurring the development of diverse EC-based device prototypes. The primary function of these systems is to deliver controllable cooling or heating to target objects. However, since both heating and cooling occur within the same material under varying electric fields, a challenge involves spatially separating these opposing thermal processes to enable effective heat transfer. This separation can be achieved through two primary approaches: utilizing a heat exchange fluid to transfer thermal energy between the EC material and the device's cold/hot ends, or implementing alternating contact between the EC material and the system's thermally isolated cold/hot reservoirs. Since the initial proposal of EC thermal management in 1979, the technology has undergone significant advancement, yet still faces substantial challenges in material development and device engineering.[61] Current EC prototypes remain at the feasibility evaluation stage, with performance limitations primarily stemming from material breakdown fields and operational fatigue under prolonged cycling. To realize widespread EC device implementation, comprehensive optimization is required across three key areas: enhancement of EC materials (including both polymers/composites and inorganic ceramics), development of integrated working bodies, and innovative device architectures. Given the intrinsic limitations of single-stage EC materials, advanced device designs increasingly incorporate regenerative heat exchange, cascaded systems, and energy recovery circuits to achieve greater T_{span} ($\Delta T > 10$ K) while improving thermodynamic efficiency. This section systematically reviews recent progress in EC thermal management devices, categorizing them into two distinct classes: polymer/composite-based systems and inorganic ceramic-based implementations, each offering unique advantages for specific application scenarios.

3.1. Calculation for quantifying performance of EC devices

3.1.1. Temperature span (T_{span})

The T_{span} refers to the maximum temperature difference between the device's hot end and cold end under near-zero thermal load conditions. The calculation of T_{span} is

$$T_{\text{span}} = T_{\text{hot}} - T_{\text{cold}}, \tag{7}$$

where T_{hot} is the temperature of the hot end of the EC device, and T_{cold} is the temperature of the cold end of the EC device. T_{span} represents the broadest temperature range within which it can modulate a target material at the same temperature as the EC device.

3.1.2. Specific cooling power density (SPD)

To enable meaningful comparison across EC thermal management devices with different structures and sizes, the cooling power of EC devices is typically normalized by the total mass of the EC material in the active area. The SPD can be calculated as follows:

$$\text{SPD} = \frac{P_{\text{cooling}}}{m_{\text{EC}}}, \tag{8}$$

where P_{cooling} represents the cooling power of the EC device, and m_{EC} represents the total mass of the EC material in the active area.

3.1.3. Coefficient of performance (COP)

The COP quantifies the cooling efficiency of an EC device relative to the electricity input. The COP can be calculated by the equation

$$\text{COP} = \frac{Q_{\text{cooling}}}{W_{\text{E}}}, \tag{9}$$

where Q_{cooling} represents the heat transferred by the EC device during the cooling process (the measurements are commonly carried out under a zero-temperature-difference condition), and W_{E} represents the total electricity consumption of the EC thermal management system, including the mechanical actuator or fluid pump.

3.1.4. COP/COP$_{\text{Carnot}}$

The COP/COP$_{\text{Carnot}}$ of an EC device at given T_{span} can be further calculated as follows:

$$\frac{\text{COP}}{\text{COP}_{\text{Carnot}}} = \frac{\text{COP} \times T_{\text{span}}}{T_{\text{hot}}}. \tag{10}$$

The value of COP/COP$_{\text{Carnot}}$ quantifies the proximity of the heat pump to its theoretical ideal, thus serving as a meaningful measure of thermodynamic efficiency under a given temperature span.

3.2. Thermal management devices based on inorganic EC ceramics

The development of EC thermal management devices has been pioneered by systems utilizing inorganic EC ceramics, which represent the earliest practical implementations of this technology. The field's foundational breakthrough was achieved in 1992 by Russian researchers Sinyavsky and Brodyansky, who demonstrated the first functional EC regenerator prototype employing lead scandium tantalate ($Pb(Sc_{0.5}Ta_{0.5})O_3$, PST) ceramic as the refrigerant (Fig. 4(a)).[62] As illustrated in the accompanying figure, their innovative design comprised five key components: (1, 2) PST EC working fluid chambers that undergo polarization/depolarization, (3, 4) heat exchangers for thermal transfer, and (5) a precision displacer regulating fluid flow direction. This system established the fundamental operating principle for subsequent EC devices: during operation, a helium-pentane heat exchange fluid is circulated by a pump while synchronized electric field application ($E \rightarrow E_{max}$) to the PST ceramic induces heat absorption at the cold end ($T \rightarrow T - \Delta T$), followed by field removal ($E_{max} \rightarrow 0$) causing heat rejection at the hot end ($T \rightarrow T + \Delta T$). Through this cyclic process of alternating polarization and fluid displacement, the device achieves continuous heat pumping and effective thermal separation, accumulating useful cooling power at the cold reservoir. This pioneering design was of great significance as it established the basic framework and operating principle for subsequent EC devices, although it was in its initial stage and might have had limitations in terms of efficiency and practical application scale.

