Universe Scientific Publishing

Clean Energy Science and Technology 2024, 2(1), 144
https://doi.org/10.18686/cest.v2i1.144

Commentary

Development and progress of radiative cooling materials

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CITATION

Jin C, Pei G, Zhao B. Development and progress of radiative cooling materials. Clean Energy Science and Technology. 2024; 2(1): 144. https://doi.org/10.18686/cest.v2i1.144

ARTICLE INFO

Received: 28 January 2024
Accepted: 7 March 2024
Available online: 28 March 2024

Since the industrial era, the extensive use of fossil energy has led to a continuous increase in greenhouse gas emissions, thereby accelerating global warming [1]. Cooling energy consumption represents a significant portion of total energy usage, accounting for approximately 20% of global energy consumption. Therefore, there is an urgent necessity to develop new cooling technologies that are low-energy consumption, highly efficient, and environmentally friendly to meet the growing demand for cooling. Radiative cooling has received widespread attention from scholars due to its characteristics of zero-energy consumption for cooling. Its fundamental principle is that objects on the Earth's surface emit their waste heat to the cold universe via thermal radiation through the high transmittance characteristics of the atmosphere in the "atmospheric window" (8–13 μm) band, thereby achieving passive cooling effects [2–4]. In the early stages, research and exploration of radiative cooling were limited to nighttime conditions, so the primary focus of radiative cooling materials research is the optimization and regulation of infrared emissivity [5]. Compared to nighttime radiative cooling, daytime radiative cooling, which can achieve passive cooling under solar radiation, holds more application value. According to the energy balance (**Figure 1(a)**), the core challenge of daytime radiative cooling is how to achieve synergistic optimization and regulation of low solar absorptivity (generally corresponding to high reflectivity) and high mid-infrared emissivity for radiative coolers.

In recent years, with the continuous advances in micro/nano-optics and manufacturing fields, near/far-field radiation control [6,7] topics have developed rapidly, which has greatly promoted research on daytime radiative cooling. In 2014, Raman et al. [8] developed a multi-layer photonic crystal structure (**Figure 1(b)**) with a solar reflectivity of 97%, which achieves daytime radiative cooling to nearly 5 °C below ambient temperature under direct sunlight for the first time. Considering manufacturing costs and large-scale applications, Zhai et al. [9] developed a metamaterial film that can be fabricated in a large area (**Figure 1(c)**). This film enhanced the infrared emissivity (>0.93) within the "atmospheric window" band by incorporating dielectric particles into the polymer, and achieved 96% solar reflectivity when combined with the silver reflective layer, ultimately reaching a net radiative cooling power of 93 $W \cdot m^{-2}$ during the day. In addition to the above-mentioned radiative cooling materials, a series of high-performance daytime radiative cooling materials have emerged through the exploration of new fabrication technologies and experimentation with different material combinations, such as ultra-white paint (**Figure 1(d)**) [10], hierarchically porous membranes (**Figure 1(e)**) [11], ultra-white wood (**Figure 1(f)**) [12], and composite electrospun film [13]. All of these materials have broadband spectral selectivity and can achieve passive cooling effects below ambient temperatures.

