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Highlight

Passive isothermal film enabled by synergistic sky radiation energy harvesting and storage

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ABSTRACT

The substantial energy demand associated with active heating, cooling, and ventilation presents a pressing challenge for sustainable development. Conventional systems rely heavily on electricity, contributing to environmental strain and high energy costs. Passive radiative cooling and solar heating offer promising alternatives but are often limited by the spatial-temporal mismatch between energy supply and demand, especially in arid climates with extreme diurnal temperature fluctuations. In a recent *Nature Communications* paper, Kim et al. reported a novel self-switchable passive isothermal film, co-driven by radiative cooling and solar heating, and coupled with sorption thermal energy storage and salt dissolution-based cold storage. This innovative design enables all-day temperature regulation in harsh climate conditions, offering a compelling solution for building energy conservation.

KEYWORDS

radiative cooling, solar heating, water sorption, thermal management, thermal energy storage

Maintaining indoor thermal comfort is crucial, especially in arid regions where diurnal temperature fluctuations often exceed 20 °C due to intense daytime solar radiation and rapid nighttime heat dissipation [1]. While conventional active heating and cooling systems can manage indoor temperatures, they have high energy consumption costs [2]. They create significant electrical power demands for cooling during the day and heating at night [3]. Therefore, developing energy-efficient thermal management strategies that reduce energy use and balance temperature fluctuations is critical.

Passive sky radiative cooling, which leverages the coldness of outer space to facilitate heat exchange, has gained significant attention as an energy-saving technology [4]. Recent advancements in optical films, coatings, photonic crystals, and metamaterials have greatly improved the emissivity in the atmospheric window, leading to remarkable daytime cooling effects [5]. Although radiative cooling effectively addresses daytime cooling needs, it exacerbates nighttime heat loss and cannot meet heating demands under cold conditions. As a result, additional energy-intensive heating systems are often required during cold nights.

We still lack an effective strategy to self-adaptively provide cold and heat by only sky radiative energy without relying on other energy sources. Due to the intense solar radiation in arid regions, passive heating is significantly remarkable during the day. Therefore, how to smartly switch solar heating in cold scenarios and radiative cooling in hot scenarios has recently caught more attention [6], but we are still on the way to perfectly solving the spatial-temporal mismatch between energy supply and demand.

Meanwhile, moisture sorption-based energy harvesting can obtain cold and heat through the sorption and desorption process [7], which has been used for the thermal management of batteries [8] and photovoltaic cells [9], achieving heat scheduling effectively. Therefore, by combining daytime solar heating and moisture adsorption-based energy harvesting technology, heat can be stored during the daytime and released at night to meet nighttime heating needs. With the rapid advancements in sky energy harvesting and storage technologies, integrating radiative cooling, solar heating, and thermal energy storage to achieve zero-energy daytime cooling and nighttime heating appears increasingly feasible.

Recently, Kim et al. proposed an exciting design of coupling sky radiative energy harvesting and thermal energy storage, successfully achieving isothermal temperature throughout the whole day in arid climates (Figs. 1(a) and 1(b)). The authors designed a multilayered film structure with specific functions, enabling the radiative cooling unit and energy storage unit (WD-ER) to collaborate effectively in achieving the isothermal effect.

The radiative cooling unit, comprising polydimethylsiloxane (PDMS) with a diffraction grating and a fused SiO_2/Ti/Ag film, works as a thermal switch to control thermal emission. Meanwhile, the WD-ER unit works as an energy storage