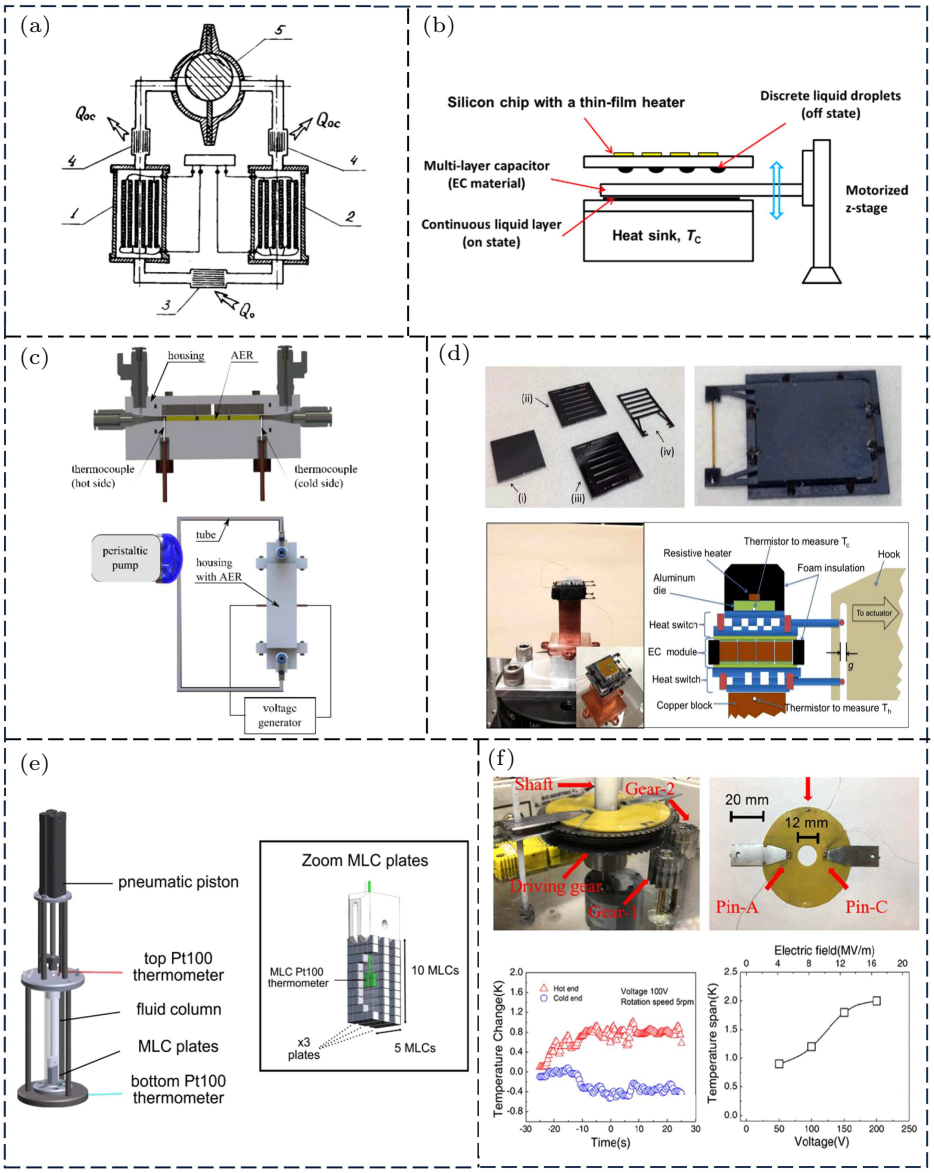


Fig. 4. (a) The first EC thermal management prototype, based on PST ceramic material. This figure is reproduced from Ref. [62] with permission of the Elsevier. (b) Linear mechanically actuated thermal management device. This figure is reproduced from Ref. [69] with permission of the AIP Publishing. (c) Pumped fluid EC regenerator. This figure is reproduced from Ref. [70] with permission of the AIP Publishing. (d) Sawtooth thermal switch EC device. This figure is reproduced from Ref. [71] with permission of the AIP Publishing. (e) Piston-type device. This figure is reproduced from Ref. [72] with permission of the AIP Publishing. (f) Disk-shaped EC regenerator. This figure is reproduced from Ref. [73] with permission of the AIP Publishing.

Subsequent advancements in ceramic-based EC systems have focused on improving T_{span} and operational efficiency through enhancing the intrinsic EC performance[52,63–68] and innovative designs of device structure. In 2012, Jia *et al.* developed a mechanically actuated system using doped $BaTiO_3$ multilayer ceramic capacitors (MLCCs) that achieved a 1 K temperature drop through linear reciprocating motion between heat source and sink (Fig. 4(b)).[69] This system represented an improvement over the earlier design. By using MLCCs and a mechanical actuation method, it explored a new way to separate hot and cold. However, the achieved temperature drop of 1 K was still relatively modest, indicating there was room for further improvement. In 2015, a significant performance leap came with Plaznik *et al.*'s work, where a PMN-10PT ceramic regenerator achieved an unprecedented 3.3 K T_{span} using optimized fluid reciprocation (Fig. 4(c)).[70] The achieved T_{span} surpassed other contemporary EC devices and approached the performance of PST ceramic-based EC systems ($T_{span} = 5$ K).[61] This result highlighted the critical role of fluid-flow engineering in enhancing heat transfer within regenerator-type architectures and demonstrated that systematic thermal–hydraulic optimization could substantially elevate the T_{span} of EC systems. In the same year, an alternative approach utilizing a sawtooth thermal switch configuration with $BaTiO_3$ MLCC arrays achieved a temperature drop of 0.3 K (Fig. 4(d)),[71] although the cooling performance of the device was relatively limited by the EC material. Its configuration served as an essential regenerator prototype and established the conceptual foundation for subsequent progress in large-T_{span} device development. In 2016, Sette *et al.* designed a compact piston-type Zr-doped $BaTiO_3$ MLCCs device, achieving a temperature drop of 0.13 K (Fig. 4(e)).[72] The fundamental principle of establishing a temperature gradient within a fluid column has been experimentally validated. The continued evolution of these systems culminated in Zhang *et al.*'s disk-shaped regenerator design, which successfully combined mechanical actuation with EC ceramic MLCCs to fabricate an EC regenerator and achieve a 2 K T_{span} (Fig. 4(f)).[73] These progressive developments demonstrate how material innovations (from PST to advanced MLCCs formulations) combined with improved heat exchange architectures (fluid-based to solid-state regenerators) have steadily enhanced device performance while addressing inherent challenges in breakdown fields and mechanical fatigue.

