Cell Reports
Physical Science

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Perspective

Radiative thermal management material for net-zero buildings

Yilin Wang,[1,4] **Zikang Liang,**[1,4] **Shaohang Shi,**[2] **Guowei Tang,**[1] **and Yucan Peng**[1,3,*]
[1]Department of Energy and Resources Engineering, College of Engineering, Peking University, Beijing 100871, China
[2]Department of Building Science, School of Architecture, Tsinghua University, Beijing 100084, China
[3]State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an Jiaotong University, Xi'an 710049, China
[4]These authors contributed equally
*Correspondence: yucan.peng@pku.edu.cn

https://doi.org/10.1016/j.xcrp.2025.102903

SUMMARY

Buildings account for approximately 30% of global primary energy consumption, with heating, ventilation, and air conditioning (HVAC) systems serving as the major contributors. Enhancing the energy efficiency of buildings has therefore become an urgent priority. Beyond conventional technologies, regulating thermal radiation through building envelopes has emerged as a promising approach to reducing energy. In response, a variety of innovative radiative thermal management materials, including passive and dynamic ones, have been developed. This perspective reviews recent advances in state-of-the-art radiative thermal management materials, including radiative cooling materials, low-emissivity materials, and dynamically tunable radiative materials, with a focus on their application to building walls, roofs, and windows. Furthermore, we summarize the prospects of these materials to enable energy-efficient and net-zero buildings and highlight the key challenges and opportunities for future research and development.

INTRODUCTION

With the rapid development of global technology and economy, energy consumption has increased substantially.[1] Among all sectors, buildings are among the largest energy consumers, responsible for over 30% of global energy use. A significant portion of this consumption is attributed to their heating, ventilation, and air conditioning (HVAC) systems, which are primarily driven by the need to maintain indoor thermal comfort.[2] Consequently, reducing energy consumption for building thermal management is imperative for fostering a sustainable net-zero built environment and mitigating greenhouse gas emissions.

Conventional strategies for regulating the thermal environment in buildings have long relied on HVAC systems, which offer precise control over indoor temperature and humidity but account for a significant portion of building energy consumption and associated carbon emissions. In recent years, efforts to enhance HVAC energy efficiency have included the development of high-efficiency compressors, variable-speed drives, advanced refrigerants with lower global warming potential, and smart thermostatic control systems that enable adaptive operation based on occupancy and environmental conditions.[3] In addition, the integration of renewable energy sources—such as solar-assisted cooling or geothermal heat pumps—has further contributed to reducing HVAC-related energy demand.[4]

Alongside improvements in HVAC systems, regulating heat transfer through building envelopes plays a critical role in reducing thermal loads and enhancing overall energy performance. These include the use of thermal insulation materials, which can benefit both heating and cooling energy saving to suppress conductive heat transfer, such as aerogels or vacuum insulation panels.[5] Furthermore, thermal energy storage materials that delay or flatten temperature peaks,[6] as well as architectural interventions such as optimized building orientation, natural ventilation, and solar shading, can also contribute to effective building thermal management.[7] These elements are typically incorporated into building envelopes—walls, roofs, and windows—to mitigate heat gain in summer and heat loss in winter.

However, conventional methods often overlook radiative heat transfer, which constitutes a substantial component of thermal exchange between buildings and their surroundings.[8] In this context, increasing attention has been directed toward regulating the radiative properties of building envelopes as a complementary and potentially more energy-efficient strategy.[9] By tailoring surface parameters, such as solar reflectance and thermal emittance, radiative thermal management materials can passively control long-wave infrared (IR) emission and short-wave solar absorption. This emerging class of materials offers promising pathways for reducing reliance on mechanical cooling and heating, thereby contributing to the development of energy-efficient and climate-resilient buildings.

We classify state-of-the-art radiative thermal regulation materials for building envelopes into three categories, as follows, along with their optimal spectral characteristics for opaque envelopes (e.g., walls and roofs) and transparent envelopes (e.g., windows), as illustrated in Figure 1. Here, only energy balance considerations are taken into account for energy-saving potential evaluation, while other factors—such as

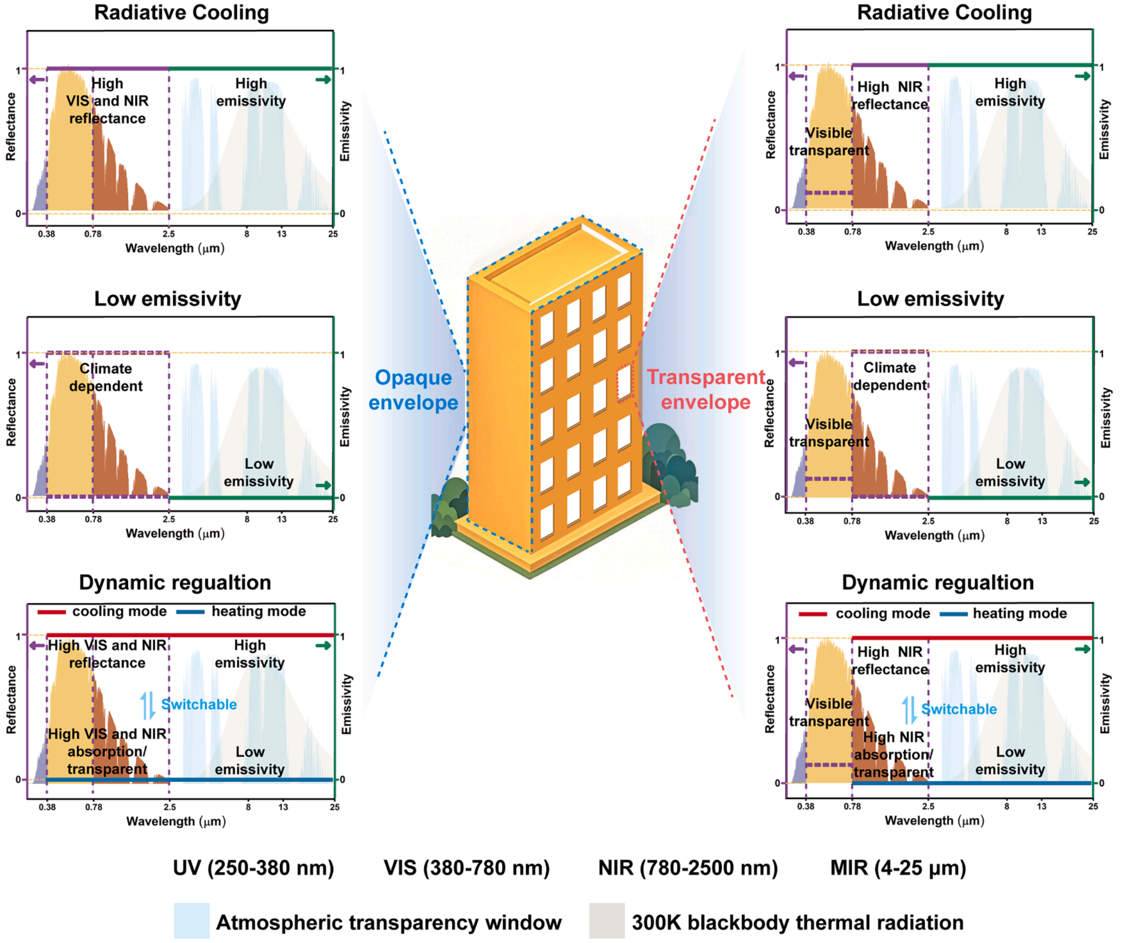

Figure 1. The ideal spectral characteristics of radiative cooling, low-emissivity, and dynamically tunable radiative materials applied to opaque and transparent building envelopes

aesthetics, durability, cost, and occupant visual comfort—are temporarily set aside.

