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Regulation Mechanisms, Material Systems and Application Progress of Dynamic Radiative Cooling

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Abstract. Radiative cooling achieves low-energy heat rejection via radiative heat exchange between the ground surface and outer space. Nevertheless, static materials possess fixed spectral properties and tend to trigger overcooling in winter, at night or under low thermal loads. This paper reviews active regulation, passive self-adaptation, near-zero energy consumption and active-passive synergy mechanisms. It compares the regulation characteristics of electrochromism, mechanical/fluid switching, thermally induced phase change, thermosensitive hydrogel, humidity response and bistable structures. Applications in buildings, electronic devices, smart textiles, vehicle energy storage and aerospace thermal management are summarized. Finally, engineering challenges including cycle life, outdoor weather resistance, encapsulation, large-area fabrication, energy consumption accounting and testing standards are discussed.

Keywords: radiative cooling, dynamic thermal management, spectral regulation, smart materials, near-zero energy consumption

1. Introduction

Global warming, urban heat islands and rising cooling demands overlap with one another, which further highlights peak electricity consumption, environmental burden of refrigerants and indirect carbon emissions brought by conventional vapor-compression refrigeration. Radiative cooling transfers heat to the sky by virtue of spectral selectivity of material surfaces instead of moving heat with compressors. It can serve as a supplement to active air conditioning and reduce sensible energy consumption for building envelopes, outdoor equipment and human body thermal management [1]. Developing cooling technologies with low energy use, low carbon emission and compatibility with existing systems constitutes an important materials science issue for high-temperature climate adaptation and energy transition.

The cold sink of radiative cooling is outer space with an effective radiative temperature close to 3 K. Mid-infrared radiation emitted by ground objects within the atmospheric transparent window of approximately 8–13 μm can partially penetrate the atmosphere and dissipate. The key to achieving sub-ambient temperature in daytime lies in suppressing absorption in the 0.3–2.5 μm solar band while enhancing thermal radiation. The radiative cooling phenomenon was observed long ago through dew and frost formation on clear nights. Modern research realizes tailor-made spectral

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responses using multilayer photonic structures, polymer-particle composites and porous media. Recent systematic reviews indicate that these material routes have attained high solar reflectance and strong mid-infrared emissivity, and are evolving from laboratory structures toward coatable, scalable daytime sub-ambient cooling materials [2].

However, the spectral properties of static materials remain nearly unchanged during service. Continuous heat dissipation is an advantage under high temperature and strong solar irradiance, yet it may lead to overcooling, dew or frost formation and increased heating energy consumption in winter, at night and under low thermal loads. Meanwhile, temperature, humidity, cloud cover, wind speed and equipment operating conditions keep varying, and fixed spectra cannot maintain optimal annual thermal balance. Accordingly, research focus has shifted from "achieving higher cooling power" to "adjusting cooling power on demand". This paper first introduces energy exchange and evaluation indices, then outlines static materials and their limitations. It emphatically discusses active regulation, passive self-adaptation, near-zero energy consumption and active-passive synergy mechanisms. The value of dynamic regulation is analyzed according to application requirements. In the end, challenges and development directions at material, device and system levels are summarized.

2. Fundamental principles and performance evaluation of radiative cooling

2.1. Energy exchange process of radiative cooling

A sky-facing radiative cooling surface simultaneously undergoes its own thermal radiation, atmospheric counter-radiation, solar absorption, as well as convective-conductive heat exchange with ambient air and supporting structures. Taking surface temperature T_s and ambient temperature T_{amb} as variables, the net cooling power can be written as:

$$P_{net}(T_s) = P_{rad}(T_s) - P_{atm}(T_{amb}) - P_{sun} - P_{nonrad} \quad (1)$$