After verifying the large EC effect of PST MLCC ceramics using both thermocouples and infrared cameras in 2019,[67] researchers accelerated the exploration of their engineering application in thermal management devices. In 2020, Torelló *et al.* used PST ceramic MLCCs as the EC element to prepare a reciprocating push-pull regenerator with a liquid medium heat transfer strategy. By simulating a cycle similar to the Ericsson–Brayton cycle, its T_{span} reached 13 K (Fig. 5(a)), validating the practical viability of PST ceramic MLCCs in thermal management devices.[74] In the same year, Wang *et al.* also used PST ceramic MLCCs as the EC element to improve the sawtooth mechanically braked regenerator, achieving a maximum T_{span} of 5.2 K and a heat flux of 135 mW/cm^2 (Fig. 5(b)).[2] Compared to previous solid-state EC devices based on inorganic materials, which achieved a temperature drop of only approximately 1 K[69] and 0.3 K,[71] significant performance enhancement can be realized through optimization of both device structure and material system. By enhancing the sawtooth mechanically braked regenerator, the researchers achieved a certain level of performance enhancement in thermal management. However, compared with Torelló's results, the lower T_{span} indicates that different structural designs and operation strategies significantly impact device performance, suggesting ample room for further optimization to boost overall performance. In 2023, Li *et al.* designed an EC regenerator using PST multilayer ceramic capacitors as EC elements and achieved a large T_{span} of up to 20.9 K and a refrigeration power of 4.2 W under a working electric field of 10 MV/m (Fig. 5(c)).[75] This achievement brings EC effect-based thermal management devices on par with traditional steam compression systems, strongly demonstrating their potential for replacement. After that, a dual-strategy scalable interdigital structure solid-state EC refrigeration device based on lead-free $BaSrTiO_3$ (BSTO) MLCCs was designed (Fig. 5(d)); the device can achieve $T_{span} = 7.13$ K and a cooling power of 119 mW.[76] Nevertheless, in practical applications, additional factors such as device durability, manufacturing costs, and compatibility with existing systems must be comprehensively considered to facilitate large-scale adoption.

Thermal management devices based on ceramic EC materials exhibit remarkable advantages in the field of thermal management owing to their excellent physical and chemical properties. The high thermal conductivity of ceramic materials ensures efficient heat conduction, enabling rapid reduction of the temperature of the heat source and maintaining the stable operation of the system. They are particularly suitable for the heat dissipation requirements of high-power density electronic chips.[45] In addition, ceramic materials can still maintain structural stability and thermal management performance in high-temperature environments, endowing them with important application value in extreme environments such as aerospace engines and industrial high-temperature furnaces. Their excellent chemical stability also ensures the long-term reliability of the devices in complex environments such as humidity, acid, and alkali. However, ceramic EC thermal management devices also have obvious limitations. Firstly, they are relatively large in size and complex in structure, making

it difficult to meet the requirements of miniaturization and lightweight design of modern electronic devices. Secondly, the brittleness and low toughness of ceramic materials make them vulnerable to mechanical or thermal shock, which may lead to cracks or even breakage, restricting their application in environments with frequent vibrations. Moreover, ceramic materials are difficult to process and require special molding and processing techniques, increasing the manufacturing cost. These limitations have restricted the widespread application of ceramic EC thermal management devices. Future research should focus on developing new composite material systems, optimizing the structural design of devices, and improving the processing technology to overcome the existing deficiencies and promote their practical application in more fields.