(1) Radiative cooling materials reduce cooling energy demand by reflecting incoming solar radiation and emitting thermal radiation to the cold outer space. Specifically, this kind of spectrally selective emitter material is designed to reflect most incoming solar radiation and emit thermal radiation primarily in the atmospheric transmission window (roughly 8–13 μm), where thermal radiation can effectively escape into space.[10,11] This spectral selectivity suppresses unwanted heating from other IR wavelengths and improves net cooling performance even under direct sunlight, enabling multi-coupling design on building applications.[12,13] For opaque building elements such as walls and roofs, these materials typically exhibit high emissivity in the mid-IR (MIR; 4–25 μm) and high reflectivity in the visible (VIS; 380–780 nm) and near-IR (NIR; 780–2,500 nm) ranges. For windows, radiative cooling materials are typically designed to retain high VIS transmittance to ensure adequate daylighting. Moreover, in balancing lighting and HVAC energy consumption, VIS light ideally achieves full transmission in winter yet exhibits moderate reflectance in summer. This requirement is consistent for both low-emissivity materials and dynamically tunable radiative materials.

(2) Low-emissivity materials are designed to minimize radiative heat exchange between indoor and outdoor environments, thereby reducing both heating and cooling energy demands. These materials are typically characterized by low MIR emissivity, which helps to limit thermal radiation transfer. Nevertheless, the optimal VIS and NIR optical properties of low-emissivity materials should be tailored to the specific climatic conditions of the building's location, as solar radiation management plays a critical role in balancing heating and cooling demands. For example, in regions dominated by annual cooling energy demand, low-emissivity materials with high solar reflectivity are preferable. Conversely, in regions dominated by annual heating energy demand, materials with high solar absorptance/transmittance are more suitable. In the case of transparent envelopes, sufficient VIS transmittance is also necessary for daylighting requirements.

(3) Dynamically tunable radiative materials are capable of actively tuning their spectral properties in response to external stimuli (e.g., temperature, electricity, and humidity).[14] In cooling mode, materials applied to opaque envelopes exhibit high MIR emissivity to facilitate radiative heat loss, along with high VIS/NIR reflectance to minimize solar heat gain. In heating mode, they shift to low MIR emissivity to retain thermal energy and reduce reflectance in the VIS/NIR range to promote solar heat gain. The spectral design principles in the NIR and MIR regions also apply to transparent envelopes, with the added constraint that VIS transmittance should remain high to preserve indoor illumination.

Significant research efforts have been devoted to advancing the development of radiative thermal regulation materials across the three major categories. In this perspective, we present a comprehensive overview of radiative thermal management strategies for building energy savings. We begin by introducing the fundamental principles underlying radiative cooling, low-emissivity, and dynamically tunable radiative materials. Next, we review recent progress in the field, with a focus on publication trends and advancements in practical applications. Finally, we summarize the current state of the art and discuss prospects and key technical challenges, with the aim of promoting the large-scale deployment of radiative thermal regulation materials in building energy conservation.

RADIATIVE COOLING MATERIALS

Radiative cooling is a passive, electricity-free thermal management technology that dissipates heat to the cold outer space via thermal radiation.[15,16] An ideal radiative cooling surface should exhibit low absorptance (i.e., high reflectance) in the solar spectrum range (0.3–2.5 μm) and high emissivity within the atmospheric transparency window.[17] Historically, radiative cooling has been restricted mainly to nighttime due to solar heating during the day. However, a breakthrough was achieved by developing a hafnium dioxide (HfO_2)/silicon dioxide (SiO_2) multilayer thin film in 2014, demonstrating approximately 97% solar reflectance and over 80% emissivity in the atmospheric window.[18] This enabled a sub-ambient cooling effect of $\sim$5°C under direct midday sunlight, marking the first successful demonstration of passive daytime radiative cooling.

Recently, various radiative cooling materials suitable for building opaque envelope integration have been developed in films, coatings, and bulk and integrated with circulating water.[19–23] For instance, Zhai et al. designed a randomized glass-polymer hybrid metamaterial film. It is composed of a transparent polymethylpentene encapsulated with randomly distributed silica microspheres, which can efficiently radiate heat in the atmospheric transparency window and reflect approximately 96% of solar radiation.[19] Mandal et al. present a simple, inexpensive, and scalable phase-inversion-based method for fabricating hierarchically porous poly(vinylidene fluoride-co-hexafluoropropene) [P(VdF-HFP)HP] coating, which achieves a sub-environmental cooling of approximately 6°C with a cooling power of about 96 $W\cdot m^{-2}$.[20] Li et al. innovatively proposed a bulk form of radiative cooling material based on processed wood (Figures 2A–2C). The "cooling wood" achieved an average 24-h cooling power of 53 $W\cdot m^{-2}$ and excellent mechanical properties, and this block-form material offers an efficient solution for thermal management of buildings.[21] Based on low-cost and scalable manufactured radiative cooling metamaterials, Zhao et al. developed the RadiCold module, which can cool water to 10.6°C below the ambient temperature at noon, proposing a building-integrated RadiCold system to achieve continuous cooling throughout the day and night.[22]

However, despite these advancements, several challenges remain, including long-term weathering, pollution, and ultraviolet (UV)-induced aging.[28,29] Moreover, compatibility with the building substrate has often been overlooked, posing additional barriers to practical implementation. Lin et al. developed a ceramic-based radiative cooling block with a hierarchical porous structure (Figures 2D–2F).[24] This multilayer ceramic exhibits $\sim$99.6% solar reflectance and high MIR emissivity across different angles, achieving a net cooling power of over 130 $W\cdot m^{-2}$ at noon. Moreover, its dense all-inorganic structure endows the cooling ceramic with excellent resistance to UV radiation, and its block form and scalable manufacturing process make it well suited for building wall layers. Zhao et al. designed a photonic "cooling glass" coating for daytime passive radiation cooling (Figure 2G).[25] This strategy was prepared through a two-step simple process, optimizing the size and content of glass and alumina (Al_2O_3) particles, enabling the coating to have high solar reflectivity and IR emissivity (Figure 2H). The glass particle protective coating on its surface can enhance the anti-pollution ability of the material and reduce the impact of pollutants on the optical properties of the material.

