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GUEST EDITORIAL

Thermal-X Materials: Emerging Material Designs for Tailoring Thermal Phenomena Across Energy, Electronics, Catalysis, and Water Technologies

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Thermal processes weave through nearly every aspect of materials behavior—shaping how structures evolve, how charges and ions move, how catalytic pathways proceed, and how structural and mechanical stability is maintained. Yet despite this pervasive reach, many application-driven fields have long regarded thermal effects as constraints to regulate rather than as levers to engineer. This perspective is undergoing a decisive shift. Across energy systems, electronic devices, catalytic platforms, and water–energy technologies, the deliberate modulation of heat flow, thermal gradients, radiative exchange, and thermally coupled transport is emerging as a powerful design axis capable of unlocking new modes of performance.

To reflect the inherently cross-disciplinary nature of this emerging area, we have curated this special collection jointly across *Advanced Functional Materials* and *Advanced Electronic Materials*, bringing together contributions that span fundamental materials design, interfacial phenomena, and device-level implementation. To capture the convergence of emerging materials-design strategies aimed at controlling thermal phenomena, we introduce the term Thermal-X Materials. Here, **"Thermal-X"** refers to *materials that tailor or exploit thermal phenomena—heat flow, thermal gradients, radiative exchange, photothermal conversion, thermally induced mass or charge transport, and thermal–chemical coupling—to achieve functions traditionally associated with different technological sectors.* The **"X"** represents the expanding landscape of cross-domain applications spanning energy, electronics, catalysis, water technologies, and human–environment interfaces. This collection assembles cutting-edge contributions that collectively illustrate this emerging paradigm.

This special collection brings together recent contributions that exemplify these principles across several broad directions:

Thermoregulatory Materials

At the scale of personal comfort and the built environment, several works develop materials whose optical and interfacial properties are tuned for thermal regulation. A sweat gland-like fabric for personal thermal-wet comfort management (adfm.202409807) shows how textile structures can be designed to manage heat and moisture simultaneously at the body interface. Solution-processable, solar-transparent mesoporous nanoparticles enable efficient and scalable radiative cooling for photovoltaics (adfm.202410478), pointing toward coatings that passively reduce operating temperature without compromising optical performance.

Smart windows and coating technologies are another central line within this theme. Bidirectional temperature-responsive thermochromic hydrogels with adjustable light-transmission intervals (adfm.202413102), 2D thermochromic perovskites for building applications (adfm.202417582), and hydroxypropyl cellulose-based thermochromic hydrogels for smart passive cooling (adfm.202420946) collectively demonstrate how temperature-dependent optical modulation can be integrated into glazing systems to manage solar gain dynamically. High-performance low-emissivity paints based on N-doped poly(benzodifurandione) for energy-efficient buildings (adfm.202419685) highlight the complementary role of emissivity control in reducing radiative heat losses.

Adaptive radiative regulation is further exemplified by ionic liquid-based reversible metal electrodeposition for radiative thermoregulation under extreme environments (adfm.202419087), where emissive properties can be switched via controllable metal deposition. Stretchable, conductive aerogels with high thermal insulation achieved through surface-confined liquid metal particles (adfm.202508954) illustrate how mechanically compliant architectures can also deliver strong thermal-barrier functionality. Fundamental understanding of heat transport supports these application-focused advances: intrinsic thermal conductivity in molecularly engineered polymers (adfm.202420708) and a revisited blackbody radiation formula accounting for inhomogeneous temperature distributions in chip-scale infrared thermal sources (aelm.202400674) provide insight into how material structure and temperature fields influence radiative behavior.

A broader view of how materials mediate interfacial thermal phenomena is provided by a review of the Leidenfrost effect on engineered surfaces (adfm.202423686), which connects surface design to boiling, vapor-layer dynamics, and heat transfer. Together, these contributions illustrate how optical, emissive, and interfacial design strategies form a core pillar of Thermal-X Materials for radiative and convective thermal management.