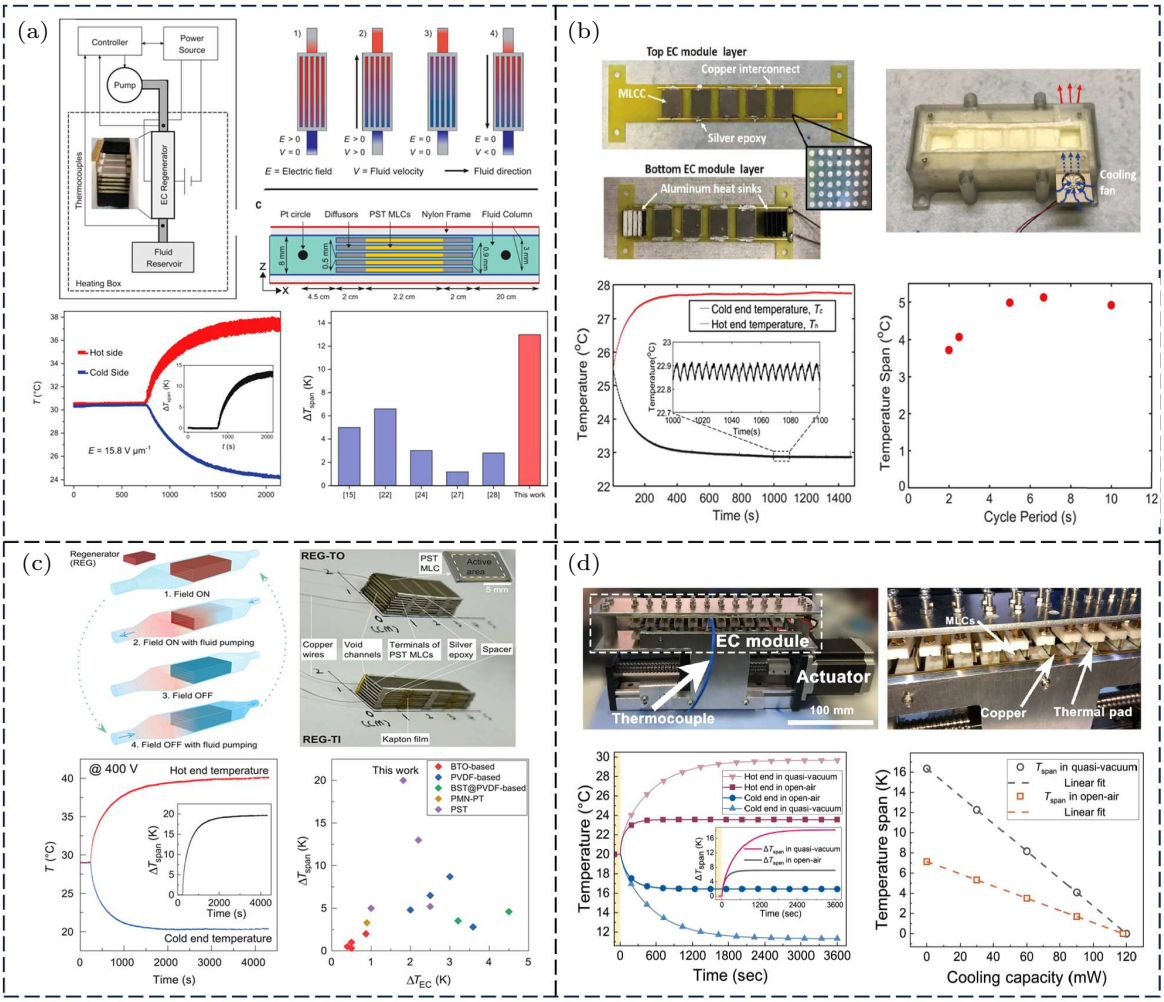


Fig. 5. EC devices using PST MLCCs. (a) Liquid-medium EC regenerator. This figure is reproduced from Ref. [74] with permission of the American Association for the Advancement of Science. (b) Zigzag mechanical-actuation EC regenerator. This figure is reproduced from Ref. [2] with permission of the American Association for the Advancement of Science. (c) Liquid-medium EC regenerator with a refrigeration power of 4.2 W. This figure is reproduced from Ref. [75] with permission of the American Association for the Advancement of Science. (d) Dual-strategy scalable interdigital structure solid-state EC device using BSTO MLCCs. This figure is reproduced from Ref. [76] with permission of the American Association for the Advancement of Science.

3.3. Thermal management devices based on polymers and their composites

Ferroelectric polymers, particularly relaxor ferroelectric polymers such as poly(vinylidene fluoride-trifluoroethylene-chlorofluoroethylene) P(VDF-TrFE-CFE) copolymers, can exhibit significant ΔS (55 J/(kg·K)) and ΔT (12 K) under an applied electric field at room temperature.[53] This indicates their strong intrinsic cooling capability. In contrast to brittle inorganic ceramic EC materials, polymers inherently possess excellent flexibility and high fracture toughness. This characteristic enables them to be readily processed into ultra-thin, large-area, and flexible elements. Such processability is crucial for developing compact, conformal, or wearable microcooling devices, offering unprecedented flexibility for the thermal management design of electronic components. Through advanced molecular design and modification, modern polymeric EC materials and their composites can achieve strong EC effects at relatively low to moderate electric fields (e.g., < 100 V/μm).[40,54,59,60,77–82] This not only reduces the demand for high-voltage power supplies and simplifies system design but, more importantly, significantly enhances the material's cyclic durability and reduces breakdown risks, ensuring long-term operational stability and reliability of the devices.