Transparent radiative cooling materials for building envelopes require balancing VIS light transmittance and emissivity in the atmospheric window bands.[30] An ideal material should reflect most UV and NIR radiation, primarily contributors to solar heat gain, while maintaining high transmittance in the VIS spectrum to ensure daylighting.[31] Zhao et al. proposed a semi-transparent radiative cooling (ST/RC) glass, which integrates selective solar energy utilization with passive radiative cooling to modulate the optical and thermal properties of building glazing (Figures 2I and 2J).[26] Experimental results showed that buildings using ST/RC glass exhibit indoor air temperatures up to 16.4°C lower than those with conventional glass. However, the VIS light transmittance decreased by approximately two-thirds, limiting its practical application as a building window.

A significant advancement was made with the development of a novel nanocomposite film composed of a high-performance thermoplastic elastomer (HTPE), tin oxide (SnO_2), and silica microspheres (Figures 2K and 2L).[27] This film exhibits over 70% transmittance in the VIS range while effectively blocking UV and NIR radiation and offering high MIR emissivity (Figure 2M). In outdoor tests, acrylic panels coated with this film exhibited surface temperatures approximately 10°C lower than those with conventional polymer coverings under daytime solar exposure. Building energy consumption simulations suggest that applying this film could reduce annual HVAC energy usage by approximately 14%–32%. Given its scalable production processes, this film holds significant promise for retrofitting

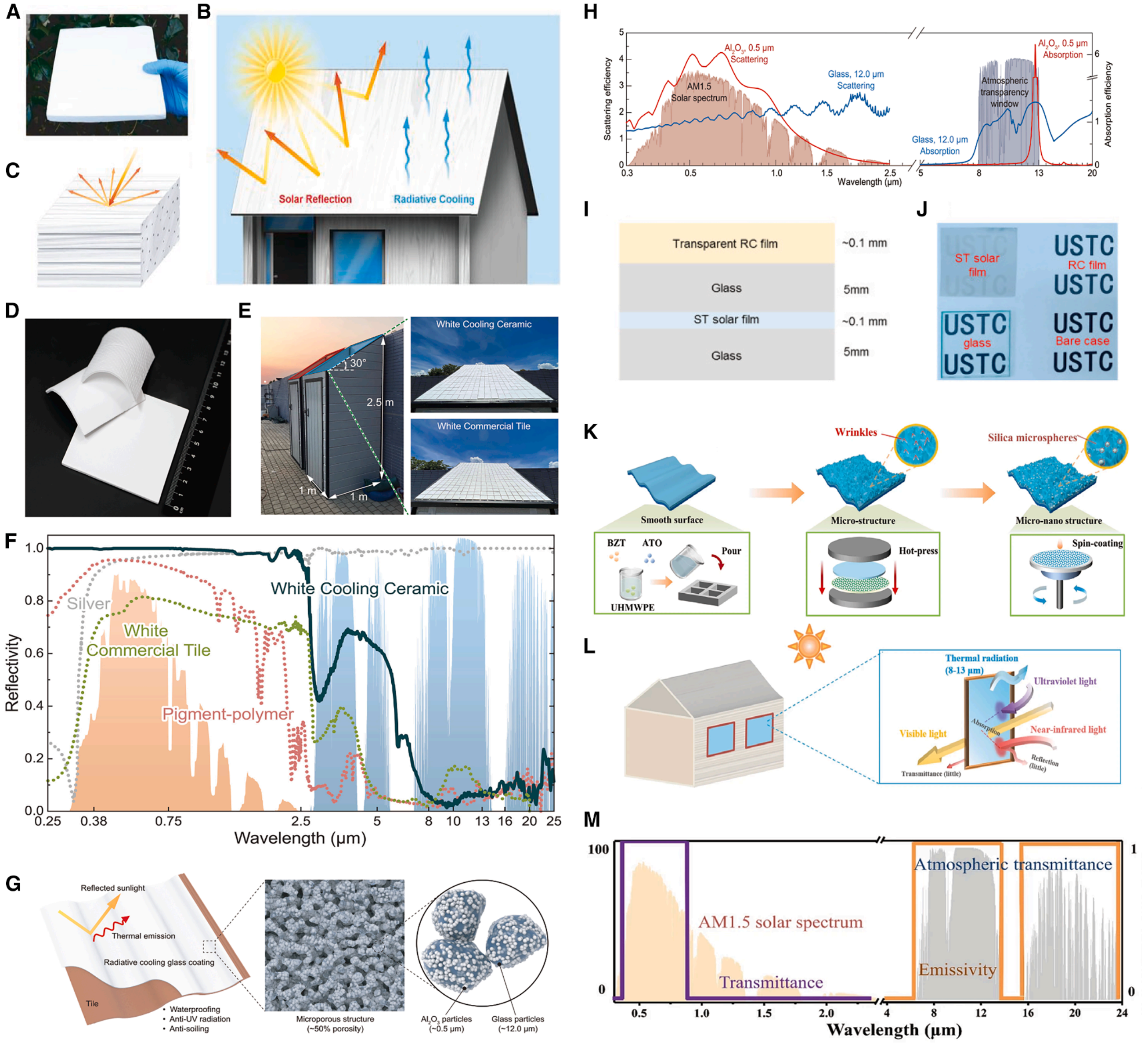

Figure 2. Representative radiative cooling materials for buildings

(A–C) A structurally engineered radiative cooling block derived from fully delignified and densified wood and its rooftop application. Reproduced with permission from Li et al.,[23] copyright 2017, the American Association for the Advancement of Science.

(D) Photograph of a hierarchically structured radiative cooling ceramic designed by alumina (Al_2O_3).

(E) The application of white cooling ceramics on model building envelopes.

(F) Comparison of the optical properties of the white cooling ceramic to those of white-pigmented polymer (Al_2O_3-doped polydimethylsiloxane), silver, and white commercial tile.

(D–F) Reproduced with permission from Lin et al.,[24] copyright 2023, The American Association for the Advancement of Science.

(G) A photonic cooling glass coating for daytime passive radiation cooling, with the optical functionality of the glass particles and Al_2O_3 particles in the composite structure.

(H) The glass shows a high reflectance in the solar spectrum and high emissivity in the atmospheric transparency window.

(G and H) Reproduced with permission from Zhao et al.,[25] copyright 2023, the American Association for the Advancement of Science.