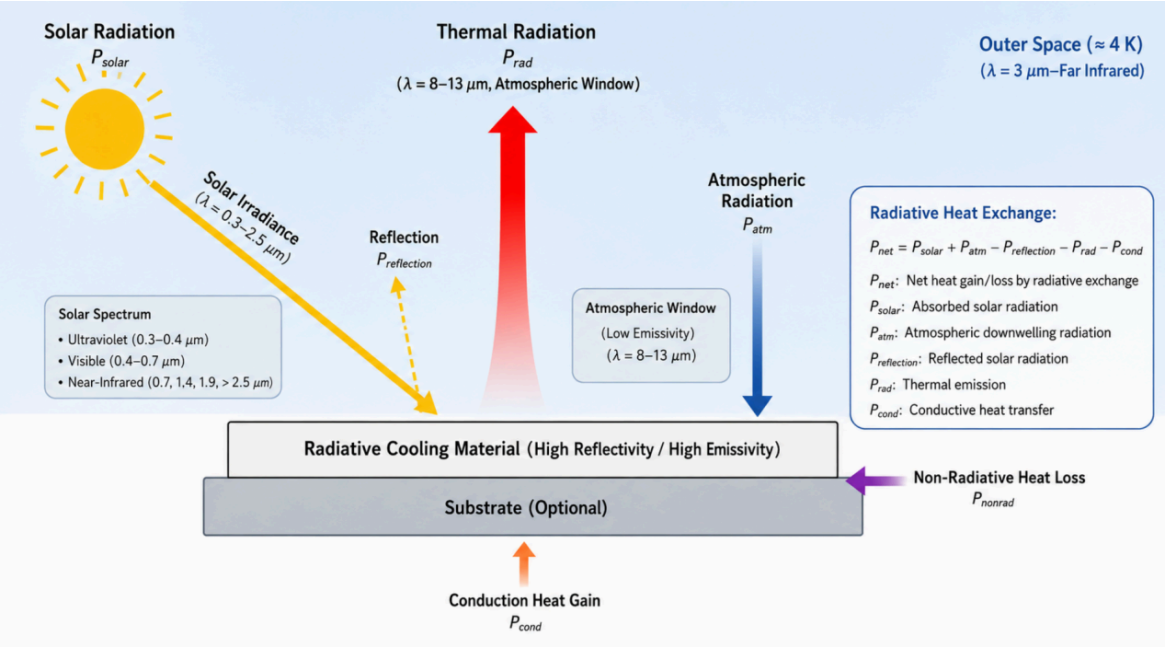


Figure 1. Energy exchange and atmospheric-window mechanism of radiative cooling

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Where P_{net} denotes the net cooling power per unit area, P_{rad} the thermal radiation power emitted outward by the surface, P_{atm} the atmospheric counter-radiation absorbed by the surface, P_{sun} the absorbed solar radiation, and P_{nonrad} the non-radiative heat exchange term caused by convection and conduction. In this paper, $P_{net}>0$ represents net heat rejection of the surface. A commonly used approximation is $P_{nonrad}=h_c(T_{amb}-T_s)$, where h_c is the combined non-radiative heat transfer coefficient. High humidity and cloud cover strengthen sky counter-radiation and weaken the atmospheric window, while strong wind raises h_c. Therefore, the measured performance of the same material may differ significantly under dry and clear, humid cloudy or high-wind environments [3]. The above energy exchange process and atmospheric window mechanism are shown in Figure 1.

2.2. Key optical performance parameters

Solar reflectance ρ_{sol} is the weighted average of material reflectance over the solar spectral energy. For opaque materials, solar absorptance $\alpha_{sol}\approx1-\rho_{sol}$, which determines solar heat gain in daytime. Atmospheric-window emissivity ε_{8-13} characterizes the radiative capacity of materials within the 8–13 μm range, while broadband infrared emissivity usually covers a wider mid-to-long wave infrared range. Net cooling power reflects instantaneous heat rejection capacity, and temperature drop $\Delta T=T_{amb}-T_s$ results from the combined effect of radiation, non-radiative heat exchange and heat capacity. The two indices cannot substitute for each other. Evaluating dynamic devices shall also report emissivity or reflectance modulation amplitude, switching temperature, response/recovery time, hysteresis width, cycle number and switching energy consumption per unit area.

Kirchhoff's law must be strictly interpreted in a spectral and angular manner: under thermal equilibrium, the emissivity of a material equals its absorptance at the same wavelength, direction and polarization state. The solar band (approximately 0.3–2.5 μm) and mid-infrared band (especially 8–13 μm) belong to different wavelength ranges. A high absorptance in the solar band cannot directly infer high emissivity within the atmospheric window. The essence of dynamic radiative cooling is to realize separate or coordinated regulation of solar heat gain and infrared heat rejection by utilizing spectrally independent material dispersion, scattering, phase change and structural resonance across different bands [4, 5].