3.3.1. EC devices based on polymer thin-film components

Polymer thin film-based EC thermal management devices represent a transformative approach to temperature regulation, leveraging the intrinsic flexibility and versatile processability of polymeric materials to enable fully compliant, shape-adaptable designs that are ideally suited for next-generation applications in wearable electronics, embodied intelligence systems, and personalized human body thermal management. The unique mechanical properties of these polymer composites facilitate conformal integration with complex geometries, while their solution-processable nature allows for cost-effective fabrication through scalable techniques such as roll-to-roll printing or 3D manufacturing. The field has witnessed remarkable progress since its inception, beginning with Gu *et al.*'s pioneering demonstration of a mechanically actuated system using radiation-modified P(VDF-TrFE) multilayer modules in 2013, which achieved a breakthrough T_{span} of 6.6 K at 1 Hz operating frequency by physically shuttling the EC elements between thermal reservoirs.[83] This work demonstrated the potential of using radiation-modified P(VDF-TrFE) multilayer modules in EC systems. In 2017, Ma *et al.*'s innovative electrostatic actuation approach employing P(VDF-TrFE-CFE) terpolymer films not only realized a 2.8 K T_{span} with a COP of 13, but also demonstrated practical viability by rapidly cooling smartphone batteries by 8 K within just 5 seconds (Fig. 6(a)).[3] The electrostatic actuation approach was innovative and showed great potential for the thermal management of miniaturized and flexible electronic devices. Subsequently, building on Ma's work, Wang *et al.* designed a photovoltaic-driven self-sustaining EC thermal management system, which shows potential for active full-day human body thermoregulation (Fig. 6(b)).[15] This system presented an exciting prospect. The use of photovoltaic drive to achieve self-sustainability was a creative idea, especially for applications in human body thermoregulation. It opened up new possibilities for the application of EC thermal management systems in the field of wearable devices and personal comfort.

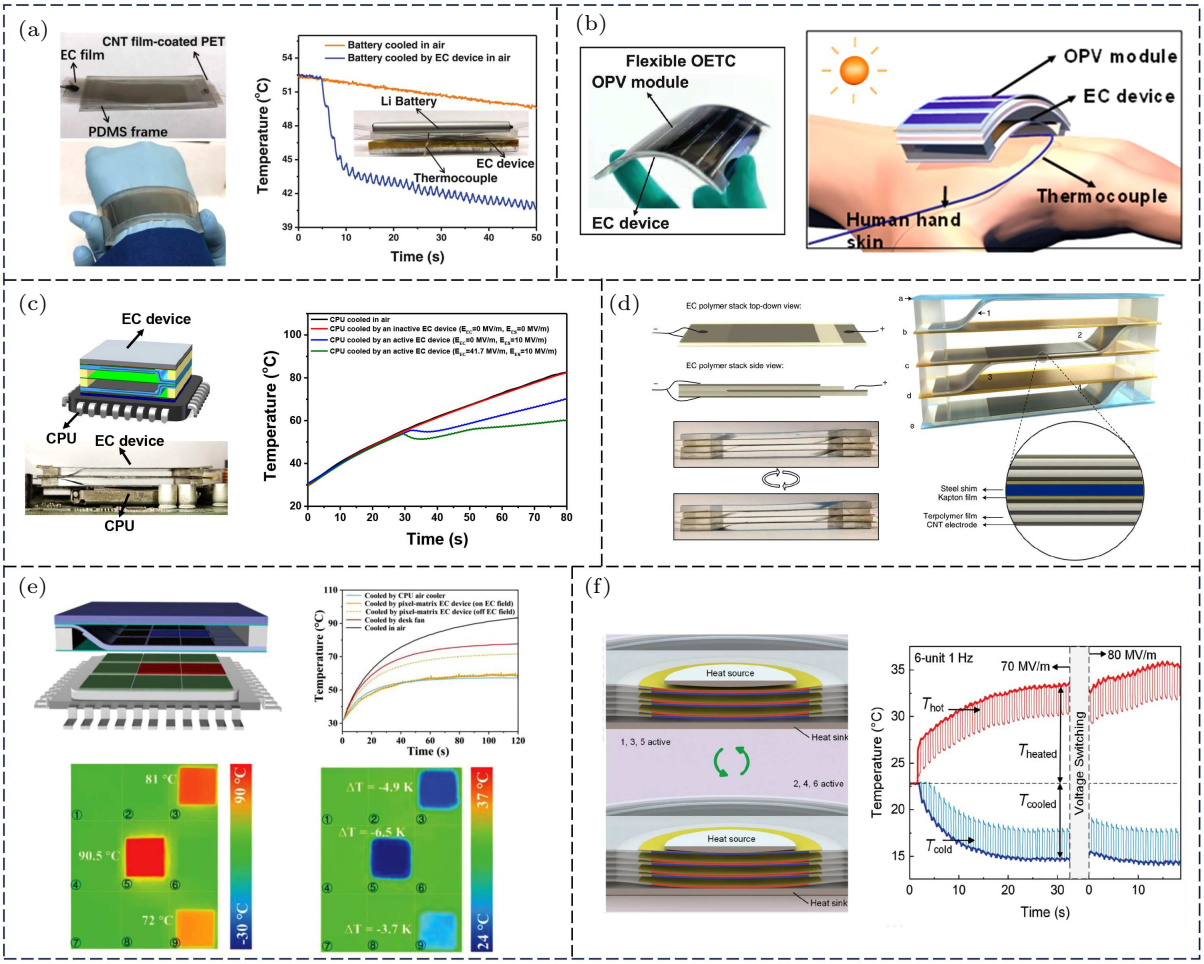


Fig. 6. EC devices based on P(VDF-TrFE-CFE) and its composite materials. (a) Electrostatically driven thermal management device. This figure is reproduced from Ref. [3] with permission of the American Association for the Advancement of Science. (b) Photovoltaic-driven self-sustaining EC thermal management system. This figure is reproduced from Ref. [15] with permission of the American Physical Society. (c) Double-unit electrostatically driven EC thermal management device. This figure is reproduced from Ref. [88] with permission of Wiley. (d) Four-layer cascaded electrostatically driven thermal management device. This figure is reproduced from Ref. [85] with permission of the Springer Nature. (e) Pixel temperature-controlled EC thermal management device. This figure is reproduced from Ref. [16] with permission of Wiley. (f) Self-regenerative EC thermal management device. This figure is reproduced from Ref. [84] with permission of the American Association for the Advancement of Science.