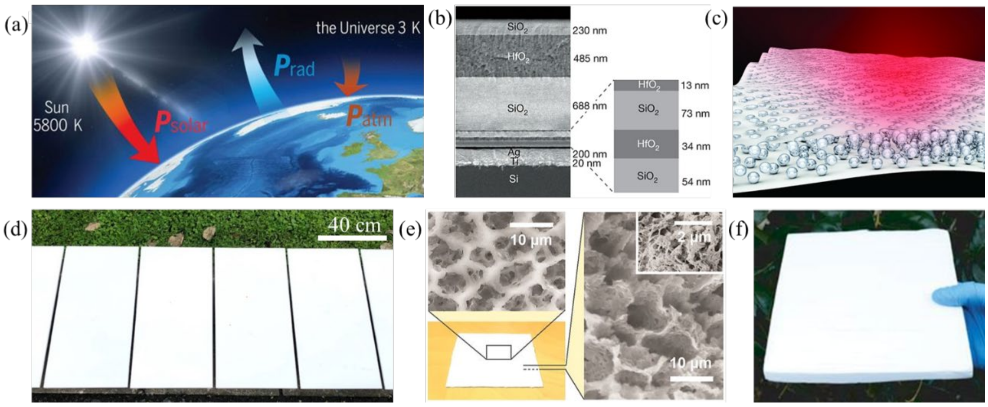

Figure 1. Principle of radiative cooling and high-performance radiative cooling materials. **(a)** Principle diagram of radiative cooling [2], where P_{rad} represents thermal radiation, P_{atm} represents absorbed atmospheric radiation, and P_{solar} represents absorbed solar radiation. **(b)** Multilayer film photonic crystal alternately composed of SiO_2 and HfO_2 [8]. **(c)** Metamaterial film formed by SiO_2 particles incorporated into polymethylpentene matrix [9]. **(d)** Ultra-white coating formed by mixing TiO_2 and fluoropolymer [10]. **(e)** Hierarchically porous membrane prepared by phase inversion method [11]. **(f)** Delignified pressed ultra-white wood [12].

Based on the optimization of spectral selectivity, the development of radiative cooling materials exhibits a diversified trend. This diversification is not only reflected in the rich selection of materials and fabrication technologies, but also in the continuously integrated performance characteristics such as superhydrophobicity, color, and thermal conductivity modulation (**Figure 2**). Superhydrophobic radiative cooling materials [14] are commonly utilized to prevent contaminants from adhering and accumulating on their surfaces, thereby preserving their spectral characteristics. The hydrophobic surface microstructure can be constructed by removing surface materials through etching and template methods, or by adding materials through depositing and layering assembly on the surface, which can make the surface of the radiative cooling material achieve superhydrophobic properties. This feature endows the material with self-cleaning capabilities, requiring only a small amount of water droplets to remove pollutants such as dust, thereby addressing the potential issue of pollution-induced cooling performance degradation of radiative cooling materials in long-term outdoor applications. In addition, considering that traditional radiative cooling materials appear silver or white, monotonous colors cannot fully satisfy aesthetic design requirements, especially in areas with obvious color requirements, such as architecture and automobiles. Therefore, the development of colored radiative cooling materials is also a research trend. For coating-type materials [15], the simplest approach is to add appropriate pigment components to achieve color presentation through narrow-band visible light absorption. For photonic crystal materials, a common method is to design color microstructures to achieve accurate color presentation. Notably, the absorption of solar radiation can also be further optimized to achieve coordinated regulation of low solar absorption and color presentation [16].

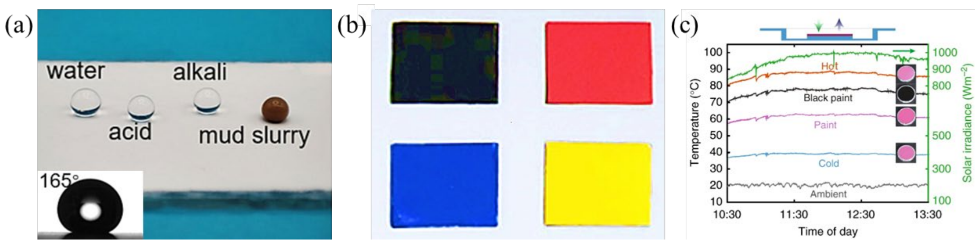

Figure 2. Versatility of radiative cooling materials. **(a)** Super hydrophobic properties. Water, acid, alkali, and mud droplets on the surface of a radiative cooling coating can maintain a large contact angle. The lower left corner shows that the contact angle of water on the surface of the radiative cooling coating is 165° [14]. **(b)** Four double-layer colorful radiative cooling coatings [15], all consisting of a top layer containing colorants and a bottom layer with radiative cooling function. **(c)** The synergetic regulation of color and light absorption characteristics of photonic radiative cooling materials. Through special photonic crystal design, the same color can be achieved, while showing different equivalent solar absorptivity, thereby producing different temperature characteristics [16].

