Dynamic Radiative Cooling: A Review of Materials for Energy-Efficient Window Applications

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Abstract：Radiative cooling materials have received enormous attention for their ability to cool below ambient temperature without energy consumption. Unlike conventional radiative cooling systems, which can result in excessive cooling during colder months, dynamic radiative cooling materials can dynamically adjust their thermal radiation properties in response to environmental changes, enabling efficient cooling and heating across different seasons. This review summarizes the recent developments in dynamic radiative cooling materials, focusing on their physical mechanisms, including mechanically assisted films, thermochromic materials, temperature-responsive gels, and solvent-assisted systems. Special attention is given to their applications in energy-efficient building windows and facades. The challenges of scaling dynamic radiative cooling technologies for widespread use and their potential for future development are discussed, with recommendations for improving performance, sustainability, and integration into modern building systems.

Keywords：*Dynamic Radiative Cooling, Thermal Transfer Materials, Energy-efficient Windows, Adaptive Thermal Management*

1. Introduction

With the rapid increase in cooling demand due to global warming, the energy consumption related to traditional air conditioning increased rapidly, accounting for 15% of the world's electricity, and contributing 10% to global greenhouse gas emissions. By 2050, the demand for cooling is projected to increase tenfold [1]. However, conventional vapor compression-based cooling systems, such as warm-air conditioning and refrigeration, consume large amounts of fossil energy, exacerbating global warming and bringing significant challenges to achieving “carbon neutrality” [2,3]. Therefore, the search for alternative refrigeration technologies has received enormous attention from relevant researchers. As a zero-energy, eco-friendly cooling strategy [4], sky radiation cooling has become a hot research topic because it does not consume electricity or refrigerant [5-8]. Radiative cooling materials (RCMs) can emit the hot earth (~300 K) to the cold universe (~3 K) in the form of electromagnetic waves through an atmospheric transparent window between 8-13 μm, thus becoming a zero-energy cooling method [9-13].

After decades of research, sky RCMs are becoming more sophisticated, transferring more heat to the external universe while reflecting sunlight efficiently [14], and the timeline of the development of RCMs is shown in Fig. 1. Early research focused on basic studies of optical properties and thermal radiation properties of materials, Daytime radiative cooling below ambient air temperature in direct sunlight was first realized by Fan's team in 2014 through an innovative multilayer photonic structure [15]. Subsequently, researchers have designed and prepared various materials, including coatings [16-19], freestanding films [20,21], white paints [22], microfabrics [23-26], wood [27], and gels [28,29], which effectively reduce ambient temperatures, especially during hot weather. This process of radiative cooling is energy efficient and environmentally friendly without any pollution or energy consumption [30].

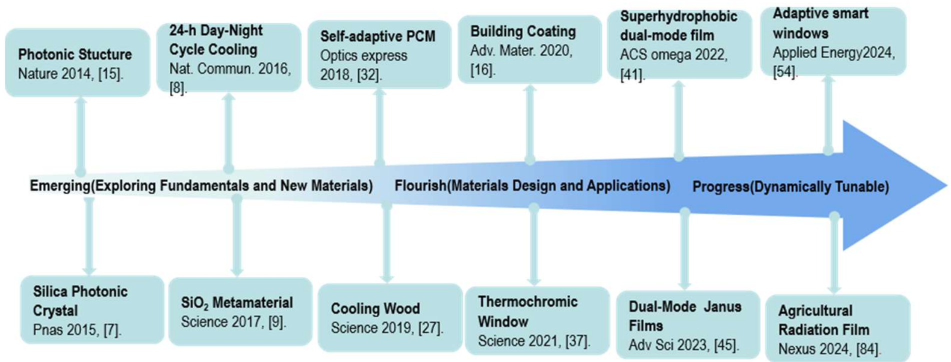

Fig. 1. The development of radiative cooling materials from 2014 to 2024.

However, most existing radiant cooling designs optically perform statically, increasing the heating load in winter and failing to meet the insulation requirements during cold nights or winter conditions, which hinders their practical application. In recent years, the need to meet the requirements of all-weather passive thermal regulation has led to the rise of dynamic radiative cooling (DRC) technology [31]. Most of the initial attempts were theoretical [32,33] or several passive DRCs were realized in the laboratory [34,35], and in 2021, Wang et al. [36] tested DRC smart windows and demonstrated energy-free, temperature-adaptive radiant coatings by field testing DRC smart windows, and it is noteworthy that Li et al. [37,38] and others conducted a study of the US DRCs in 15 climate zones were numerically simulated and found that for most climate zones, DRCs provided higher energy savings compared to static radiatively cooled materials, especially in areas with significant temperature variations.

Based on this, this article aims to shed light on the development of DRC materials and forms of cooling, offering a variety of promising DRC materials based on specific physical mechanisms, including mechanically-assisted DRC films, thermochromic vanadium dioxide (VO_2) and gels, and solvent-assisted DRC. The article also points out the integration of DRC materials into building facades to achieve higher demand for all-weather energy efficiency and discusses the challenges and future trends of DRC to provide a reference for the design of dynamic radiant coolers and to stimulate more new ideas and innovations to promote the application of DRC technology. Fig. 2 demonstrates the framework diagram of this paper.

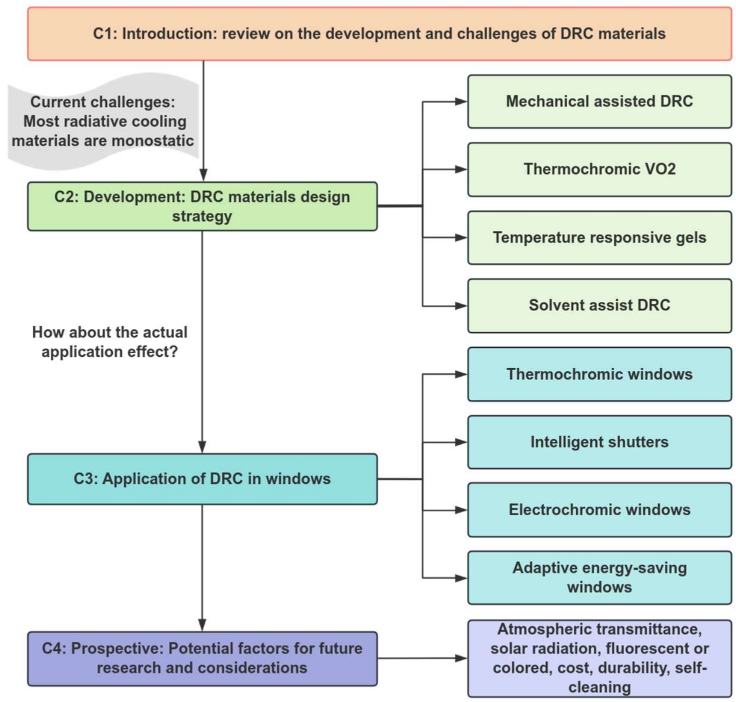

Fig. 2. Framework of the review.