In order to further increase the cooling performance, a double-unit EC device using modified P(VDF-TrFE-CFE) stacks was designed, demonstrating a T_{span} of 4.8 K and effective cooling for CPU (Fig. 6(c)). In 2019, a novel energy recovery system suitable for the EC effect has been proposed by Defay *et al*. which can recovering 75%–80% of the energy, significantly enhancing the energy utilization efficiency of EC materials during operation,[84] which was crucial for the practical application and competitiveness of EC thermal management devices. Based on these works, a significant leap forward occurred in 2020 when Meng *et al*. developed a sophisticated four-layer cascaded device architecture incorporating P(VDF-TrFE-CFE) and an advanced energy recovery system, pushing the T_{span} to 8.7 K while dramatically improving COP (Fig. 6(d)).[85] It demonstrated the effectiveness of integrating different technologies and design concepts to enhance the performance of EC devices.

In 2021, Kang *et al.* fabricated an electromagnet-driven system that can achieve a 1.1 K temperature change during the cooling process,[86] while Li *et al.* used a ceramic-polymer composite with 3D thermally conductive networks as EC elements.[87] Both works employed electromagnets to magnetically drive materials, successfully achieving effective separation of hot and cold regions. However, the heat generation issue of electromagnets requires further consideration and optimization. Recent breakthroughs include Bai *et al.*'s BST ceramic-reinforced double-bond modified terpolymer system, which can reach 4.6 K T_{span} and achieve pixel-matrix temperature control (Fig. 6(e)).[16] The combination of BST ceramic reinforcement and double-bond modification of the terpolymer not only achieved a certain T_{span} but also enabled pixel-matrix temperature control, which provided new possibilities for more precise thermal management applications. In 2024, Wu *et al.* carried out a six-layer self-regenerative heat pump, setting new performance benchmarks with a 14.2 K T_{span} and exceptional 1.5 W/g cooling capacity (Fig. 6(f)),[84] effectively eliminating the dependency on external driving components, thereby acting as a key enabler for the miniaturization and integrated design of next-generation refrigeration devices. These advancements collectively demonstrate the field's remarkable evolution through three pivotal technological trajectories: molecular-scale precision engineering achieved via sophisticated chemical modifications such as strategic double-bond incorporation, the development of innovative hybrid material architectures that synergistically combine flexible polymer matrices with high-thermal-conductivity ceramic components, and the emergence of revolutionary self-actuating mechanisms that fundamentally transform device operation by eliminating dependence on external driving systems. The rapid progression from initial demonstrations to systems achieving $T_{span} > 10$ K within a decade underscores the tremendous potential of polymer-based EC technologies, particularly for applications demanding mechanical compliance, lightweight construction, and efficient microscale thermal management in next-generation electronic and biomedical devices.

3.3.2. EC devices based on polymer fibers/tubes components

Beyond conventional thin films or multilayer capacitor architectures, polymer EC material research has witnessed groundbreaking innovations that are significantly expanding the technological frontiers of this field. A particularly promising direction involves leveraging the exceptional processability of polymer EC materials to fabricate unconventional geometries such as fibers and microcapillaries, which has emerged as a vibrant research frontier. These fiber/tube-shaped EC materials offer unique advantages due to their distinctive structural characteristics and physical properties, opening new possibilities for applications in self-actuating thermal management systems and advanced microfluidic cooling devices. A landmark achievement in this area was reported by Wang *et al.*, who developed a novel spray-coated EC fiber utilizing the intrinsic electrostrictive properties of P(VDF-TrFE-CFE) terpolymer. Their innovative design achieved autonomous cold-hot separation and demonstrated a measurable cooling temperature difference of 0.7 K (Fig. 7(a)).[89] This pioneering work not only confirmed the feasibility of P(VDF-TrFE-CFE)-based materials for self-powered thermal regulation but also established crucial design principles and fabrication methodologies that have inspired subsequent research in fiber-based EC systems. The unique advantages of these fiber architectures include enhanced specific cooling power density for improved heat transfer, inherent mechanical flexibility for conformal integration, and the potential for scalable manufacturing through continuous fiber production techniques — features that could revolutionize applications ranging from smart textiles with built-in temperature regulation to minimally invasive medical cooling devices.