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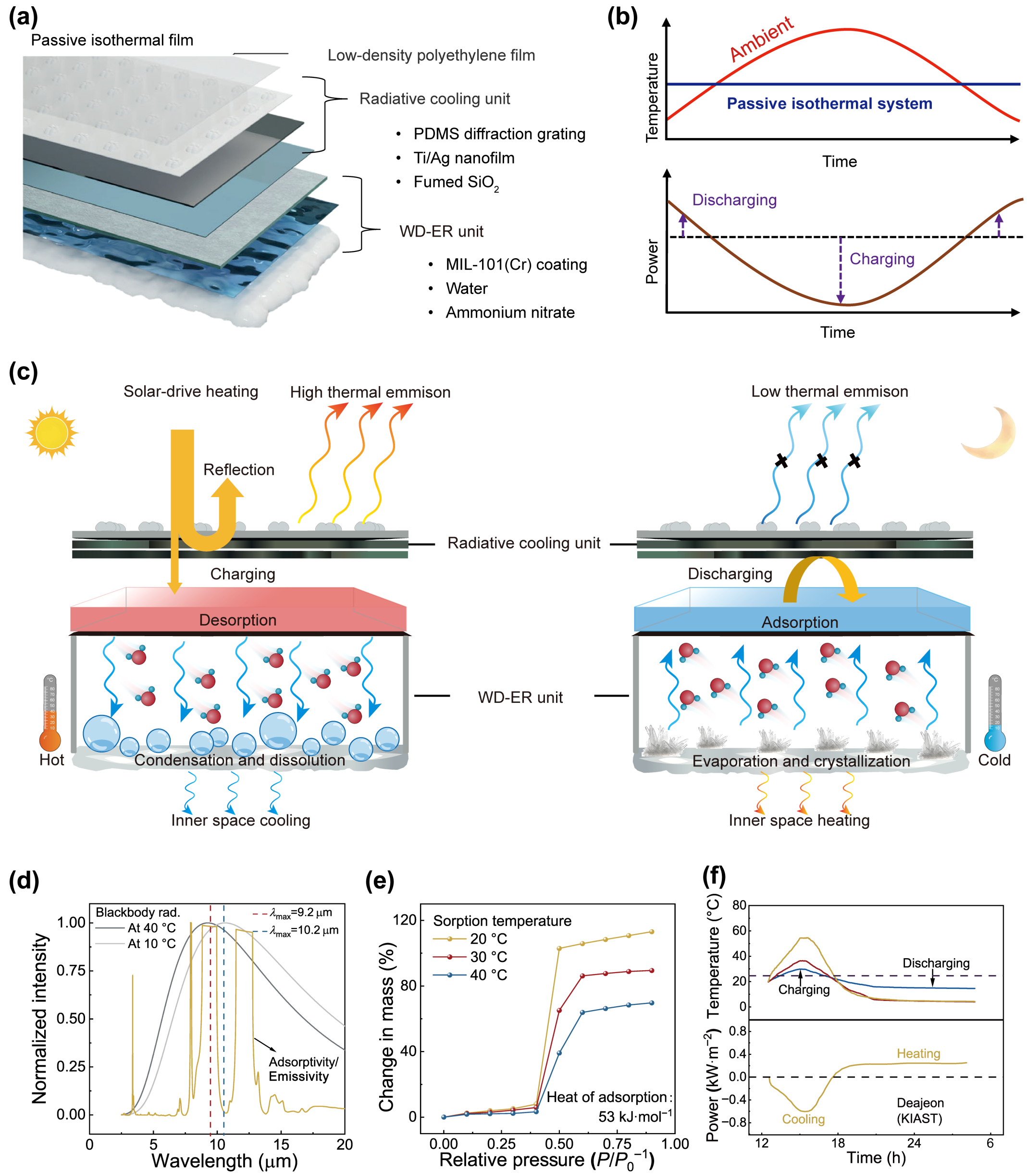

Figure 1 The design, mechanism, and application of the passive isothermal film. (a) Structure illustration of the passive isothermal film. (b) The mechanism of the film's self-switchable temperature regulation. The film absorbs heat for storage at hot ambient temperatures and releases heat at cold ambient temperatures. (c) The working mechanism of the passive isothermal film. (d) The absorptivity/emissivity of the radiative cooling unit in the IR region. (e) Isothermal water adsorption curve of MIL-101(Cr). (f) Outdoor demonstration of the passive isothermal film in Daejeon in KAIST. (a)–(f) Reproduced with permission from Ref. [10], © Kim, S. et al 2024.

component, charging in hot ambient temperatures and discharging in cold ambient temperatures, consisting of chromium(III) terephthalate metal-organic framework (MOF) of MIL-101(Cr), water, and ammonium nitrate. The thermal switch is activated to dissipate heat and store thermal energy in the hot daytime and is deactivated to retain heat and release thermal energy at night. By coupling thermal switching and energy storage functions, the film can maintain a constant temperature under significant diurnal temperature fluctuations in arid climates.