(I) Schematic of a semi-transparent radiative cooling glass.

(J) Photo of the semi-transparent solar film, transparent radiative cooling film, and ordinary glass.

(I and J) Reproduced with permission from Zhao et al.,[26] copyright 2021, Elsevier.

(K–M) Fabrication process (K), application (L), and spectral characteristics (M) of a facile, spectrally selective transparent ultrahigh-molecular-weight polyethylene composite film.

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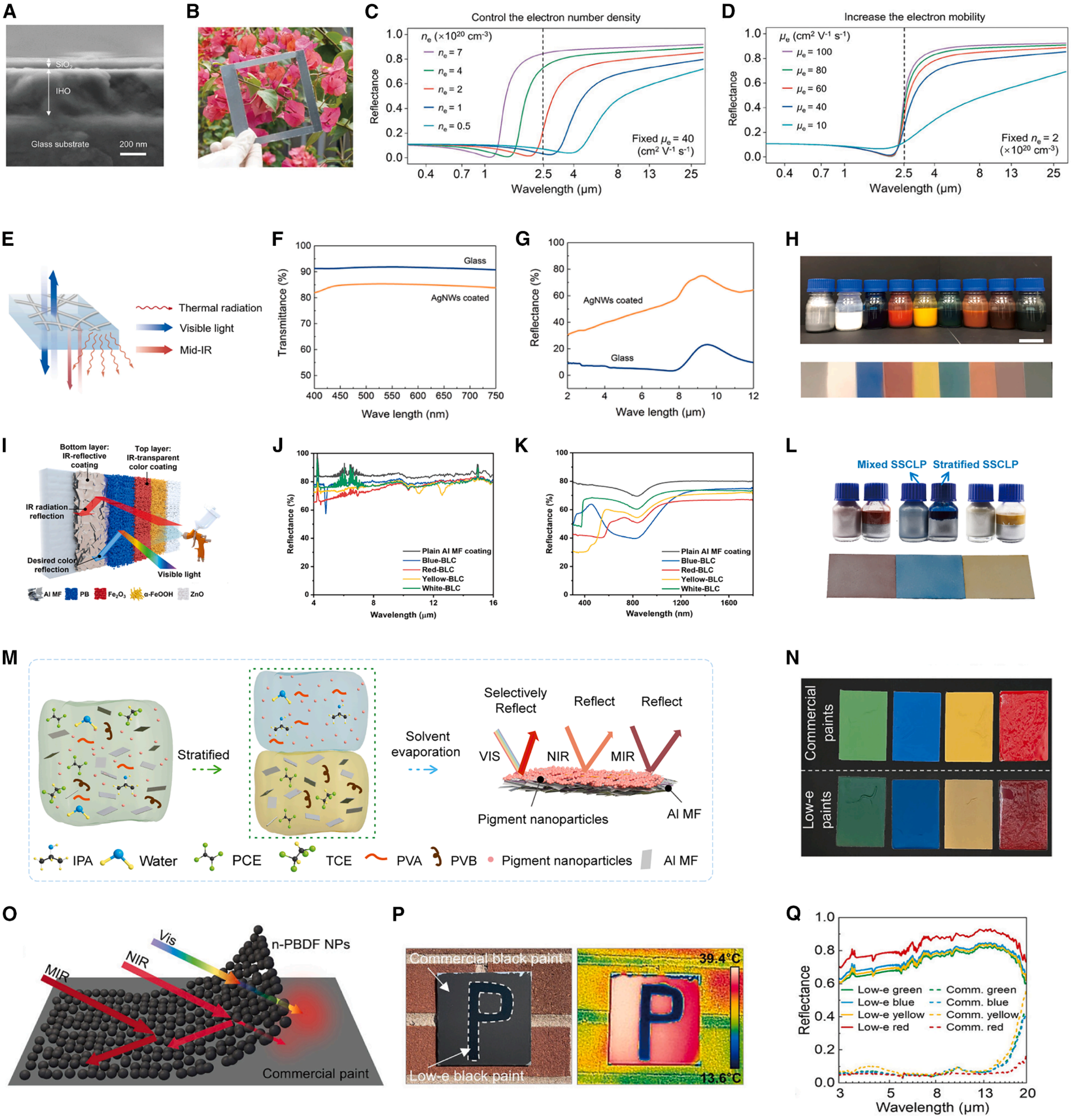

Figure 3. Transparent and opaque low-emissivity materials

(A and B) Characterizations of radiative warming glass incorporating IHO glass with anti-reflective SiO_2 coating.
(C) Calculated reflectance spectra for varying electron density (n_e) with fixed electron mobility (μ_e).
(D) Calculated reflectance spectra for varying electron mobility (μ_e) with fixed electron density (n_e).
(A–D) Reproduced with permission from Zhou et al.,[44] copyright 2024, Wiley.
(E) Structural and functional schematic of AgNW-coated glass.
(F) Optical transmittance of reference glass and AgNW-coated glass.
(G) MIR reflectance of the reference glass and AgNW-coated glass.
(E–G) Reproduced with permission from Lin et al.,[45] copyright 2019, Elsevier.
(H) Photograph of the formulated paint solutions and low-emissivity coatings in various colors produced by the paint solutions for the bottom layer (far left) and the top layer (in various colors). Scale bar, 5 cm.
(I) Schematic illustration of the working mechanism of the colorful low-emissivity paints and the designed bilayer structure.

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single-pane glass windows.[32] However, its inherent cooling effect presents a potential drawback in winter, when thermal insulation is needed.[33] In addition to polymer-based micro/nanoparticle composite materials, other transparent radiative cooling approaches have been explored, such as metamaterial films fabricated on glass substrates and coatings composed of cellulose nanoparticles.[34,35] However, most of these technologies remain in the laboratory research stage, and their large-scale applicability remains to be demonstrated.