Building upon previous advancements in polymer EC materials, significant progress was made in 2022 when Cui *et al*. developed an innovative composite system by incorporating BST nanoscale ferroelectric ceramics into a P(VDF-TrFE-CFE) matrix (Fig. 7(b)). This strategic material design achieved a remarkable enhancement in the composite's elastic modulus while preserving its EC properties. Utilizing advanced wet spinning technology, Cui *et al*. successfully fabricated a self-supporting EC capillary structure from this composite material, which demonstrated both superior mechanical robustness and exceptional thermal management capabilities. Through an ingenious magnetic actuation mechanism, the system achieved fluid-based cold–hot separation with a

T_{span} of 1.4 K,[90] marking a significant step forward in active thermal regulation technologies. The following year, 2023, Bai *et al.* conducted further research by developing a novel P(VDF-TrFE-CFE)/P(VDF-TrFE)@BN composite deposited on a polyimide (PI) film substrate (Fig. 7(c)). Through an innovative winding technique and multi-stage cascade design, they engineered a high-performance cooling tube architecture that achieved an impressive 4.2 K T_{span}.[91] This achievement not only validated the effectiveness of combined material and structural optimization approaches but also established new paradigms for developing self-driven EC thermal management systems. Polymer-based EC materials, particularly PVDF and its copolymers, offer unparalleled advantages in thermal management applications due to their exceptional flexibility, conformability, and versatile form factors. These properties enable seamless integration with complex geometries, from the curved surfaces of human skin to irregular electronic components, while maintaining optimal thermal contact. For instance, PVDF-based materials can undergo repeated folding and stretching without performance degradation, making them ideal for next-generation wearable electronics where they have demonstrated cooling capabilities on human skin prototypes. The ability to process these materials into various configurations-including fibers, tubes, and conformal coatings-combined with their lightweight and scalable manufacturing potential, positions them as transformative solutions for applications ranging from flexible electronics cooling to personalized thermal therapy devices.

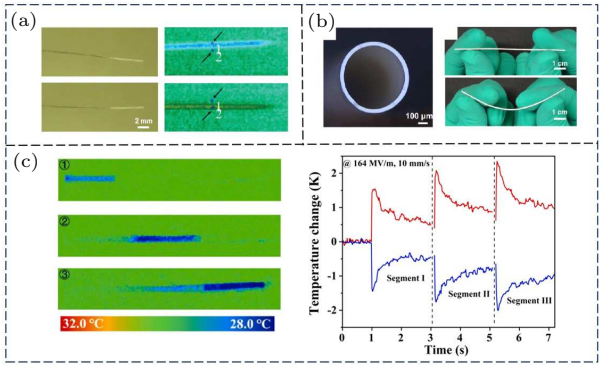


Fig. 7. Based on P(VDF-TrFE-CFE) and its composite materials. (a) Self-driven EC fiber. This figure is reproduced from Ref. [89] with permission of Wiley. (b) EC composite capillary microtube. This figure is reproduced from Ref. [90] with permission of the Cell Press. (c) Cascaded EC microtubes. This figure is reproduced from Ref. [91] with permission of Elsevier.

3.3.3. Challenges for polymer EC materials and its device

Polymer EC materials demonstrate exceptional advantages for miniaturized and integrated thermal management systems, primarily due to their compatibility with advanced microfabrication techniques. These materials can be precisely processed into ultrathin films or complex micro/nanostructures through cost-effective solution-based methods, such as spin-coating, blade coating, and inkjet printing, enabling seamless integration with modern microelectronic components. This unique processability allows for the creation of highly compact thermal management units with minimal footprint areas, perfectly aligning with the stringent size and weight requirements of next-generation electronics while enabling unprecedented chip-level and even on-die thermal regulation. However, several critical challenges must be addressed to fully realize their potential. The temperature-dependent performance stability remains a significant limitation, as thermal agitation above 80–100 °C can disrupt the carefully aligned dipole structures in polymers like PVDF-based copolymers, leading to degradation in EC response. While laboratory-scale fabrication achieves excellent results, industrial-scale production faces hurdles in maintaining consistent crystallinity and dipole alignment across large-area samples. The current technological limitations significantly hinder large-scale commercialization, driving urgent research efforts toward developing thermally stable polymer composites through advanced material engineering approaches; optimizing hierarchical architectures for robust performance across extreme temperature conditions; and perfecting high-throughput manufacturing processes that ensure consistent quality. Breakthroughs in these critical areas would unleash the transformative potential of polymer EC materials, paving the way for revolutionary applications, including adaptive thermal regulation in flexible electronics and precision thermal management in advanced computing systems, thereby ushering in an era of intelligent thermal solutions that seamlessly integrate nanoscale precision with system-level functionality.

3.4. Comparative analysis of structural designs between ceramic/polymer EC material based coolers

Currently, ceramic-based EC coolers primarily employ regenerator-type structures, which rely on heat-transfer fluids or mechanical solid–solid contact to transport heat between the EC material and the hot/cold reservoirs, thereby achieving a large T_{span} and significant cooling power. This design approach is necessitated by the inherent brittleness, limited elastic deformation, and relatively low fracture toughness of ceramic materials, which render them unsuitable for actuation mechanisms that depend on the material's own strain. In fluid-based regenerators, although there is a certain risk of fluid leakage, the structural design ensures that the ceramic elements remain stationary during operation. The fluid medium concurrently fulfills the functions of heat exchange and thermal isolation. This mechanism effectively reduces localized mechanical fatigue caused by reciprocating motion in the system and significantly minimizes wear on the ceramic components. In contrast, all-solid-state thermal-switch configurations eliminate the need for a fluid medium, but they still

require precise external actuators and robust mechanical supports to prevent material fracture.