During the hot daytime, the passive isothermal film generates cold energy through two steps: i) radiative-induced cooling driven by high thermal emissivity and solar reflection, ii) an endothermic reaction driven by water desorption and salt dissolution (Fig. 1(c)). The PDMS diffraction grating primarily allows solar irradiation to pass through, achieving an emissivity close to one at 9.2 μm within the temperature range of 30 °C–60 °C due to the constructive interference (Fig. 1(d)), and the SiO_2/Ti/Ag layers reflect sunlight to avoid overheating.

Notably, this approach differs from prior investigations that predominantly pursue high solar reflectance. The device is able to absorb a fraction of incident solar energy in the daytime, which will be released at night to maintain a comfortable, warm condition. Thermal energy can be effectively stored via water desorption from porous materials and dissolution of ammonium nitrate in water. In a word, it is clear that the passive isothermal film exhibits heat absorption (charging) to maintain indoor temperature when heated by part of solar energy.

During the cold nighttime, the system reverses its operation, providing heat to maintain indoor temperature (Fig. 1(c)). The authors leverage the solubility characteristics of ammonium nitrate, whose solubility decreases with the decrease in temperature, inducing the spontaneous crystallization of salt at night. Hence, the crystallization of the ammonium nitrate and water evaporation was initiated at night, followed by the water vapor adsorption of MOFs (Fig. 1(e)).

Since the emissivity converges near 0 at 10.2 μm at low temperature (Fig. 1(d)), the thermal emission of the radiative cooler is suppressed by destructive interference of PDMS diffraction. This design reduces heat loss caused by radiative cooling at night, realizing the function of the thermal radiation switch. Additionally, the WD-ER unit releases thermal energy via water adsorption, supplying heat to the indoor environment. Accordingly, passive isothermal films exhibit heat release (discharging) to maintain indoor temperature when the environmental temperature drops.

To demonstrate the feasibility in real arid climate conditions, Kim et al. conducted field tests in Daejeon at KAIST, achieving near-isothermal conditions within a manageable temperature range (Fig. 1(f)). Their results showed that the passive isothermal film reduced cooling and heating loads by approximately $-1.1\ kW\cdot m^{-2}$ and $0.3\ kW\cdot m^{-2}$, respectively, highlighting its potential for practical development and application.

In contrast to recent open-system designs for sorbent-based thermal management in batteries [7], PV panels [8], and electronics [11, 12], Kim et al. introduced a closed sorption system in this work, where water undergoes evaporation and condensation within a sealed chamber during the sorption and desorption processes. While the closed system has a more complex structure and a lower overall energy density than open systems, it offers several distinct advantages. The sealed environment significantly enhances system reliability, and the pure water vapor atmosphere promotes rapid mass transfer. Moreover, the design facilitates cold energy release during water desorption through an endothermic salt dissolution reaction (ammonium nitrate) in the condensed water. This innovative approach provides greater flexibility for cold energy discharge, overcoming the limitations of conventional systems that rely solely on water evaporation cooling during the energy discharge process.

Overall, the innovative idea in this work will inspire more research in this field. In our opinion, the short-term development goals of this device will still focus on the materials, specifically on how to develop high-performance radiative cooling materials and high-energy-density thermal storage materials, together with deeply elucidating the characteristics of salt dissolution-based cooling. In the long term, to advance from proof-of-concept to practical applications in buildings, more attention should be given to improve the cyclic stability and durability of this sophisticated film device. We envision that future research may focus on smart regulation, where introducing electrochromism, thermochromism, or photochromism into the device could further enhance its adaptability for all-climate and all-season thermal management. With collaborative efforts across materials science, chemistry, and engineering, the practicality and efficiency of the passive isothermal film are expected to be further enhanced, positioning them to play a crucial role in building energy saving.

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Declaration of conflicting interests

The authors declare no conflicting interests regarding the content of this article.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and/or the Supplementary Materials. Additional data related to this paper may be requested from the corresponding author upon request.

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