From a practical application perspective, the large-scale implementation of radiative cooling still faces several challenges. Opaque coatings or films applied to rooftops may only affect upper-level indoor temperatures in multi-story buildings.[36,37] Their cooling effectiveness may be limited for lower floors. On the other hand, given the prevalence of large-scale glass curtain walls in modern architecture, transparent radiative cooling materials, such as those suitable for windows or curtain walls, may offer broader applicability. Furthermore, since radiative cooling materials are typically designed to exhibit high reflectivity in the VIS spectrum and high emissivity in the IR band, these characteristics often restrict the range of available colors. However, for widespread adoption in building design, developing radiative cooling materials that also offer aesthetic and color versatility is of critical importance.[38,39]

Nowadays, the multi-coupling design of radiative cooling and other functions in building envelopes has also received extensive attention. For instance, Liu et al. developed a silica hybrid cellulose acetate (SHCA) aerogel cooler.[40] The solar reflectivity of this aerogel reached 96%, and the emissivity of the atmospheric transparent window reached 97%, realizing the combination of heat insulation and radiant cooling functions. Meanwhile, the addition of a self-cleaning function can significantly extend the effective service life of radiative cooling materials. Tsai et al. prepared scalable superhydrophobic silica meta-fibers (sh-SMFs) by electrospinning combined with fluoro silane surface modification.[41] The optically engineered sh-SMFs could attain an extremely high average reflectivity (~97%) with near-zero absorption in the solar spectral region, and the excellent weather resistance against acid rain and UV exposure endowed the sh-SMF with long-term cooling performance. Color design is another important direction, which can balance aesthetics and heat dissipation. To achieve colored radiative cooling materials, Chen et al. developed a coated double-layer colored radiative cooling coating. The bilayer attains higher near-to-short-wavelength IR (NSWIR) reflectance (by 0.1–0.51) compared with commercial paint monolayers of the same color and stays cooler by as much as 3.0°C–15.6°C under strong sunlight.[42]

LOW-EMISSIVITY MATERIALS

In contrast to radiative cooling materials that dissipate heat via high-emissivity surfaces, low-emissivity materials suppress MIR radiative exchange to provide an enhanced heat insulation effect. They block external incoming thermal radiation in summer to reduce cooling loads while minimizing internal heat loss in winter to decrease heating demands, offering year-round energy-saving potential. Owing to this dual-function thermal regulation mechanism and their independence from sky exposure, low-emissivity materials hold significant promise for energy-efficient building applications. Functionally, they are complementary to high-emissivity materials, and together, they contribute to the advancement of integrated thermal management strategies toward net-zero energy buildings.

Low-emissivity materials can be classified into transparent and opaque categories. Transparent low-emissivity materials include indium tin oxide (ITO), dielectric/metal/dielectric (D/M/D) composites, silver nanowires (AgNWs), etc.[43–47] As shown in Figures 3A–3D, Zhou et al. developed hydrogen-doped indium oxide (IHO) with high solar transmittance ($T_{\mathrm{sol}} = 0.836$) and low emissivity ($\varepsilon = 0.117$) by tuning its electron density (n_e) and electron mobility (μ_e). Energy simulations indicate that applying IHO in high-latitude climate zones could reduce annual heating energy consumption by up to 6.6%.[44] In a typical three-layer D/M/D design, an ultrathin metal core (Ag, Au, Cu, and Al) is sandwiched between wide-band-gap oxides (TiO_2, SnO_2, ZnO, and HfO_2), with carefully matched thicknesses and refractive indices to exploit Fabry-Pérot interference, which can maximize VIS transmittance while preserving low MIR emissivity.[48] Herguedas et al. further showed that increasing the number of D/M/D layers from one to three concurrently increases VIS transmittance and NIR/MIR reflectance.[49] In addition, as depicted in Figure 3E, Lin et al. developed a solution-sprayed AgNW coating technique for transparent low-emissivity window applications,

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(J) Measured total MIR reflectance of glass substrate coated with a single layer of aluminum microflakes (Al MFs) and bilayer low-emissivity coatings (BLCs) in blue, red, yellow, and white.

(K) Measured total reflectance in the visible and NIR ranges for the same coatings as in (J).

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(L) Photograph of the formulated self-stratifying colorful low-emissivity paint solutions in evenly mixed conditions (left) and stratified conditions (right) and coating samples on glass substrates.

(M) Schematic of the self-stratifying mechanism and optical properties of the self-stratifying colorful low-emissivity coating. The solvent system includes isopropanol (IPA), water, perchloroethylene (PCE), and 1,1,2,2-tetrachloroethane (TCE). The polymer binders contain polyvinyl alcohol (PVA) and polyvinyl butyral (PVB). The fillers include Al MFs and pigment nanoparticles.

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(N) Photographs showing the commercial-colored paints and the dual-layer low-emissivity counterparts.

(O) Schematic illustrating the working principle of the colored low-emissivity paint. The bottom layer is a colored commercial paint that provides the desired appearance. The top layer is the VIS-transparent n-PBDF-based coating layer with high MIR reflectance.

(P) Photograph (left) and corresponding IR image (right) showing a low-emissivity "P" contrasting with the commercial black paint with high thermal emittance.

(Q) The reflectance spectra of commercial paints (solid curves) and the low-emissivity paints (dashed curves) in the MIR region.

(N–Q) Reproduced with permission from Liu et al.,[52] copyright 2024, Wiley.