3. Static radiative cooling materials and their limitations

3.1. Spectral design requirements for static radiative cooling

Static daytime radiative cooling generally requires high $\rho_{sol}$to reduce P_{sun}, and high emissivity within 8–13 μm to increase P_{rad}. For devices whose temperature is obviously higher than ambient temperature, broadband high infrared emissivity facilitates rapid heat dissipation. For surfaces targeting deep sub-ambient cooling, selective emission can reduce parasitic heat exchange with the atmosphere outside the window bands. Material selection shall combine target temperature, sky window, installation angle and non-radiative heat exchange conditions, rather than judging performance merely by a single emissivity value.

3.2. Typical static material systems

Typical systems include: multilayer nanophotonic structures that achieve spectral selectivity via thin-film interference and photonic bandgaps; polymers such as PDMS and PVDF with strong mid-infrared molecular vibrational absorption; composite coatings generating Mie scattering using

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particles including SiO_2, TiO_2, ZnO, $BaSO_4$; and porous polymers and aerogels obtaining broadband scattering from the refractive index contrast between air and polymer. Liu et al. adopted roll-to-roll technology to fabricate microstructured photonic coatings containing Al_2O_3/TiO_2 nanoparticles, with solar reflectance and thermal emissivity reaching 96.0% and 97.0% respectively, and the measured cooling power of 39.1 $W \cdot m^{-2}$ [6]. Zhang et al. constructed hierarchical thin films using Al_2O_3 particles and PDMS, achieving solar reflectance of approximately 0.96 and mid-infrared emissivity of approximately 0.95, and realizing sub-ambient temperature drop of about 12.4 ℃ under direct solar irradiation [7]. Sun et al. prepared superhydrophobic coatings with SiO_2-coated glass microspheres, whose solar reflectance and mid-infrared emissivity reached 96% and 98% respectively, with outdoor temperature reduction of 11.1 ℃ [8]. These studies demonstrate that static materials can balance high performance and manufacturability [6-8].

3.3. Core limitations of static radiative cooling

The biggest systematic problem of static materials is insufficient matching between "when cooling is needed" and "continuous cooling of materials", rather than inadequate cooling power. Persistently high emissivity in winter and cold nights increases heat loss of building envelopes; electronic devices with low thermal loads may produce condensation due to overcooling. When the radiative cooling surface temperature falls below dew point, frost may form and alter spectral properties. High humidity, cloud cover and pollution reduce practical benefits, while fixed spectra cannot respond to fluctuations in temperature, solar irradiance and thermal loads. It needs to be emphasized that composite materials merely with fixed spectral characteristics still fall into static radiative cooling. Only materials introducing reversible phase change, deformation, wetting or electrochemical processes to achieve state switching can be classified as dynamic regulation [9].