In addition to the above-mentioned functional characteristics, it is also important to consider the weather resistance and service life of materials in the development and application of radiative cooling materials. Weather resistance determines the stability of the material when exposed to harsh environments for extended periods, such as high temperatures, low temperatures, rain erosion, and ultraviolet light, while service life is directly related to the economic and sustainability issues of radiative cooler. Recently, the journal *Science* published three papers on this topic [17–19]. Lin et al. [17] developed a porous alumina radiative cooling ceramic based on the structure of white beetle scales through phase inversion and sintering methods (**Figure 3(a)**), achieving a solar reflectivity of up to 99.6% and a net radiative cooling power of 130 W·m^{-2} at noon, capable of radiative cooling to 1.0 ℃ to 8.8 ℃ below ambient temperature in different regions. Building energy consumption simulation results show that indoor air conditioning can save over 10% of energy annually in extremely hot areas. Zhao et al. [18] fabricate a porous photonic composite, combining a microporous glass framework and dielectric particles (**Figure 3(b)**). This material not only possesses good optical properties but also maintains long-term stability under various working conditions. These ceramic-based materials effectively overcome the limitations of polymer-based and photonic crystal radiative cooling materials in practical applications, further promoting the development of radiative cooling technology.

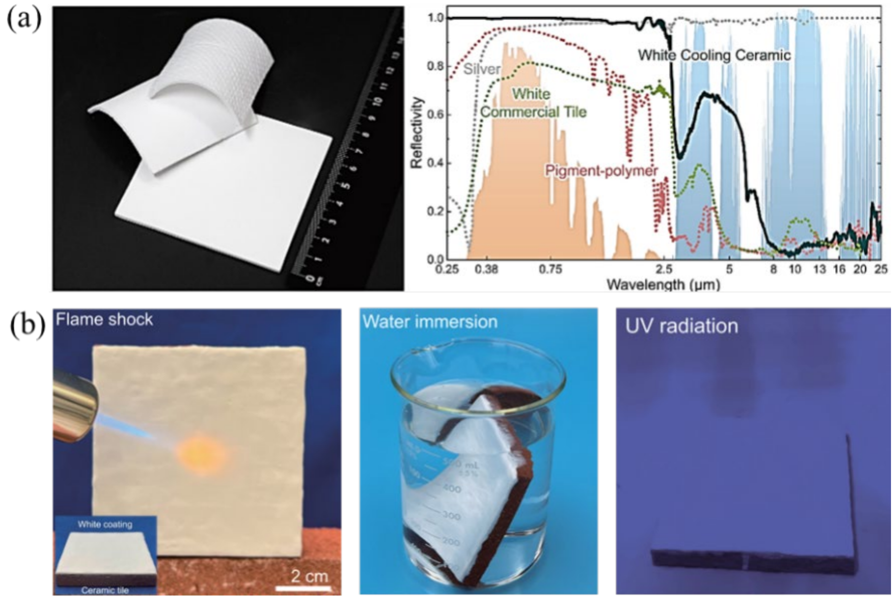

Figure 3. Two ceramic-based radiative cooling materials. **(a)** The left image shows porous alumina ceramics that can be sintered into different shapes according to usage requirements, and the right image shows the spectral properties of cooling ceramics, filler polymers, silver films, and white commercial ceramic tiles [17]. **(b)** Ceramic-based radiative cooling glass coating sintered after solution treatment and its stability test: high-temperature flame shock test, water immersion test, and ultraviolet exposure test [18].

Radiative cooling, as a new renewable energy cooling method, holds significant research value and potential in promoting sustainable energy development and mitigating global warming. Radiative cooling can efficiently emit thermal radiation into cold space and achieve passive cooling without consuming additional energy, displaying significant energy-saving advantages in various application scenarios. For instance, radiative cooling can be used in the building field by applying radiative cooling materials to exterior walls, roofs, and other parts to significantly reduce indoor air temperatures in summer and reduce the load of air conditioning, thereby achieving energy savings and emissions reduction. Additionally, radiative cooling can be applied in the thermal management of vehicles, which benefits stabilizing internal temperatures, improving occupant comfort, and reducing energy consumption. Furthermore, transparent radiative cooling materials can also cool solar panels to improve photovoltaic conversion efficiency. In the future, with breakthroughs made in material durability, stability, system compatibility, energy efficiency, and economic feasibility, the large-scale market application of radiative cooling technology will experience rapid growth.

Acknowledgments: This work was funded by the National Natural Science Foundation of China (52106276, 52130601) and the Young Elite Scientists Sponsorship Program by CAST (2023QNRC001).

Conflict of interest: The authors declare no conflict of interest.

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