2 Design of DRC materials

The DRC material can switch the optical properties autonomously according to the solar spectrum and the thermal emission spectrum of the atmospheric transparent window. As shown in Fig. 3 Schematic and an ideal spectral diagram of DRC. When daily/seasonal variations in solar intensity and periodic start/stop of internal heat-producing devices generate indirect heat flux [39], DRCs have attracted much attention for their ability to adapt to the need for heating or suppressed cooling. In this section, we discuss the development and cooling forms of DRC materials, which can be classified into several categories based on specific physical mechanisms: mechanically-assisted DRC films, thermochromic VO_2 and gels, solvent-assisted DRCs.

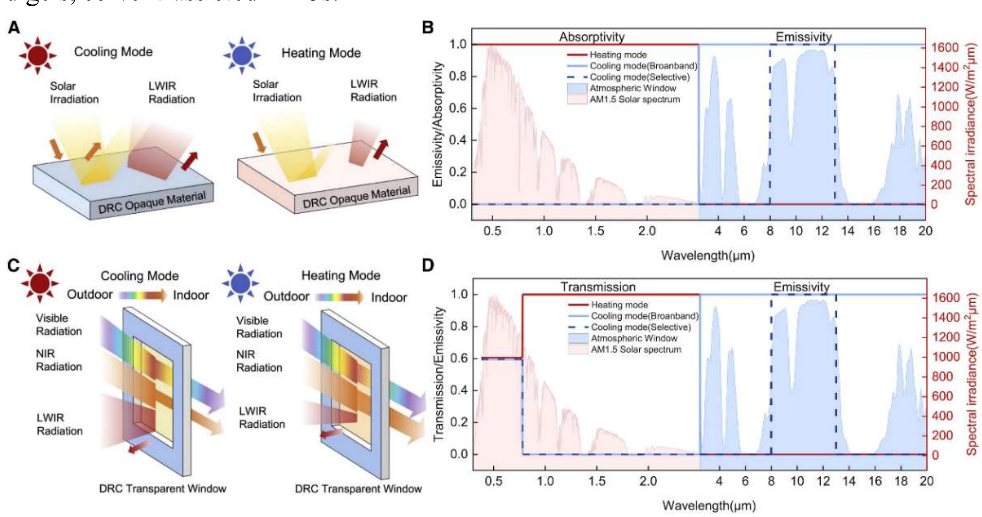

Fig. 3 Schematic an ideal spectrum of dynamic radiative cooling. The schematic (A), ideal spectrum for broadband and selective emissivity, as well as ideal spectrum for solar absorptivity (B) of DRC on opaque substrate. The schematic (C), ideal spectrum for broadband and selective emissivity, as well as ideal spectrum for solar transmission (D) of DRC on transparent substrate, [40].

2.1 DRC materials with mechanical assistance

DRC films provide on-demand control and fast response with the help of mechanical assistance, through simple mechanical stimulation, such as tensile compression, flipping one side to a cooling side and one side to a heating side, without the need for complex mechanical actuation, by simply flipping the film over, the film will behave with the desired optical properties according to the ambient temperature, solar heating or solar reflection and radiative cooling, which is a simple class of dynamic modulation mechanisms. Table 1 summarizes the relevant literature on mechanically assisted DRC material design. For example, Zhao et al. [31] developed a bifunctional dynamic porous silicon membrane for energy efficient cooling and heating, which can be reversibly continuously adjusted from a highly porous state to a transparent solid, and is the first environmentally friendly DRC membrane that can both cool and heat. Wang et al. [41] utilized styrene-ethylene-butene-styrene/SiO_2 porous coated white side for radiative cooling with carbon nanotube/ polydimethylsiloxane (PDMS) nanocomposite coated black side for solar heating, and this bimodal film has superhydrophobic self-cleaning properties due to the micro-nano structure of the cooling and heating surfaces. Similarly, Shi et al. [42] modified MXene nanosheets on porous polyvinylidene fluoride (PVDF) through phase conversion to prepare all-weather dual-mode films. The solar reflectance and infrared emissivity on the cooling side were as high as 96.7% and 96.1%, respectively, and were suitable for radiation cooling. The ultra-thin MXene coating enables the dual-mode film to have a low infrared emissivity of 11.6% and a solar absorption rate of 75.7%. The dual-mode film easily switches between cooling and heating modes by flipping over to accommodate dynamic cooling and heating scenarios, creating an all-weather DRC film. Janus materials exhibit opposing optical behaviors on opposite sides of the material in the solar and/or long-wave infrared (LWIR) ranges due to their asymmetric optical properties, resulting in a fast, energy-efficient transition between cooling and heating modes [43]. For example, Janus-structured MXene-nanofiber aerogels based on an asymmetric structure allow for switchable functionality of radiative heating and cooling alternately in winter and summer [44]. Similarly, Yang et al. [45] designed bimodal Janus films with bonded interfaces, and for the first time, NaH_2PO_2 particles with high infrared radiation (IR) emissivity of up to 97.2% were embedded in porous polymethylmethacrylate films (PMMA), and a wide temperature range was obtained by flipping the bimodal Janus films for thermal management. While the aforementioned bimodal DRC films are usually composed of organic polymers and metal/inorganic non-metallic materials composite, Xiang et al. composed two polymers, i.e., polyvinylidene fluoride-co-hexafluoropropylene (PVDF-HFP) and polypyrrole, into a fiber-based film, which can achieve a solar ambient cooling temperature of about 4.5°C and an ultra-ambient heating temperature of 35.8°C, with excellent outdoor temperature regulation [46].