4. Regulation mechanisms of dynamic radiative cooling

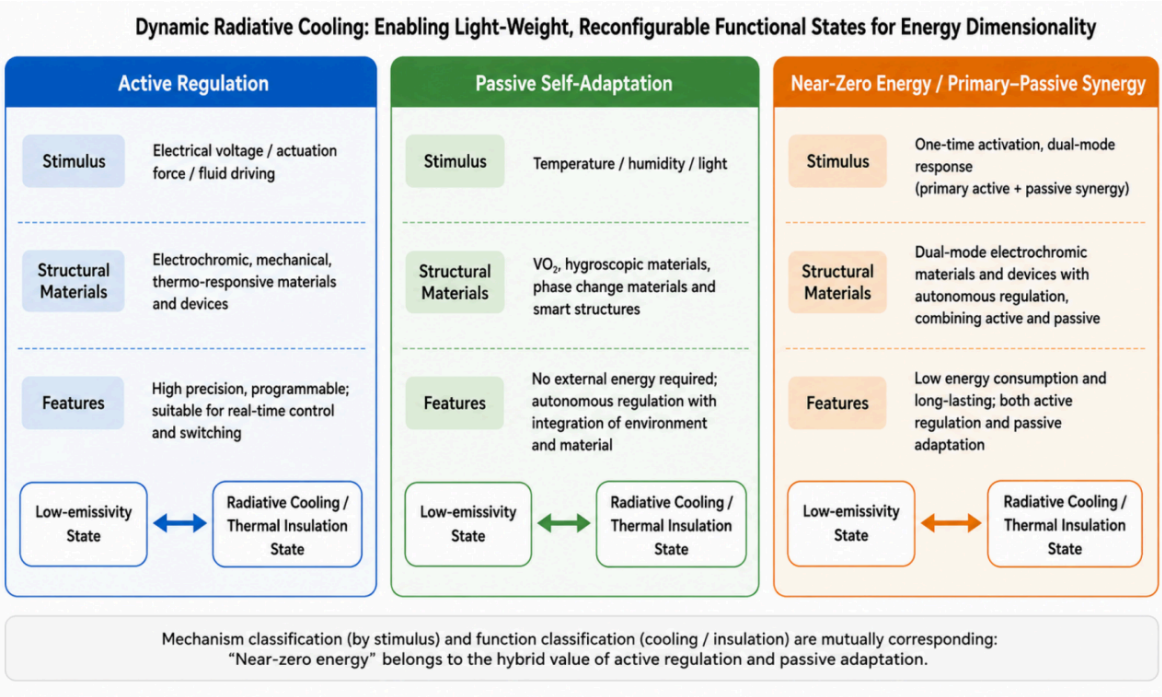


Figure 2. Regulation pathways and state switching of dynamic radiative cooling

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Dynamic radiative cooling switches devices between "enhanced heat rejection" and "suppressed heat rejection / utilization of solar heat gain" by altering solar-band reflectance/transmittance or mid-infrared emissivity. Three dimensions shall be distinguished in classification: active and passive describe triggering mechanisms; cooling state and thermal insulation (or heating) state describe functional outcomes; near-zero energy consumption describes energy required for maintenance and switching, while active-passive synergy describes the control architecture. Figure 2 presents the three types of pathways and their boundaries.

4.1. Active regulation mechanisms

Electrochromism and electric-field modulation modify the complex refractive index and metal coverage of materials through electrochemical redox reactions, ion intercalation, carrier concentration variation or reversible metal deposition, so as to tune mid-infrared absorption/emission or solar reflectance. Sui et al. adopted graphene transparent electrodes and reversible copper deposition to tune thermal emissivity within the range of 0.07–0.92 while retaining flexibility [9]; Zhao et al. realized reflectance switching between approximately 89% and 17% via reversible silver deposition. The cooling mode delivers net cooling power of 20–60 $W \cdot m^{-2}$, and the heating mode allows roughly 70% of sunlight to pass through [10]; the transparent dynamic infrared regulator reported by Jia et al. achieves modulation amplitudes of 0.51 and 0.41 in the 3–5 μm and 7.5–13 μm bands respectively, with response time shorter than 600 ms and more than 10^4 switching cycles [11]. This route features wide modulation range and programmable response, yet electrodes, electrolytes, encapsulation and control circuits are required. Long-term outdoor operation also needs to address ion migration, corrosion and sealing issues.

Mechanical regulation changes exposed area, optical path and effective emissivity by flipping double-sided materials, stretching porous/wrinkled structures, folding or kirigami deformation. Chen et al. combined polyaniline electrochromic layers with kirigami structures. The energy consumption for a single switching is lower than 5.58 $mJ \cdot cm^{-2}$, the thermal comfort zone can be expanded by 4.9 ℃, and nearly no energy is consumed during state retention [12]. Fluidic or microfluidic devices modify the optical response of pores by injecting liquids with different refractive indices, absorption characteristics or wetting states. They deliver considerable modulation amplitude and readily realize multi-state operation, yet pumps, valves and flow channels increase volume, leakage risk and parasitic energy consumption. In addition, Chen et al. constructed stretchable SEBS fiber convection shielding layers, enabling transmittance tuning in the solar band and atmospheric window from 28.8% to 72.9% and from 27.0% to 80.5% respectively, demonstrating the regulation capacity of mechanical deformation for dynamic radiative cooling [13]. Active mechanisms suit scenarios requiring precise temperature setting, sensor linkage or remote control, at the cost of higher system complexity and maintenance cost.