Thermally Mediated Water and Vapor Transport for Water–Energy Technologies

Thermally mediated water and vapor transport forms a powerful basis for advancing water–energy technologies. The works in this collection show how soft and polymeric materials can couple heat with evaporation, humidity uptake, and interfacial flow, enabling platforms for desalination, environmental energy harvesting, and multiphase resource extraction.

Hydrogel-based photothermal-catalytic membranes for efficient cogeneration of freshwater and hydrogen in membrane distillation (adfm.202416768) exemplify how a single materials platform can support both desalination and chemical production. Seawater interfacial evaporation in composite gels that simultaneously enable photovoltaic cooling, seawater desalination, and enhanced uranium extraction (adfm.202420651) demonstrates how interfacial evaporation and gel design can be harnessed to combine thermal management, clean water production, and resource recovery.

A suite of hygroscopic and evaporative systems highlight moisture as a resource. Self-sustained water and electricity generation from ambient humidity via metal-ion-controlled hygroscopic hydrogels (adfm.202420936), moisture harvesting by structure-regulated hygroscopic hydrogels for energy and water sustainability (aelm.202400802), and electricity generation from ambient water evaporation in the absence of sunlight using PVA-based porous hydrogels (adfm.202423371) collectively show how polymer network structure and composition can be tuned to direct water uptake, release, and associated energy conversion. Active thermal field integration for Marangoni-driven salt rejection and water collection (adfm.202421067) further illustrates how imposed temperature fields can be used to steer interfacial flows for salt management and liquid collection.

These hydrogels and polymeric systems exemplify Thermal-X Materials in which thermal, sorption, and fluidic processes are co-designed, yielding multifunctional platforms at the water–energy nexus.

Photothermal and Thermocatalytic Materials

A third theme focuses on catalytic and reactive systems where thermal effects are tightly interwoven with light absorption and material design. Photothermal-catalyzed hydrogen peroxide production enabled by gold–organic frameworks (adfm.202420941) demonstrates how catalyst architectures can be tailored to couple light harvesting with thermally enhanced reaction pathways. Recent progress in designing catalysts for photothermal conversion of plastic wastes (adfm.202419801) addresses the pressing need for materials that can valorize polymer waste streams using light and heat.

On the conceptual and materials-design side, a perspective on thermal management materials and strategies for photothermal catalysis (adfm.202420723) and a comprehensive review of plasmonic nanomaterials in photothermal catalysis and artificial photosynthesis—focusing on hot electron dynamics, design challenges, and future prospects (adfm.202503186)—collectively frame how plasmonic and photothermal materials can be engineered to control energy localization, dissipation, and transfer at catalyst surfaces. These works show that in catalysis, as in thermal management, the precise control of where and how heat is generated and dissipated is essential for unlocking new performance regimes.

Some of the hydrogel-based platforms discussed earlier, such as the photothermal-catalytic membrane for cogeneration of freshwater and hydrogen (adfm.202416768), naturally bridge this catalytic theme with the water-energy nexus, underscoring the cross-cutting nature of Thermal-X strategies.

Thermoelectric, Caloric, and Thermally Modulated Materials

The fourth major theme brings together materials designed to convert heat into electrical signals, provide solid-state cooling, or manage thermal transport in electronic and energy systems.

Thermoelectric materials are strongly represented. High-performance n-type organic thermoelectric aerogels for flexible energy harvesting and sensing devices (aelm.202400824), a platform for characterizing thermoelectric materials using photo-crosslinked ionic gel electrolytes (aelm.202500042), highly efficient and flexible thin-film thermoelectric materials based on blends of PEDOT:PSS and $AgSb_{0.94}Cd_{0.06}Te_2$ (aelm.202500118), and cement–SnSe thermoelectric devices with high Seebeck coefficients (aelm.202500649) collectively illustrate how organic, hybrid, and structural materials can be engineered for scalable, flexible, or infrastructure-integrated thermoelectric applications. A review on flexible thermoelectrics for wearable electronics, covering solid-state and ionic materials, textile architectures, interface engineering, and device performance (aelm.202500396), provides a broad overview of design principles for these systems.