Table 1 Comparison of mechanically assisted DRC material design and performance

DRC materials	Cooling			Heating		References
	R	E	ΔT/°C	A	ΔT/°C	
Porous organosilicon films	0.93	0.94	5	0.95	18	Zhao et al. [31]
SiO_2 and carbon Nanotubes/PDMS	0.94	0.92	11	0.98	35.6	Wang et al. [41]
MXene and porous PVDF	0.97	0.96	9.8	0.76	8.1	Shi et al. [42]
Janus MXene-nanofibrils Aerogels		0.88	9.8	0.97	5.5	Yang et al. [44]
Janus NaH_2PO_2-PMMA	0.93	0.97	8.8		39.3	Yang et al. [45]
PVDF-HFP and polypyrrole			4.5		35.8	Xiang et al. [46]

Table 1 summarizes the scenarios in which dual-mode films are switched between cooling and heating modes by flipping to accommodate dynamic cooling and heating. There are also studies on the engineering of mechanical stress deformation and optical properties by rotating or rolling wheels, which can design dual-mode intelligent thermal management devices with ideal dual-mode optical properties, with solar energy utilization of more than 93%, saving 19.2% of heating and cooling energy consumption [47]. Meanwhile, Liu et al. [48] proposed an intelligent cooling system consisting of PDMS as a nanograting radiative cooler, where the continuous stretching of the material can be achieved by the deformation of the elastic PDMS substrate for DRC. Tang et al. [38] proposed a mechanically flexible coating to investigate thermal regulation from an all-seasonal point of view, optimally absorbing the solar energy and switching the thermal emissivity from 0.2 at lower than 15°C to 0.9 above 30°C. Li et al. [49] proposed a strain tunable reflectivity fiber membrane with 95.6 % reflectivity and 93.3 % IR emissivity by reversible stretching to change its optical reflectivity, reaching a temperature drop of 10 °C at noon and adjusting the tensile strain for a net increase of 9.50 °C in the ambient temperature above the absorbing substrate. Simulations show that the DRC film outperforms existing roof coatings in terms of energy savings in most climates, the fabrication method is simple, fast, and environmentally friendly, and the mechanically assisted DRC can be easily switched between cooling and heating modes by flipping or flexible deformation, and the realization of highly efficient all-day, dual-mode DRC provides a feasible strategy.

2.2 Thermochromic materials

In addition to bimodal films that rely on mechanical flip-flops, thermochromic DRC materials do not require external energy input and exhibit reversible transition optical properties in response to changes in temperature, enabling adaptive thermal regulation. VO_2 as a typical thermochromic material, undergoes a reversible metal-insulator transition at a critical temperature of 68°C. Above the critical temperature, it is in the metallic rutile phase with high infrared reflectivity, and below the critical temperature, it is insulating and transparent to near-infrared light. VO_2 can modulate infrared radiation without raising the room temperature, and its transmittance change in response to temperature is negligible; therefore, dynamic VO_2 radiative modulators can provide sufficient sunlight in buildings, and adaptive radiative cooling photonic structures based on VO_2, which can adaptively turn on and off radiative cooling according to the ambient temperature without any additional energy input for switching, dynamic VO_2 radiative modulators have great potential for application [32,50,51]. However, the high critical temperature of VO_2 and the tunability of the emissivity limit its application. Initially, the preparation of VO_2 thermochromic thin films was relatively simple, and the polyvinylpyrrolidone-deposited VO_2 films consisted of nearly pure monoclinic/rutile (M/R) phases, and the phase transition temperature of VO_2 could be adjusted by doping with tungsten [52]. Subsequently, Gao et al. [53] prepared transparent, stable and flexible VO_2-based composite films for the first time using a full-solution process, which could be switched from a low-temperature IR transparent state to a high-temperature IR reflective state due to its good temperature response in the near infrared radiation (NIR) region. The high infrared reflectivity of VO_2 at high temperatures is contrary to the practical needs. In order to solve the feature mismatch problem, a VO_2-based Fabry-Perot (FP) resonance [54] is proposed to be excited by a top nanoparticle assembly and a bottom multilayer assembly, which makes it possible to control the emissivity from the NIR to the FIR region at the same time, and realizes the ideal regulation of the IR emissivity, that is, the strong emission at high temperatures and the weak emission at low temperatures. Taylor et al. prepared a tunable ultrathin film emitter consisting of an aluminum reflective film and VO_2 in the laboratory, with the spectral emissivity varying with temperature and thus DRC [34]. Notably, Gu et al. reduced the phase transition temperature of a VO_2-based smart IR radiomodulator by nearly 27.5°C by doping with tungsten, with an emissivity tunability of 0.51, and an IR camera showing good dynamic thermal regulation [35]. Due to the passive response of VO_2 to ambient temperature, some studies have focused on modification of the phase transition temperature and improvement of T_{lum} and T_{vis}, e.g., Ke et al. [55] homogeneously dispersed VO_2 nanoparticles in transparent elastomers with dynamic micro-folds, and the dynamically controlled visible transmittance could be varied from 60 to 17%, which added a new dimension to the VO_2-based stand-alone dual-mode windows. Wang et al. [56] designed and fabricated a tungsten-doped VO_2@SiO_2 core-shell structure to achieve a higher T_{lum} of 43.11%, realizing ΔT_{sol} of 10.64% and $\Delta\varepsilon_{\mathrm{LWIR}}$ of 0.23 for smart window applications. VO_2, as a promising material for smart windows, can be used due to its reversible metal-insulator transition, resulting in significant optical transmittance variations to provide sufficient light for buildings, and is expected to be applied to architectural and automotive glazing to improve energy efficiency.