In contrast, EC polymers, based on their inherent flexibility and processability, enable not only mechanical actuation and fluid-based methods but also controlled deformation of the material itself. For example, EC films can be integrated into electrostatic actuators to achieve thermal separation without requiring fluid and mechanical actuation systems. Additionally, their intrinsic electrostrictive effect allows self-actuating structures, such as EC films or fibers, to autonomously move between a heat source and a heat sink under a square-wave voltage. This "material-as-actuator" concept simplifies system architecture and facilitates further miniaturization. Moreover, these devices can be integrated onto curved or flexible surfaces, making them suitable for providing effective thermal management in wearable and implantable electronics. However, their practical application remains constrained by material limitations, such as low melting points and electrical/thermal aging. Developing polymer-based EC materials with a broad operating temperature range and high electric field endurance is crucial for advancing this field.

Therefore, these two pathways are not simple substitutes but rather complementary solutions tailored to different application scenarios. The future development of EC cooling technology will rely on a deep understanding of the intrinsic material properties, enabling the collaborative design and optimization of both materials and structures to meet specific application requirements.

4. Conclusion and perspectives

In summary, as a highly promising solid-state refrigeration technology, EC effect-based thermal management devices offer significant advantages in addressing the high energy consumption and environmental pollution of conventional refrigeration while meeting modern electronics' miniaturization demands. Despite notable progress in material performance and device design, commercialization challenges persist due to material limitations: inorganic ceramics exhibit brittleness, poor processability, and miniaturization difficulties, while polymer-based systems face temperature sensitivity, high-temperature performance degradation, and aging issues. Further research is required to optimize material selection across operating conditions, enhance cycling efficiency, and improve structural versatility. The future advancement of electrocaloric technology hinges on synergistic progress across four interconnected domains.

(1) Investigating long-term material stability Long-term material stability is essential to ensure the reliable and sustained operation of solid-state EC thermal management devices. Future research should focus on the aging behavior and failure mechanisms of both classes of materials under various environmental conditions, such as high and low temperatures, high humidity, and corrosive atmospheres. For polymer EC materials and their composites, the focus should be on their dielectric properties, polarization stability, and phase structure evolution. For inorganic EC materials, systematic studies on the stability of their domain structures, fatigue characteristics, and performance degradation are necessary. Through advanced material characterization techniques, such as *in-situ* x-ray diffraction, high-resolution electron microscopy, and dielectric spectroscopy, the evolution of microstructures, chemical composition changes, and degradation mechanisms during prolonged operation can be thoroughly investigated. Based on these insights, targeted strategies such as developing protective coatings, optimizing material compositions, and refining microstructural design can be implemented to significantly enhance the cycling life and environmental adaptability of EC materials and corresponding devices.

(2) Challenges in multi-physics field coupling and regulation Thermal management systems are often subjected to the combined effects of multiple physical fields in application scenarios, such as electric, magnetic, thermal, and stress fields. Therefore, overcoming the challenges of multi-physics coupling and regulation to achieve precise and efficient control of the thermal management process is necessary. The EC effect strongly depends on the coupling relationships among electric fields, temperature, and stress, often exhibiting hysteresis and nonlinear characteristics. Utilizing multi-physics simulation, accurate coupled models can be established to investigate the interaction mechanisms between different physical fields and their influence on the EC effect. By combining experimental and simulation approaches, strategies for optimizing multi-physics regulation can be explored. Examples include designing gradient or pulsed electric field modulation schemes to enhance material response efficiency, developing domain structure regulation methods based on phase-field simulations, and establishing synergistic control algorithms for temperature, electric field, and stress. Ultimately, these efforts will enable precise and dynamic regulation of the thermal management performance of EC devices, meeting the demands of diverse application scenarios.

(3) Optimization of miniaturization and integration processes With the rapid advancement of AI technology, microelectronics and wearable devices continue trending toward miniaturization and integration, placing higher demands on the micro-fabrication and integration processes for thermal management devices. Future work may further optimize miniaturization and integration techniques tailored to different types of EC materials to achieve highly integrated thermal management devices within electronic systems. Technologies such as advanced micro- and nano-fabrication techniques, including thin-film deposition, photolithography, etching, and nanoim-

printing, are required to achieve high-precision, miniaturized device fabrication. Additionally, novel heterogeneous integration and packaging technologies, such as 3D printing, transfer printing, and microfluidic assembly, should be explored to organically integrate polymer and inorganic EC material modules with electronic circuits, sensors, and other functional components, constructing compact and efficient thermal management systems. During integration, interfacial thermal resistance, mechanical stress matching, and heat dissipation path optimization should also be considered to ensure efficient heat transfer within limited spaces.

(4) Exploration of dynamic environment-adaptive mechanisms The growing intelligence of contemporary application scenarios demands that thermal management systems possess robust dynamic adaptive capabilities. Future research may explore environmental-adaptive mechanisms based on both polymer and inorganic EC materials, enabling thermal management systems to automatically adjust operational modes and parameters in response to changes in ambient temperature, humidity, light intensity, and device workload, thereby achieving optimal thermal management performance. By incorporating highly sensitive temperature and dielectric sensors, real-time monitoring of environmental and material state parameters can be achieved. Coupled with advanced control algorithms, such as fuzzy logic control, neural network control, and model predictive control, intelligent adaptive regulation of EC thermal management systems can be realized. These advancements will significantly expand the application prospects of EC thermal management systems in complex and dynamic environments.

As these key challenges are gradually addressed and resolved, EC thermal management systems are expected to achieve large-scale practical applications in areas such as thermal protection, smart wearables, photonic integration, and automotive electronics. Through complementary material systems and integrated innovation, these technologies will drive the microelectronics and wearable device industries toward higher performance, greater reliability, and enhanced intelligence.

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