Caloric materials offer complementary approaches to thermal-to-functional conversion. Harnessing outer space for improved electrocaloric cooling (adfm.202419891), advances in soft mechanocaloric materials (adfm.202420997), and soft solid-state electrocaloric refrigeration (adfm.202506625) highlight how electrocaloric and mechanocaloric responses in compliant materials can be employed for solid-state cooling and actuation. Together, these works outline pathways toward devices that use electric fields or mechanical loading to modulate temperature in a controlled, reversible manner.

More broadly, several contributions examine thermal transport and temperature fields in electronic and energy materials. Internal temperature evolution metrology and analytics in Li-ion cells (adfm.202417273) address how spatially and temporally resolved temperature information informs battery safety and performance. Thermal control of vortex motion in nanoscale superconductors (aelm.202400946) illustrates how local temperature can modulate electronic states in quantum materials. Epoxy nanocomposites containing in-situ-generated silver nanoparticles on boron nitride nanosheets (aelm.202500245) target advanced packaging applications where high thermal conductivity and tailored interfacial behavior are essential. Together with the previously mentioned studies on intrinsic polymer thermal conductivity (adfm.202420708), Leidenfrost phenomena (adfm.202423686), and inhomogeneous temperature fields in infrared thermal sources (aelm.202400674), these works delineate a rich landscape of Thermal-X Materials devoted to controlling and exploiting thermal transport across length scales.

The collection also includes a review on wearable haptic feedback interfaces (adfm.202417906), which covers thermal haptic actuation alongside mechanical and electrotactile modes, highlighting how controlled heat flux at the skin interface is emerging as an important dimension in next-generation body-interfaced systems.

Conclusions and Outlook

Across all these contributions, a unifying message emerges: thermal phenomena are not merely boundary conditions but powerful levers for materials design. The works featured in this joint collection illustrate how controlling heat flow, radiative exchange, thermal–mass transport coupling, localized temperature fields, and thermal gradients can unlock performance modes that would be inaccessible through structural, chemical, or electronic tuning alone. Together, they demonstrate that Thermal-X Materials constitute not a single category, but a design philosophy that spans soft matter, functional polymers, hydrogels, catalytic systems, electronic materials, and multifunctional composites.

Looking ahead, several directions offer particular promise. First, the field will benefit greatly from multiscale thermal characterization and modeling frameworks capable of linking molecular interactions, mesoscale structure, and device-level response. Many contributions in this collection highlight sophisticated materials innovations; translating these into scalable technologies will require tools that resolve dynamic, heterogeneous thermal behavior with high spatial and temporal fidelity.

Second, sustainability-oriented thermal design is emerging as a central theme. Passive cooling coatings, thermochromic and radiative materials, hygroscopic and evaporative platforms, and photothermal catalytic processes illustrate how judicious manipulation of thermal fields can directly contribute to water security, decarbonization, and low-energy operation. Long-term durability, environmental stability, and manufacturability will be key in advancing these concepts from proof-of-principle studies to practical deployment.

Third, the rapid advancement of adaptive and programmable thermal responses—including reversible electrodeposition, dynamic emissivity control, thermochromism, and field-driven caloric effects—signals an exciting shift toward materials that can autonomously adjust to external stimuli. Realizing such capabilities at meaningful scales will demand deeper progress in soft-matter mechanics, interface robustness, and fatigue-resistant architectures.

Finally, as electronics densify and energy systems become increasingly distributed, there is a growing need for materials that integrate thermal, optical, electrical, and mechanical functionality in a coherent, application-ready form. The contributions in this collection highlight how Thermal-X concepts can bridge these traditionally distinct domains, enabling multifunctional systems capable of operating efficiently under complex thermal environments.

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