4.2. Passive self-adaptive mechanisms

Passive self-adaptive materials convert environmental variables directly into spectral changes without continuous external control. VO_2 undergoes insulator-to-metal phase transition near approximately 68 ℃; doping, strain and defects can reduce the transition temperature. Phase transition induces changes in mid-infrared dielectric functions, but the rule of "cooling at low temperature and thermal retention at high temperature" is not fixed. The actual rise or fall of emissivity depends on VO_2 layer thickness, reflective backplane, optical cavity and working waveband. Geng et al. fabricated near-room-temperature variable-emissivity reflectors based on W-

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Mg co-doped VO_2 and Fabry–Perot structures, with solar absorptance of around 0.40 and infrared emissivity modulation amplitude $\Delta\varepsilon$ of 0.69, and maintained stability after 10000 cycles [14]; printable PEAC overlay can automatically raise atmospheric-window emissivity from 0.25 to 0.85 and is compatible with roll-to-roll manufacturing [15]. Ono et al. adopted solution-processed VO_2/ZnS/Al one-dimensional structures and achieved peak emissivity modulation exceeding 50% within the atmospheric window [16]. Therefore, evaluating phase-change materials such as VO_2 and GST must report transition temperature range, hysteresis, phase transition direction, cycle fatigue and encapsulation stability simultaneously. GST features non-volatility and large optical contrast, yet it generally requires high temperature or pulse writing, and stress from crystallization/amorphization impairs service life.

Thermosensitive hydrogels and polymers usually undergo hydrophilic-hydrophobic transition and phase separation near the lower critical solution temperature. Microscale refractive index inhomogeneity enhances solar scattering and switches the transparent/heat-absorbing state to the reflective/cooling state; the materials reabsorb water and recover upon temperature drop. Liquid thermoresponsive smart windows can also achieve near-room-temperature transition, fast response and large solar modulation amplitude via PNIPAm-based chain-particle synergy [17]. Guo et al. integrated high-emissivity polymers, thermochromic HPC hydrogels and black solar absorbing layers. The system adaptively switches between heating and cooling modes by tuning solar transmittance, with theoretical energy consumption reduced by approximately 20.3% [18]. Such materials allow easy design of response temperature and large-area coverage, but dehydration, freeze-thaw cycles, ultraviolet aging and water vapor transport after encapsulation determine cycle life. Humidity-responsive materials adjust infrared transmittance and emissivity using moisture-induced swelling, changes in yarn spacing or pore wetting; moisture-absorbing polyacrylic hydrogels can couple radiation and evaporative cooling through nighttime water uptake and daytime evaporation regeneration [19]. Wei et al. used humidity-driven pore opening and closing of high-twist cotton/cellulose acetate yarns to raise infrared transmittance by 30%–35% and realize enhanced passive heat dissipation [20]. Thermomechanical bilayers, shape-memory polymers and bimetallic strips convert temperature variation into flipping or opening-closing motions. Their advantage lies in intuitive structure, while limitations include mechanical fatigue, response speed constrained by thermal inertia and threshold drift.

4.3. Near-zero energy consumption and active-passive synergistic regulation

Near-zero energy consumption dynamic radiative cooling does not mean absolute zero energy consumption. It emphasizes that continuous holding power is unnecessary within a complete working cycle. Common implementations include one-time pulse triggering, intermittent low-power control, bistable/non-volatile structures, intrinsic material response and passive retention after active triggering [21]. It is not mutually exclusive with active or passive mechanisms: an electrochromic device consuming energy during switching but no energy for state retention can be categorized as actively triggered with near-zero holding energy; adaptive phase-change materials are passively triggered and may also approach zero in system energy accounting. Active-passive synergy further combines active controllability with passive feedback or retention functions.

Representative studies demonstrate different "low-energy" pathways. First, the reversible silver deposition device developed by Tao et al. applies voltage only during switching, and the formed state can remain stable for 24 h, delivering an emissivity modulation amplitude of 0.48 within 2.5–25 μm, representing "active pulse — bistable retention" [22]. Second, Zhang et al. constructed temperature-driven dual-mode surfaces that automatically expose radiative cooling surfaces at high

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temperature and flip to solar heat-absorbing surfaces at low temperature. Experiments obtained cooling power of approximately 126.0 $W \cdot m^{-2}$ and solar heating power of 859.8 $W \cdot m^{-2}$ respectively; switching does not rely on external operational energy, belonging to "passive sensing — mechanical actuation" [23]. Third, reconfigurable interwoven surfaces or kirigami smart windows alter the coverage sequence of high- and low-emissivity regions through mechanical structures and cooperate with thermosensitive hydrogels to tune solar transmittance. Ke et al. obtained $\Delta\varepsilon_{LWIR}=0.57$ [24], and Wang et al. achieved solar transmittance modulation of roughly 24% and infrared emissivity modulation of 0.50 [25]. Such systems combine seasonal adaptability and manual intervention capability, yet the conclusion of "near-zero" shall still include full-life-cycle energy consumption from sensors, controllers, pumps/batteries, standby power and material fabrication. Table 1 compares triggering modes, holding energy consumption, main advantages and applicable scenarios of the three types of mechanisms.