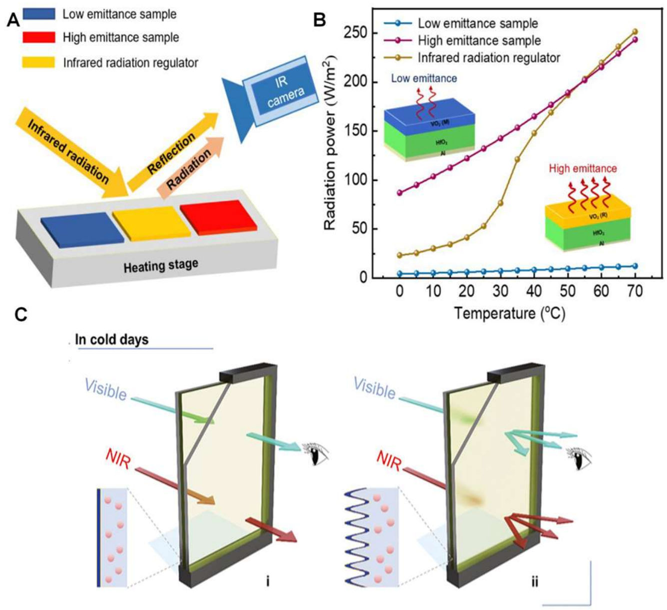

Fig. 4. Schematic diagram for the structure of VO2-based infrared regulator: (A) when the temperature is below Tc, the IR emittance is low; (B) when the temperature is above Tc, the IR emittance is high, [35]. (C) Schematic of the film consisted of well-dispersed VO2 (M/R) NPs in the PVA-PDMS bilayer structure, and its four representative states of the design to meet the different window modes: (C i) normal, (C ii) privacy, [55].

In addition to the above dynamic regulatory materials, there are also such as titanium dioxide (TiO_2) for reflectance modulation of the temperature adaptive radiative cooling coatings. Researchers [57] prepared thermochromic materials by doping TiO_2 into a suitable binder to be coated on a glass substrate, and the coating was yellow at 20°C and white when heated to 30°C. The addition of TiO_2 improves the reflectivity of its colorless phase in the visible and infrared ranges. The addition of TiO_2 can improve the reflectivity of its colorless phase in the visible and infrared ranges. TiO_2 is the most widely used white pigment in the preparation of coatings, plastics, and paper, but due to its high price, high pollution, and potential cancer risk, Wang et al. [58] reported scalable aqueous TiO_2-free thermochromic coatings for adaptive passive radiative cooling and heating. The TiO_2-free white coating has higher solar reflectance (~0.96) and near-normal emissivity in the long-wave infrared (~0.94), achieving cooling of ~7.8°C at night and ~7.1°C in direct sunlight. Specifically, the coating enables solar heating above ambient temperatures ($\Delta T_{\text{cooling-heating}}$ = 9.5°C), extending the range of year-round energy-saving applications.

2.3 Temperature responsive gels

DRC has significantly impacted global energy savings, and gels, which are temperature-responsive in the visible range, are another promising approach to realizing DRC. The behavior of temperature-responsive hydrogels is attributed to the transition between a hydrophilic state with high transmittance and a hydrophobic state with low transmittance [59]. That is, from a state that allows sunlight to pass through, to a state that blocks incoming light and radiation. Fang et al. [60] utilized a proposed sandwich-structured thermal stabilizer based on the temperature-responsive hydrogel poly(N-isopropylacrylamide) (pNIPAm) as shown in Fig. 5a, which maintains its own temperature difference within 1.2°C by self-regulating solar transmittance, the transparent radiative cooling membrane at the top and the temperature-sensitive hydrogel in the middle can effectively realize DRC. Similarly, Mei et al. [61] designed an adaptive film based on a sandwich structure of pNIPAM hydrogel and PVDF, Fig. 5C, with large visible reflectance/transmittance modulation (ΔR_{vis} =70% and ΔT_{vis} = 86.3%), and long-wave infrared emissivity of 0.96, which can adaptively achieve radiative cooling in the range of 1.8-3.7°C during hot daytime, and cold daytime solar heating of 4.3-5.8°C above ambient. The temperature-responsive hydrogel performance demonstrates its potential for cooling/heating applications in different geographic locations and weather conditions, suitable for applications such as transparent windows. In addition, gels can also fulfill IR adaptive radiative cooling, Tang et al. [39] utilized a bilayer structure composed of SiO_2 and pNIPAM to achieve spectral dynamic switching between selective IR emission (85%) and broadband emission (92%), which provides a methodology for the design of selective emitters for atmospheric windows. Figure 5 shows temperature-dependent DRC gel materials, which can realize efficient dynamic cooling in different climates and different geographical locations due to the drastic change of their transmittance between hydrophilic and hydrophobic properties, combined with a great potential for application in architectural windows.

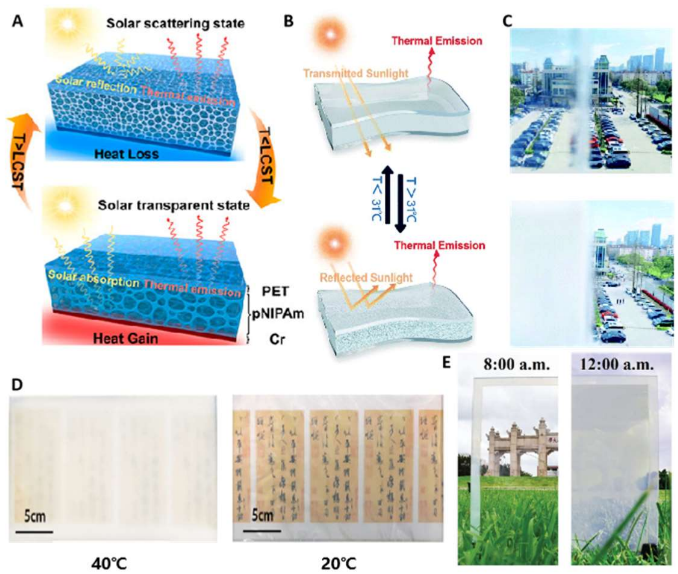

Fig. 5. Temperature response DRC materials. (A) Principle of operation of the hydrogel dynamic radiation equalizer. (B) Temperature versus time curve of the dynamic radiator [60]. (C) Sandwich-structured membrane based on thermosensitive hydrogel showing intelligent regulation of sunlight scattering [61]. (D) Optical photographs of the membrane at 20°C and 40°C, respectively [62]. (E) Photographs of a 40 × 40 cm window on a summer university campus at different times and temperatures [63].