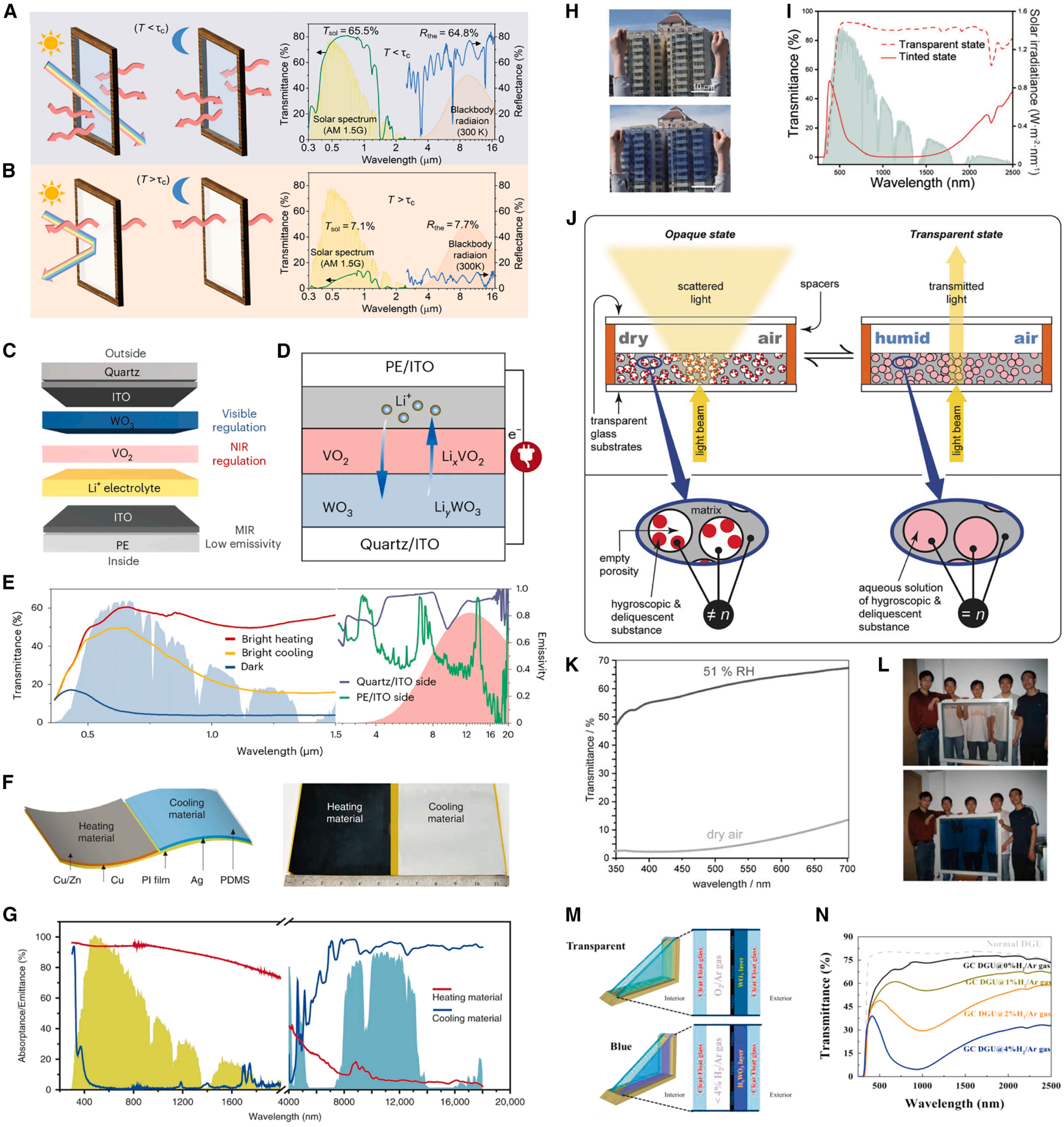

Figure 4. Dynamically tunable radiative materials

(A and B) Schematics and optical performance of the radiation modulation of the temperature-responsive window under (A) cold and (B) hot ambient. Reproduced with permission from Lin et al.,[71] copyright 2022, the American Association for the Advancement of Science.

(C) Schematics of the optimizing-multispectral electrochromic device with a low-emissivity surface.

(D) Schematic internal ionic diffusion of the electrochromism.

(E) Transmittance spectra (0.35–2.5 μm) of the optimizing-multispectral electrochromic device in bright heating (+1.5 V), bright cooling (−1.5 V), and dark (−3.0 V) states and MIR emissivity (2.5–20 μm) of the inside and outside faces. AM 1.5 G, air mass 1.5 global.

(C–E) Reproduced with permission from Shao et al.,[74] copyright 2024, Springer Nature.

(F) Structure of dual-mode heating/cooling material and a photo of the dual-mode material shows the different visible appearance of the heating/cooling parts.

(G) Absorptance/emittance of dual-mode material. Solar spectrum (yellow shaded area) and atmospheric transmittance window (green shaded area) are plotted for reference.

(legend continued on next page)

achieving 83% VIS transmittance and 69.8% MIR reflectance (Figures 3F and 3G).[45]

Opaque low-emissivity materials are predominantly metallic, such as aluminum (Al) and silver (Ag). These materials typically exhibit a metallic gray appearance and are characterized by their low MIR emissivity, which enables effective suppression of radiative heat transfer. They have been used in the form of metal foils and coatings embedded within wall assemblies, brick inner surfaces, and attic roof interior surfaces.[53] However, they typically appear metallic gray, limiting their exposure on VIS surfaces in architectural applications, primarily due to aesthetic constraints and design flexibility requirements.[54–56]

To address this, Peng et al. fabricated colored low-emissivity films by incorporating Al foil with an IR-transparent pigment-polyethylene composite. The films exhibit high MIR reflectance (~90%) and selective VIS reflectance for desired colors. For a typical mid-rise apartment, simulations show that these films can help reduce heat gain and loss by up to 257.6 MJ per installation wall area annually.[57] To overcome the application limitations associated with film-based materials, they further developed a bilayer colored low-emissivity paint that can be applied through a two-step process, as shown in Figures 3H and 3I. In this design, the bottom layer of the Al microflake (MF) coating serves as a broadband reflector, while the top layer, composed of an IR-transparent but visibly selectively reflective coating, provides the desired color appearance. As shown in Figures 3J and 3K, the resulting bilayer coatings show high MIR reflectance (up to 80%) and NIR reflectance ranging from 65% to 75%, achieving simulated energy savings of 27.24 $\mathrm{MJ \cdot m^{-2} \cdot y^{-1}}$ for buildings.[50] Furthermore, to simplify the application process and reduce manufacturing costs, Wang et al. proposed a self-stratifying colorful low-emissivity paint (Figure 3L). As illustrated in Figure 3M, appropriate solvent-solute pairing combined with differences in solvent polarity and density drives spontaneous stratification of the color and low-emissivity layers in a single-step coating process. This formulation achieves MIR emissivity as low as 0.107 and NIR reflectance as high as 0.817, making it a promising alternative for scalable, aesthetically flexible radiative thermal management.[51] In addition, Liu et al. sprayed a transparent n-doped poly(benzodifurandione) (n-PBDF) layer onto commercial colorful paint (Figures 3N and 3O), producing a colored low-emissivity coating (0.19) enabled by efficient π-electron transport within the polymer backbone (Figures 3P and 3Q).[52]

For vertical surfaces of building envelopes, angle-selective emitters have been proposed, enabling directional thermal regulation through differentiated material emissivity: high-emissivity, high-solar-reflectance materials are pointed toward the sky to enhance radiative cooling, while low-emissivity materials face the ground to reflect thermal radiation and reduce building heat gain.[58–60] For instance, Zhou et al. developed a micro-wedge structure combining an Al-coated upper surface ($\varepsilon \approx 0.1$) with a PDMS lower surface ($\varepsilon \approx 0.9$), achieving broadband directional emissivity modulation through magnetically responsive soft materials, along with potential heating energy savings.[59] Additionally, Xie et al. designed a sawtooth grating structure integrating nano-porous polyethylene film and Ag/silicon nitride multilayers, enabling sub-ambient radiative cooling on vertical surfaces under direct sunlight.[60]

DYNAMICALLY TUNABLE RADIATIVE MATERIALS

In contrast to the fixed optical properties of statically regulated radiative cooling materials and low-emissivity materials, dynamically tunable radiative materials exhibit switchable optical performance, integrating dual cooling and heating functions. These materials can actively or passively respond to external stimuli (such as temperature, electric fields, mechanical force, or light), dynamically adjusting their optical properties to achieve optimized building energy efficiency across different climatic regions and seasonal conditions. Based on the type of external stimulus, dynamically tunable radiative materials can be primarily categorized into six classes: thermal-responsive, electro-responsive, mechano-responsive, photo-responsive, humidity-responsive, and gas-responsive categories.[61–64]