Table 1. Comparison of dynamic radiative cooling mechanisms

	Triggering / Representative Structures	Energy Consumption for Maintenance and Response	Key Advantages	Major Challenges	Typical Applications
Active Control	Electrodeposition, electrochromism, mechanical/fluidic switching	Usually requires external control; ms–min	Wide tuning range, high precision, and programmability	Encapsulation, actuators, parasitic energy consumption, and system complexity	Smart windows, electronic devices, and spacecraft thermal management
Passive Adaptation	VO_2/GST, PNIPAm, humidity-responsive fibers, thermomechanical structures	No continuous power supply required; s–h	Intrinsic material-level sensing and simple system configuration	Threshold matching, hysteresis, aging, and cycling lifetime	Building envelopes, textiles, and outdoor equipment
Near-Zero-Energy / Hybrid	Bistable electrodeposition, self-flipping dual-mode surfaces, thermoresponsive + kirigami composites	Switching/intermittent energy consumption; near-zero maintenance energy consumption	Combines controllability with low maintenance energy consumption	Insufficiently defined system boundaries and inadequate life-cycle accounting	Year-round buildings, wearable devices, and mobile platforms

5. Application scenarios of dynamic radiative cooling

5.1. Building energy conservation

Building roofs, external walls and windows are subject to seasonal, diurnal and room load variations. Static high-emissivity facades are beneficial in summer yet may increase heat dissipation of building envelopes in winter. Dynamic systems can raise solar reflectance and infrared emissivity under hot conditions, reduce emissivity or increase solar transmittance/absorptance under cold conditions, and coordinate with air-conditioning setpoints. Electrodeposited smart windows deliver programmable dual solar-infrared modulation [10], while thermally induced phase-change coatings and thermosensitive hydrogels take surface temperature as feedback. The core of building applications lies not merely in peak temperature reduction, but in comprehensive optimization of annual energy consumption, indoor thermal comfort, daylighting and appearance.

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5.2. Thermal management of electronic devices

Heat flux density of electronic devices varies significantly among operating, standby and shutdown states. Static high-heat-dissipation surfaces can suppress peak temperature rise, yet may lead to excessively low temperature or condensation under low loads and humid environments. For batteries and energy storage systems, low temperature also degrades power output and service life. Dynamic emitters can increase or decrease radiative heat dissipation according to chip or battery temperature, and work hierarchically with thermal interfaces, phase-change heat storage and air-cooling systems. This scenario demands fast response, low thermal resistance, insulating encapsulation and long cycle life. The driving energy consumption and benefits from reduced fan or refrigeration energy use shall be evaluated together [11].

5.3. Personal thermal management and smart textiles

Human metabolic rate, activity level, ambient temperature and humidity keep changing. Fabrics with only thermal insulation or only heat dissipation cannot cover the full comfort zone. Dynamic textiles enhance heat dissipation during exercise and high humidity, and suppress radiative heat loss at rest and low temperature by flipping high/low-emissivity surfaces, adjusting yarn spacing or electrochemically tuning emissivity [12, 20]. Apart from spectral modulation, wearable systems must also balance flexibility, air permeability, skin compatibility, wash resistance and low-voltage safety. Therefore, electrochromic devices with non-volatile states and humidity self-responsive fibers are particularly suitable for low-power personalized thermal comfort.

5.4. Vehicles, outdoor equipment and energy storage systems

Vehicle cabins, outdoor communication equipment, photovoltaic modules and energy storage enclosures are simultaneously exposed to solar irradiation, operational heat generation and nighttime cooling. Static cooling layers can lower daytime peak temperature, yet may push batteries out of the optimal temperature range during cold startup or at night. Dynamic surfaces can activate cooling during parking under strong sunlight or high equipment loads, and deactivate cooling for low-temperature startup, preheating during charging or nighttime conditions. Mechanically flipped and thermally induced phase-change structures can also reduce reliance on on-board power supplies. Practical design needs to integrate waterproofing, dustproofing, impact resistance, flame retardancy and maintenance strategies, instead of merely comparing laboratory spectral data [1, 3].