2.4 Solvent-assisted DRC materials

Another way to realize DRC is to control the interfacial refractive index between different components, where the refractive index-matched liquid and coated components are switched between drying and wetting, thus automatically adjusting the solar reflectance and infrared transmittance for dynamic thermal conditioning. Mandal et al. [64] presented the first refractive index matching for optical conditioning by demonstrating that by reversibly wetting porous polymer coatings, their transmittance to solar and thermal radiation can be changed. For example, in Fig. 6B, white PVDF-HFP becomes transparent when wetted with refractive index-matched isopropyl alcohol liquid, with a solar transmittance change value of ΔT_{sol} of 0.74; wetting of infrared-transparent polyethylene by the alcohol liquid leads to reversible optical switching of the porous coating, and, in Fig. 6C, enables switching between the sub-ambient cooling of 3.2°C and solar heating of 21.4°C modes. Porous polymer coatings based on dual-mode thermal conditioning are limited by thickness limitations due to their need for both high solar reflectance and high transmittance, then large and small thicknesses, respectively, in DRC materials, but a researcher [65] proposed a single-layer coating prepared in a simple one-step method, Fig. 6E, which, after ethylene glycol moistening, achieves a fast switching between high solar reflectance (99.6%) and high solar transmittance (86.6%), switching rapidly between high solar reflection and high solar transmission, achieving unprecedented performance through this unique layered porous structure, and breaking the traditional thickness limitations. Zhang et al. [66] by using a porous SiO_2 coating with refractive index-matched liquid wetting/dehumidification, as shown in Fig. 6F, the transmittance is only 11% in opaque mode, and when the refractive index-matched liquid replaces the air in the porous multilayered structure, the solar transmittance is 94%, and the whole switching process is completed in 3 min, and the temperature is increased by about 10°C in cold weather, and the temperature in hot weather is about 5°C decrease, this fast and simple thermal management device provides methods for constructing light-controlled devices and heat-controlled building materials.

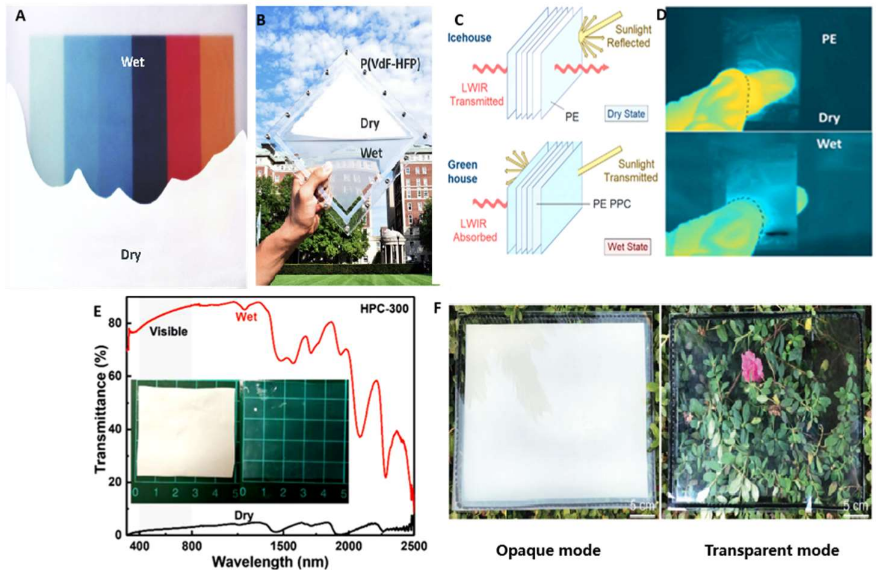

Fig. 6. Solvent-assisted DRC materials. (A) Schematic of solvent-assisted DRC. (B) Photograph of the system showing dry and wet states. (C) Icehouse-to-greenhouse switching of porous polymers encapsulated, exemplified by a PE-air/ alcohol system. (D) LWIR thermographs of porous polymers encapsulated and enclosed in PE films when dry and wetted with alcohol [64]. (E) Optical images of HPC-300 upon state transition (HPC-300 is wetted by ethylene glycol), indicating excellent optical switchability [65]. (F) Optical photographs in transparent and opaque modes [66].

3 Applications in energy-efficient building

3.1 Thermochromic smart window

Smart window technology, which refers to on-demand windows that dynamically adjust light transmission, has been recognized as a promising direction for the next generation of windows. Smart windows reduce heat loss in cold environments while promoting heat dissipation in hot conditions and are energy efficient in all weather. An ideal smart window must have high reflectance in the NIR band and high emissivity in the LWIR band in summer, while it must have high transmittance in the NIR band and low emissivity (low-e) in the LWIR band in winter [36,67]. Consideration of DRC is missing in general smart window design, and Nanyang Technological University first proposed an ideal smart window with switchable frontal longwave infrared emissivity (0.95-0.1), solar modulation capability of 51%, and higher light transmittance of 72% as shown in Fig. 7 to adapt to the thermal performance requirements and energy saving requirements in different seasons [62]. The thermochromic VO_2 film is applied to the interior side of the window, which enables a dual smart window, where the heat gain from solar radiation and longwave thermal radiation is suppressed by the VO_2 window, which reduces the cooling energy by 21.7%. On cloudy days, VO_2 at low temperatures has a relatively high solar and visible transmittance, allowing more solar and visible radiation to enter the room, with the advantage of dynamically modulating solar and longwave radiation [68]. Similarly, Chen et al. [63] and Lin et al. [69] utilized a lower critical transition temperature (32.5-43.5°C) of thermoplastic color-changing hydrogel for all-weather building temperature modulation applied to smart windows by adjusting the number of silver nanowires to balance the trade-offs between solar transmittance and thermal modulation, Fig. 7D, with adaptive and reversible solar transparent to opaque and thermal reflective to emissive switching to achieve solar modulation of 58.4% and thermal modulation of 57.1%, and an indoor simulation investigation from winter to summer, which reduces the indoor temperature by 7.3°C in summer, and has thermal insulation performance in winter, which saves 4.30 J/m^3 of energy. Durability is a key consideration for thermochromic smart windows due to their constant heating-cooling cycles, and researchers [70] prepared a nanocomposite thermochromic smart window with a service life of 33 years with a low transition temperature of 56.6°C. After 50 days of accelerated aging, the thermochromic color rendering rate reaches more than 90% with an aging factor of 240, which is equivalent to nearly 33 years in a normal environment. The smart window panels have a wide range of selective solar spectrum tunability under dynamic climatic conditions in energy-efficient buildings, which greatly improves energy-saving performance globally.