Thermal-responsive dynamically tunable radiative materials exhibit reversible changes in optical properties in response to ambient temperature. Their regulation mechanisms are generally classified into two main types: thermochromism and thermally induced deformation.[65] Thermochromic materials modulate their optical behavior through temperature-driven transitions in molecular or crystal structures, often accompanied by VIS color changes and shifts in optical parameters. Representative examples include vanadium dioxide (VO_2) and perovskites, which undergo phase transitions near critical temperatures, significantly altering their optical properties.[66–68] Other examples include temperature-sensitive hydrogels, which adjust optical transparency via thermally driven swelling and shrinking, and liquid crystals, which enable selective light modulation based on temperature-dependent molecular orientation.[69,70] For instance, Lin et al. developed a composite material integrating poly (N-isopropylacrylamide) and AgNWs. As shown in Figure 4A, under cold

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(H) Photos of 30 × 40 cm^2 photochromic films prepared by the blade-coating method in transparent state (left) and tinted state (right).
(I) Transmittance spectra of the photochromic films at transparent and tinted states (by irradiation with outdoor sunlight for 6 h) against a normalized AM1.5 global solar spectrum (green shadow).
(H and I) Reproduced with permission from Meng et al.,[76] copyright 2023, Wiley.
(J) Conceptual working principle of a humidity-driven light transmittance switching material.
(K) Visible spectra of a humidity-driven optical device working with dry and humid air.
(J and K) Reproduced with permission from Castellón et al.,[63] copyright 2017, Wiley.
(L) Fully bleached and fully colored states of the gasochromic prototype.
(M) Configuration illustration of gasochromic double glass unit.
(N) Transmittance spectra of the gasochromic double glass unit under different states.
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conditions, the materials exhibit high solar transmittance (T_{sol} = 65.5%) to promote heat gain and high MIR reflectance (R = 64.8%) to suppress heat loss (Figure 4B). Under hot conditions, the composites transition to low solar transmittance (T_{sol} = 7.1%) and low MIR reflectance (R = 7.7%), enhancing radiative heat dissipation.[71] Shape-memory alloys and shape-memory polymers are typical thermally deformable materials that regulate their optical properties by undergoing temperature-triggered shape transformations.[72,73]

Electro-responsive dynamically tunable radiative materials modulate optical properties in response to applied electrical signals, categorized into four mechanisms: electrochromism (electric-field-driven redox reactions), reversible metallic electrodeposition (ion deposition/dissolution on electrodes), liquid crystal modulation (field-induced molecular reorientation), and carrier concentration tuning (localized surface plasmon resonance absorption adjustment via carrier density changes).[77–79] Contemporary research concentrates overwhelmingly on electrochromic systems, with a focus on scalable large-area fabrication, spectrally selective control over wide wavelength ranges, and increasing modulation range. For example, Shao et al. developed a tungsten oxide (WO_3)/VO_2 electrochromic window with a controllable lithium-ion intercalation depth, enabling three optical states (bright heating, bright cooling, and dark) to modulate VIS and NIR transmittance independently. In the MIR, it maintains a high-emissivity exterior and low-emissivity interior (Figures 4C–4E). Such tri-modal switching enables real-time adaptation to varying climatic conditions, demonstrating strong potential as a smart window material for dynamic and energy-efficient building thermal regulation.[74]

Mechano-responsive dynamically tunable radiative materials can be classified into two categories based on the mode of external force: flip and stretching/compression.[75,80,81] A representative flipping device, reported by Li et al., employed electrostatically controlled thermal contact conductance to switch between cooling and heating modes (Figure 4F). In cooling mode, the device achieves 97.3% solar reflectance and 94.1% MIR emissivity, while in heating mode, it reaches 93.4% solar absorption and 14.2% MIR emissivity (Figure 4G). Building energy simulation shows that nationwide deployment across the United States could reduce annual heating and cooling energy by 19.2%.[75] For the stretching/compression class, Zhou et al. fabricated a mechano-responsive polydimethylsiloxane and poly (3,4-ethylenedioxythiophene) polystyrene sulfonate bilayer window. In a strain-free state, the film exhibits ~80% solar transparency and 41% thermal reflectance. Increasing tensile strain to 50% decreases solar transmittance and thermal reflectance to ~25% and ~16%, respectively, demonstrating efficient strain-programmable optical and thermal modulation.[81]

Photo-responsive dynamically tunable radiative materials primarily modulate their optical properties through photochromic effects, which can be categorized into organic and inorganic systems based on material composition.[76,82,83] Organic photochromic materials can be further subclassified based on their recovery mechanisms. One type changes color under UV irradiation and returns to its original state upon exposure to VIS light or thermal stimulation, while the other type requires specific VIS wavelengths to induce a reverse transition.[84] For inorganic photochromic materials, some can switch colors by irradiating/removing UV radiation, such as borosilicate aluminate and WO_3.[84,85] Some materials, such as titanium dioxide (TiO_2), require air (or oxygen) exposure to revert to their original state.[62] For example, as shown in Figure 4H, Meng et al. developed a polymethyl methacrylate-based photochromic film embedded with Cu-doped WO_3 nanoparticles, demonstrating dual modulation of both VIS light (modulation of VIS transmittance ΔT_{lum} = 73%) and solar heat (modulation of solar transmittance ΔT_{sol} = 73%). The film shows reversible UV-induced darkening (Figure 4I), with complete optical transparency recovery upon UV removal.[76]

Humidity-responsive dynamically tunable radiative materials can reversibly modulate their optical properties in the solar spectrum by altering transparency/color through moisture absorption/desorption processes.[63,86] Regarding transparency modulation, Castellón et al. developed a composite film consisting of calcium chloride (a hygroscopic agent) embedded within a silica-titania hybrid matrix. Under high relative humidity (RH) conditions, water molecules fill the porous structure of the material. Since the refractive index of water closely matches that of the matrix, this results in significantly enhanced light transmittance. Conversely, under dry air conditions, the release of water molecules restores the light-scattering state of the material (Figure 4J). As a result, the VIS transmittance (measured at 633 nm) reaches 0.67 at 51% RH, while it decreases to 0.06 under dry conditions (Figure 4K).[63] For RH-dependent color modulation, Yao et al. developed a chiral nematic solid cellulose nanocrystal film incorporating polyethylene glycol, which exhibits tunable structural coloration in response to humidity variations. This dynamic color shift can modulate VIS and NIR transmittance.[86]

Gas-responsive dynamically tunable radiative materials exhibit tunable optical properties when exposed to specific gaseous environments. Typical materials for such applications include WO_3, nickel oxide (NiO), and magnesium alloys.[87,88] As shown in Figures 4L and 4M, WO_3 demonstrates reversible optical switching between a bleached state (high transmittance) under an argon-oxygen (Ar/O_2) atmosphere and a colored state (reduced transmittance) under an argon-hydrogen (Ar/H_2) atmosphere. Notably, as shown in Figure 4N, the optical transmittance of WO_3 decreases progressively with increasing hydrogen concentration, confirming its hydrogen-dependent optical modulation capability.[64] Current research mainly focuses on addressing challenges related to performance, durability, and building facade integration.[88]