5.5. Aerospace and infrared thermal management

Spacecraft experience a wide range of surface heat fluxes affected by solar incidence, attitude, orbital day-night cycles and internal power consumption. Coatings with fixed emissivity struggle to satisfy both cold and hot working conditions. Electrochromic and phase-change emitters can modulate radiative heat dissipation without direct refrigeration and reduce the load of heaters or mechanical louvers. Infrared thermal camouflage requires tuning radiative signatures within target wavebands to match background temperature, which is often coupled with visible-near-infrared optical requirements [9, 11, 22]. Evaluations for such applications should be made cautiously based on published academic research, focusing on reliability under vacuum, atomic oxygen, ultraviolet radiation, particle irradiation and extreme temperatures. Laboratory infrared images shall not be equated to full stealth capability.

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6. Challenges and development prospects

The translation of dynamic radiative cooling from material specimens to engineering systems still faces multi-scale bottlenecks. At the material level, phase-change materials such as VO_2/GST suffer from mismatches between transition temperature ranges and practical operating temperature ranges, hysteresis, phase-change stress and cycle fatigue. Hydrogels are prone to dehydration, freeze-thaw damage and biological contamination. Electrochemical devices are limited by electrode corrosion, electrolyte volatilization and sealing lifetime. At the device level, emissivity modulation amplitude, solar modulation amplitude, response speed, mechanical stability and visible-light performance often restrict one another. Large-area fabrication further reveals problems including film thickness uniformity, defects, edge sealing and yield. Outdoor humidity, cloud cover, wind, dust and surface aging alter thermal balance, making laboratory data obtained under vacuum or clear-sky conditions difficult for direct extrapolation.

Future research shall shift from "larger modulation amplitude" toward "more appropriate system windows". First, develop phase-change materials near room temperature with low hysteresis and high cycling stability, and determine the correct direction of emissivity change through the collaborative design of doping, strain and optical cavities. Second, construct multi-stimuli responsive materials sensitive to temperature, humidity and illumination, combining passive sensing with low-power active calibration. Third, develop water-based processes compatible with roll-to-roll printing, coating and lamination, and improve outdoor weather resistance via barrier layers, self-healing and modular encapsulation. Fourth, establish unified testing protocols to report at least spectra, angular dependence, weather conditions, non-radiative heat transfer coefficients, switching energy consumption, holding power and cycle life. Fifth, carry out full-scale verification on buildings or equipment, and evaluate net benefits using annual energy consumption, life-cycle carbon emissions, cost and maintainability. For multi-band thermal management, responses in the solar band, 3–5 μm and 8–13 μm must be optimized simultaneously to prevent new parasitic heat flux introduced by performance improvement in a single waveband.

7. Conclusions

The core advantage of dynamic radiative cooling lies in converting fixed spectral selectivity into tunable heat flux that varies with environments and loads, so as to mitigate overcooling of static materials under winter, nighttime and low-load conditions. Active regulation relies on electrical, mechanical or fluidic actuation and delivers high precision and programmability. Passive self-adaptation depends on phase change, swelling/shrinkage or thermomechanical deformation; its system structure is simple yet constrained by threshold, hysteresis and stability. Near-zero energy consumption and active-passive synergy strike a balance between control freedom and holding energy consumption through one-time triggering, bistable retention or material feedback. These three categories represent complementary routes under different evaluation dimensions rather than mutually exclusive labels.

Current key bottlenecks have expanded from mere spectral design to long-term weather resistance, cycle life, encapsulation, large-area manufacturing and system energy accounting. For practical applications, the most promising directions include low-hysteresis materials tunable near room temperature, multi-stimuli adaptive devices, coordination of passive sensing and low-power control, and scalable modules validated through year-round field tests. With the gradual establishment of unified testing standards and life-cycle assessment, dynamic radiative cooling is

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expected to evolve from laboratory "switchable surfaces" into intelligent, low-energy thermal management units for building, electronic, transportation and aerospace systems.

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