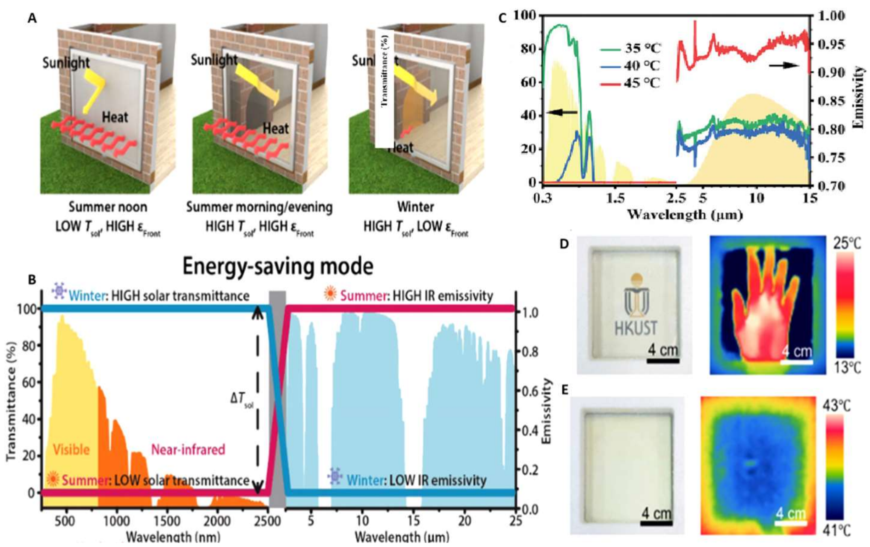

Fig. 7. Smart window structure and DRC schematic. (A) Working principle of smart window panel in summer and winter. (B) Ideal smart window concepts in VIS, NIR, and LWIR bands in energy-saving modes in summer (red line in the spectrum) and winter (blue line in the spectrum); and the important parameters of energy-saving smart windows: Tlum, Tsol, ΔTsol, and ε LWIR [62]. (C) Transmission spectra and thermal emissivity of smart windows from 35°C to 45°C [63]. (D) Visible and infrared images of the smart window in the cold state. (E) Visible and infrared images of the smart window at high temperature [69].

3.2 Shutters

Another shutter structure can also realize the DRC of the window, and the shutter structure is placed not only vertically but also parallel to the ground, which is more conducive to heat exchange with low temperature outer space. For the existing shutter structure can not play a positive role in winter, researchers [71] further improve the design, for the first time, proposed the use of a temperature-controlled V-shaped phase change structure to realize the temperature self-adaptation of the cooler, this structure can be automatically adjusted according to the temperature of the opening angle of the shutter sheet, the structure is shown in Fig. 8A, lower than 12 °C when the sheet is are fully closed to regulate the cooling capacity of the cooler inside the chamber, and the maximum temperature difference throughout the day is reduced from 19.6℃ to 9.7℃. In Figure 8C, the light-adaptive shutter can autonomously switch between open and closed states according to solar illumination fluctuations, storing heat efficiently and radiatively cooling at night, and the silver coating on the backside prevents radiative dissipation, providing near-zero net radiative dissipation for efficient solar thermal storage [72]. Inspired by the shutter structure, researchers [73] integrated radiative cooling, natural daylighting, and solar heating into a multimodal device, as shown in Fig. 8D, where selective radiative cooling materials and solar heating materials are bonded together as the blades, which are rotated to regulate the incoming solar flux into the room, blocking the sunlight in hot weather to prevent solar heating, and at the same time, through the atmospheric window to the outer space of longwave radiation is maximized, further reducing cooling requirements. In cold weather, multimodal devices switch to heating mode, absorbing sunlight to maximize heat gain and reducing longwave radiation to minimize heat loss. However, these thermally conditioned materials lack energy storage properties. Another type of switchable multifunctional device integrating heating, cooling, and latent heat storage by connecting layers of radiative cooling emitting membranes, phase change membranes, and solar heating membranes to form a sandwich structure for building temperature regulation and window energy saving is shown in Fig. 8E. The radiative cooling and solar heating membranes exhibit excellent abrasion and ultraviolet (UV) resistance, and the phase change layer can control the temperature at a steady state under dynamic weather conditions [74]. Conventional windows are the most energy-dissipating component of the building envelope, and the integration of DRC materials utilizing excellent spectrally selective DRC materials into windows is essential to improve the dynamic regulation of building heat loads and indoor comfort.