CONCLUSION AND PERSPECTIVES

Building radiative heat regulation materials presents novel solutions for building energy efficiency. Existing strategies can be broadly categorized into three classes: radiative cooling, radiant barriers for thermal insulation, and dynamic radiative control. Radiative cooling materials, characterized by their high MIR emissivity and high solar reflectance, efficiently dissipate heat to the cold sky and offer a passive means to lower indoor air temperatures. Low-emissivity materials function by suppressing radiative heat exchange, thereby reducing thermal losses in winter and heat gain in summer, contributing to year-round energy savings. Dynamically tunable radiative materials, which respond to external stimuli of various types, enable adaptive modulation of thermal emissivity or solar reflectivity. These materials hold significant promise for reducing the energy consumption of HVAC systems and enhancing the adaptability and resilience of building thermal management under variable environmental conditions.

To fully realize the potential of these strategies, it is essential to address the key challenges that hinder their widespread application. The following discussion provides a perspective on building radiative heat regulation materials, focusing on existing limitations and opportunities for advancing material performance and integration in real-world settings.

Firstly, the spectral design of radiative materials, along with the identification of suitable material systems to realize such designs, remains a core requirement. Effective thermal regulation relies on the ability to selectively control solar and MIR radiation, enabling either heat rejection or retention depending on seasonal or climatic demands. Spectral control must become increasingly refined to maximize energy-saving performance under specific conditions. For example, selective emitters that suppress MIR radiation outside the atmospheric transparency window are more suitable for certain radiative cooling applications. Angle-selective thermal emitters, which enable directional control of thermal emission, offer particular advantages when applied to vertical building surfaces, enhancing cooling energy savings. In addition, spectral design also needs to be more customized to suit diverse climatic zones, building functions, and even facade orientations. For instance, in cold climates, materials that allow selective solar gain while minimizing IR heat loss are more desirable, whereas in hot arid regions, broadband reflectors with directional emission properties may be preferred. To enable such precise and application-specific spectral control, material systems must evolve accordingly. This includes not only tailoring intrinsic optical properties and constructing hierarchical structures but also ensuring compatibility with scalable fabrication methods and long-term environmental stability.

Secondly, there is a growing trend toward the development of smart and adaptive systems that can dynamically respond to changing environmental conditions. Unlike conventional static materials, such smart systems are capable of modulating their optical and thermal properties, particularly solar reflectance and MIR emissivity, in real time, driven by external stimuli. Such dynamic regulation is particularly valuable in regions with large daily or seasonal temperature fluctuations, where static solutions often fail to maintain optimal thermal performance throughout the year. These capabilities improve indoor thermal comfort and reduce HVAC energy loads, while supporting greater operational flexibility and occupant-driven control. Therefore, endowing buildings with dynamic radiative regulation capabilities represents an important future direction. The integration of smart radiative materials into building envelopes is expected to play a pivotal role in next-generation sustainable building design. Despite these advantages, several critical challenges must be addressed to translate smart materials into large-scale, durable building components. These include limited response speed, hysteresis effects, degradation under long-term environmental exposure, and compatibility with construction materials. Moreover, the development of scalable, low-cost manufacturing processes and integration strategies remains a bottleneck. Advancing this field will require continued research into novel switching mechanisms, material stability, and multifunctional integration, laying the foundation for advanced radiative heat regulation systems that are both adaptive and robust.

Thirdly, the practicality of radiative heat regulation materials must be considered to ensure successful deployment. Beyond laboratory performance, these materials must demonstrate environmental robustness, architectural compatibility, and functional versatility to meet the complex demands of real-world building applications. Environmental durability is particularly critical, as radiative materials are often exposed to harsh outdoor conditions over extended periods. They must maintain stable optical and thermal properties under prolonged exposure to UV radiation, temperature-humidity fluctuations, mechanical abrasion, and pollutant deposition, without significant degradation. Additionally, aesthetic compatibility with modern architectural design plays a significant role in determining the feasibility of large-scale implementation. Materials must be available in forms, colors, and textures that align with design preferences and regulatory requirements. Furthermore, the integration of multifunctional properties, such as self-cleaning surfaces, acoustic insulation, anti-fouling behavior, or even load-bearing capabilities, can significantly enhance their overall utility, reduce maintenance costs, and improve user acceptance.

Lastly, the advancement and implementation of radiative thermal management materials rely fundamentally on interdisciplinary research. Addressing the complex challenges of this field requires close collaboration among experts in materials science, optics, thermal engineering, architecture, and environmental science. For example, working closely with professionals in the building and architectural sectors can help to clearly define material performance requirements, installation constraints, and long-term functional expectations in real-world settings. Architects may prioritize materials that combine radiative performance with visual transparency or aesthetic flexibility, while building engineers may emphasize fire resistance, mechanical stability, or compatibility with insulation systems. Such input is crucial for guiding the development of materials that are not only thermally effective but also practical and compliant with building codes and construction workflows. Concrete examples of successful interdisciplinary integration include radiative cooling paints that can be directly applied to existing roofing membranes without altering structural load and multilayer coatings for glass facades that preserve VIS light transmission while enhancing thermal emissivity control. These advances demonstrate how cross-sector collaboration can transform laboratory-scale innovations into deployable solutions. Moving forward, establishing shared testing standards, co-design frameworks, and pilot-scale demonstration projects will be key to accelerating the translation of radiative thermal management materials into sustainable, scalable building technologies.

In summary, building radiative heat regulation materials hold great promise for enhancing energy efficiency and thermal comfort in the built environment. Realizing this potential requires progress on multiple fronts: the refinement and customization of spectral design, the advancement of smart and adaptive systems, the improvement of material practicality and multifunctionality, and the strengthening of interdisciplinary collaboration to bridge the gap between fundamental research and real-world application. By addressing these challenges holistically, future research can enable the large-scale deployment of radiative thermal management materials as integral components of sustainable, climate-responsive building systems. We are confident that radiative thermal management materials will play an increasingly significant role in the future of net-zero buildings.

ACKNOWLEDGMENTS

This work is funded by the National Natural Science Foundation of China (22475007) and the State Key Laboratory for Strength and Vibration of Mechanical Structures (SV2024-KF-02).

AUTHOR CONTRIBUTIONS

Conceptualization, Y.P., Y.W., and Z.L.; visualization, Y.P., Y.W., and Z.L.; writing – original draft, Y.W., Z.L., and Y.P.; writing – review & editing, Y.P., Y.W., Z.L., S.S., and G.T.; funding acquisition, Y.P.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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