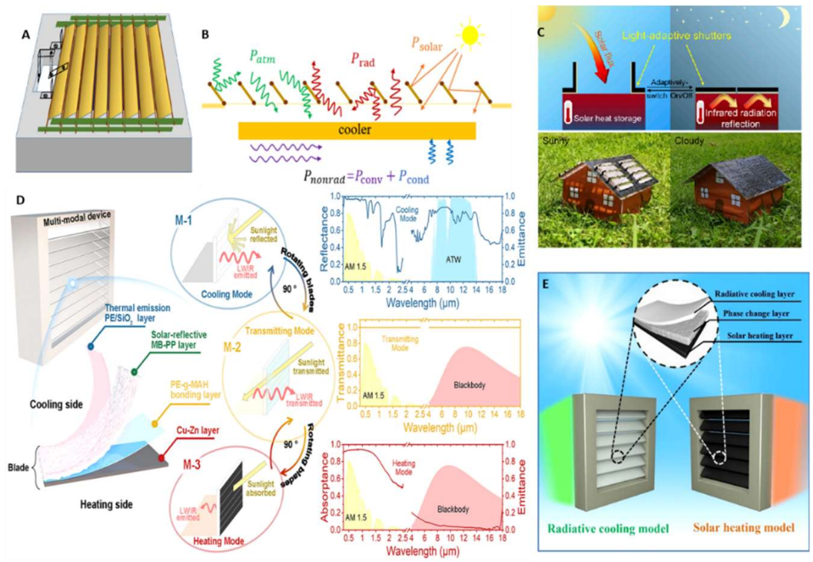

Fig. 8. Device structure for DRC with shutter structure. (A) DRC shutter structure. (B) Energy flow diagram showing the possibility of realizing adaptive radiative cooling [71]. (C) Mechanism of the dynamic louver structure to promote solar thermal storage. During a clear day (left), the light-adaptive shutter (LAS) is open and solar heat is stored in the thermal storage device. At night or on cloudy days (right), the LAS is closed and the infrared radiation is almost completely reflected back due to the high reflectivity of the silver-plated layer on the back of the LAS [72]. (D) Structure of the multifunctional device and the principle of mode conversion [73]. (E) Radiative cooling model of a multifunctional shutter device [74].

3.3 Electrochromic windows

Electrochromic materials can reversibly change their transmittance or reflectance in the visible and infrared light ranges in response external electrical or electrochemical stimulis, and the modulation of the infrared emissivity of electrochromic materials has been further developed in recent years into infrared electrochromic devices [75,76]. The structure of electrochromic devices depends on the actual electrochromic application in different wavelength regions, e.g., some are used for smart windows. Deng et al. [77] proposed an electronically controlled polymer dispersed liquid crystal smart window with ultra-fast switchable passive radiative cooling characteristics, in which the liquid crystals are forced to switch between uniform and random alignment along the direction of the electric field by controlling the voltage, and the film is switched from a transparent state to a colored light-scattering state. Not only the electro-optical properties but also the radiative cooling efficiency can be regulated, illustrating stable and on-demand multilevel modulation at a given voltage, which is reported for the first time. The commercialization of electrochromic devices is faced with high cost and complicated fabrication process. Jia et al. [78] developed a new dual deposition and dissolution mechanism “electrode-free” electrochromic window, whose color change function is realized by the corresponding solid-liquid conversion reaction on the cathode and anode, which achieves uniform color change through the simultaneous deposition and dissolution of anode Cu/Cu^{2+} and cathode MnO_2/Mn^{2+}, thus eliminating the need for complicated preparation steps of electrochromic layers and facilitating large-scale production. Moreover, a high optical contrast of 85% and a transmittance of 0.01% in the visible wavelength band were achieved, providing the first example of electrode materials based on deposition/dissolution reactions applied to electrochromic devices.

Another electrochromic material is inorganic tungsten oxide for building energy-saving dual-band or even triple-band electrochromic smart windows. Chen et al. [79] innovatively proposed an inorganic all-solid-state dual-band electrochromic smart window based on orthogonal oxygen-deficient tungsten oxide film, which skillfully integrates the efficient oxygen-deficiency-promoted charge-transfer mechanism with a stable transmission path provided by orthogonal crystalline structure, which synergizes the two. Able to selectively regulate the transmittance of visible and near-infrared light, the smart window realizes indoor temperature regulation of up to 15.6℃. In response to the research on the separate optimization of the three bands in the visible, near-infrared, and mid-infrared wavelength ranges, Shao et al. [80] proposed a three-band electrochromic smart window with adaptive radiative properties, utilizing a WO_3 thin film structure with a controllable lithium-ion embedding depth, a high emissivity quartz substrate on the outdoor side, and low-e indium tin oxide (ITO)/polyethylene on the indoor side, with the two surfaces optimize radiative heat exchange between the indoor and outdoor environments using electrodes with preferred emissivity, combining radiative cooling of mid-infrared light with maximized utilization of visible and near-infrared light.

3.4 Other energy-saving windows

Dynamic windows for adaptive solar radiation and emissivity control have long been prohibitively expensive, mainly due to the fact that complex broadband spectral manipulation requires complex material designs. The most commonly used transparent conductor ITO is widely available on the market, and Li et al. [81] proposed a broadband adaptive radiative heat management window, compared to the common ITO-based counterpart, the IHO-based window shows a 70% enhancement in NIR power regulation ability (10.9%) with remaining emissivity regulation ability (0.26). Compared with conventional low-e windows, the global annual energy saving and equivalent CO_2 emissions are reduced by as much as 20 % ($411 MJ \cdot m^{-2}$) and 244 tons/year, making a great contribution to energy saving. Another type of liquid crystal device, which is widely used commercially for large-area applications, the main modulation performed by switching the liquid crystal window is by blurring the light transmission [82]. Deng et al. [83] demonstrated an energy-efficient smart window for active tunable passive radiative cooling and multi-mode heating regulation by integrating an emission-enhanced polymer dispersed liquid crystal (SiO_2 @ PRC PDLC) film and a low-e layer. Year-round HVAC energy simulations show that when applied in different climate zones, LCD smart windows show energy-saving potential not only in northern cities such as Harbin (85.9 $MJ \cdot m^{-2}$), Urumqi (79.9 $MJ \cdot m^{-2}$), and Beijing (78.6 $MJ \cdot m^{-2}$). The energy-saving capacity is prominent in southern cities, including Haikou (154.6 $MJ \cdot m^{-2}$), Shanghai (76.6 $MJ \cdot m^{-2}$), Chongqing (62.7 $MJ \cdot m^{-2}$), and Fuzhou (82.2 $MJ \cdot m^{-2}$). As a result, the device offers substantial advantages in terms of energy savings, with comprehensive energy-saving potential across the climate zone. For the whole building energy consumption, Chen et al. [84] proposed a zero-energy switchable radiant cooler that utilizes different thermal expansion coefficients of the materials to seamlessly switch between cooling and heating modes at any preset temperature point, which greatly reduces the energy consumption in the building in response to the global climate crisis. Moreover, energy efficiency maps for different climate zones were developed, reducing building energy use by 14.3 %, significantly contributing to global energy savings. With the changing environment and climate, DRC as a promising zero-energy thermal management solution for energy-efficient window applications can dynamically regulate the cooling efficiency of a building to maintain thermal comfort with significant energy saving potential.

4 Conclusion and perspective

In summary, after a decade of static to dynamic development of radiant cooling, the latest developments in DRC materials for on-demand radiant cooling and solar heating provide an up-to-date narrative. On-demand stimulation of materials has emerged as one of the most promising approaches for manufacturing switchable thermal management devices. Typically stimulus-responsive DRC materials are discussed, as well as their application to thermochromic smart windows, shutter structures, electrochromic smart windows, and energy-efficient windows, with VO_2 and temperature-responsive as well as humidity-controllable materials considered promising candidates for dynamic optical switching to dynamically regulate radiant refrigeration and solar heating and heat storage to maximize energy use. Research to date has focused on the deployment of DRC materials in urban areas, such as architectural window and roof coatings, and has estimated energy savings by simulating HVAC systems in different regions, providing a guiding value for future DRC development in urban environments. Despite significant efforts in developing new DRC strategies, many challenges remain, along with the potential to realize on-demand switching capabilities and other features. Future directions and potential solutions for DRC building thermal management technologies are presented below.

(1) With commercialization and real-world applications, DRCs face challenges ranging from an adjustable depth of thermal emissivity and solar heating optimization to cost, lifetime and sustainability. These factors place high demands on the optical properties, material processing and extended manufacturing of DRCs. A key issue is that the radiative cooling capacity is affected by external atmospheric factors, especially atmospheric transmittance. On the other hand, the heating capacity is highly dependent on the varying solar radiation. Overcoming this unstable thermal performance is a critical research gap. Durability and service life are equally important for DRC, as they determine the long-term application costs. The above depends greatly on the composition, the material, and the application environment. To meet this challenge, organic polymer materials that are compatible with low-cost and large-scale manufacturing, such as PVDF and polyethyleneimine, can be used [85].

(2) Most conventional static radiative coolers are designed for cooling only, and therefore they are mostly white [86,87] in order to have broadband reflectivity in the visible spectrum to minimize solar absorption. However, in practice, colored coolers are preferable to white coolers under the simultaneous requirements of aesthetics and light pollution reduction, with fluorescence-induced heat gain offset and concomitant efficient solar reflectance achieving both cooling performance and bright colors [88]. Fluorescent and colored colors enhance the absorption of visible light, the top layer absorbs specific visible wavelengths to display specific colors while the bottom layer maximizes reflection to reduce solar heating levels, the integration of structural color modulation capabilities enhances the visual aesthetics of the human experience, the study of colored radiative cooling based on fluorescent materials has been achieved in yellows, greens, reds, and blues, and has demonstrated sub-ambient cooling performance [89]. Color-patterned surfaces [90] DRC will see greater attention.

(3) Transparent roofs and walls are the ones that provide a compelling solution to utilize natural light,

and if placed on outdoor roofs static radiant cooling materials may degrade the thermoregulation performance due to the accumulation of dust and deposits on the surface. The multi-functional superhydrophobic material studied by Huang et al. [91] has a contact angle of 152° while being 6°C cooler than the ambient temperature, and the self-cleaning property can effectively improve its durability and lifetime. The development of scalable DRC coatings capable of adapting to seasonal temperature variations while maintaining the superhydrophobic self-cleaning function is crucial for practical applications, and it is even more challenging to incorporate passive cooling and heating functions with conflicting optical properties in superhydrophobic coatings [92].

(4) Roofs facing directly to the sky are one of the application scenarios where DRC technology is more effective. Optical timber roofs for energy-efficient buildings [93] allow switching between radiant cooling and daytime heating, maintain indoor thermal comfort levels, are potentially energy efficient in all seasons, have a high degree of diffuse reflectance, do not suffer from secondary light pollution caused by direct reflections, and also protect privacy. Ultra-high visible transparency radiative cooling layers with all-day dynamic radiative cooling [94,95] have also attracted much attention, and coating-based DRCs capable of adaptive switching and regulation of temperatures throughout the season provide an important avenue and future research direction for large-scale application on building surfaces. In addition to a single optically modulated thermal management energy efficient window, those with multi-mode multifunctionality in one are more suitable for practical applications, such as radiant cooling, droplet power generation, and defrosting/defogging multifunctionality in one [96], with more energy efficient results. Spectrally dynamically modulated coatings adaptively and continuously derive cooling energy and power generation strategies from the hot sun and the cold universe [97], maximizing the use of environmental energy.

(5) In addition, the future application of DRC to agriculture is also worthy of attention. Crop straw resource utilization is made into cellulose radiation cooling film [98], which has a certain degree of light transmittance, thermal conductivity and high solar reflectance to alleviate heat stress in agriculture and improve yields, and greenhouses, as a representative of the technology of agricultural facilities, have high temperatures as an unfavorable factor limiting the production of greenhouses in summer, and radiation cooling film is used as a cover film for solar greenhouses [99] or soil-cooled mulch films [100,101], with significant energy savings and yield increases, further research and development in this direction is still urgently needed, and future trials will require more crop varieties and different soil types to validate the radiatively cooled mulch performance in the field. In conclusion, the unique advantages of DRC are expected to bring great opportunities in a variety of thermal control applications, and have great potential for future research focuses including solving functionalization problems, achieving temperature self-adaptation, and meeting the needs of different application scenarios.

Abbreviations		*Nomenclature*	
RCM	radiative cooling material	R	reflectivity
DRC	dynamic radiative cooling	E	emissivity
VO_2	vanadium dioxide	T	temperature
TiO_2	titanium dioxide	A	absorption
LWIR	longwave infrared	T_{lum}	light transmittance
NIR	near-infrared radiation	T_{vis}	visible transmittance
IR	infrared radiation	T_{sol}	solar modulation

PDMS	polydimethylsiloxane	ε_{LWIR}	LWIR emissivity
PVDF	polyvinylidene fluoride		
PMMA	polymethylmethacrylate		
FP	Fabry-Perot		
pNIPAM	poly(N-isopropylacrylamide)		
low-e	low emissivity		
PVDF-HFP	Polyvinylidene fluoride - hexafluoropropylene		
UV	ultraviolet		
LAS	light-adaptive shutter		
ITO	indium tin oxide		

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