electrode surface for more efficient and selective CO_2R reaction, and tuning the anodic reaction to achieve carbon circulation with other reusable sources. We also eagerly anticipate that in-depth understanding on these aspects could enlighten further performance improvement, and eventually practical promotion, of the solar-driven CCU system, which we have faith in.

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (NSFC, nos. 22220102002, 22025505, 22209111), the Program of Shanghai Academic/Technology Research Leader (no. 20XD1422200), and the Shanghai Pujiang Program (no. 22PJ1404700).

DECLARATION OF INTERESTS

The authors declare no competing interests.

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Scalable and durable temperature-stabilizing Janus thermal cloak

Jiachen Li[4,5] and Kaichen Dong[1,2,3,*]

Overcooling is a major challenge of conventional passive radiative cooling materials, especially for thermal regulation of houses, electric vehicles, and space objects. In a recent paper published in *Device*, Qiao and co-workers reported a Janus film system that keeps objects cool in hot-weather daytime and warm in cold-weather nighttime.

With the uprising concern of global climate change, the timely demands of passive thermal regulation technologies have been emerging in various application scenarios. As an appealing energy-saving technology, passive radiative cooling boosts heat dissipation in terrestrial objects without any external energy input by emitting excess heat to outer space, which is a natural heat sink at a temperature of ∼3 K. To maximize the cooling efficiency, passive radiative cooling materials are always designed to have minimum absorption in the solar radiation wavelength range (0.25–2.5 μm) and maximum emissivity in the atmospheric window (8–13 μm).[1–3] Despite the great daytime cooling performance of previously reported passive radiative cooling materials, the challenge known as

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https://doi.org/10.1016/j.joule.2023.06.019

"overcooling" works against practical applications that require stabilization of the temperature, such as the heating, ventilating, and air conditioning (HVAC) systems in buildings and the thermal management of battery in electrical vehicles (EVs).

The HVAC system accounts for about 50% of the total energy consumed in buildings and about 20% of the total energy consumption around the world.[4] On the other hand, EVs are promoted by governments with a soaring global market, but the reduced battery efficiency under extreme temperatures is a persistent problem that leads to reduced range between charges and tremendous energy waste. To achieve efficient thermal regulation in all weather conditions, dynamic spectral tuning radiators have been developed in the form of thermochromic coatings, electrochromic tuning, reversible metal deposition, and reversible liquid wetting.[5–9] However, the application of these materials is strongly limited by the cost, scalability, lifetime, or energy waste caused by the external energy input.

In a recent paper published in *Device*, a scalable and durable Janus thermal cloak (JTC) for all-season passive thermal regulation was reported.[10] Qiao and co-workers proposed and experimentally demonstrated a Janus film system that can function at opposite extreme temperatures, such as cooling in hot-weather daytime and keeping warm in cold-weather nighttime. The JTC is made with low-cost, earth-abundant materials such as silica fibers, hexagonal boron nitride (hBN), and aluminum (Al) alloy foil. Moreover, it can be produced with spinning and roll-to-roll processes, making it easy to scale up. The JTC consists of two types of materials, a solar-blocking infrared radiator (SBIRA) facing the sky and a wideband infrared reflector (WIRE) facing the indoor space (Figures 1A–1C).

The SBIRA features near-unity reflectance in the solar range and thermal emittance in the atmospheric window, enabling strong radiative cooling power (Figure 1B). To achieve this, Qiao and co-workers judiciously designed the SBIRA as a quasi-three-dimensional (2.5D) shallow straight-joint weave silica fabric (Figure 1D) covered by hBN nanoflakes.[10] Specifically speaking, surface phonon polariton was formed in silica by the coupling between the optical phonon and the infrared photons, resulting in a Reststrahlen band that only covers part of the atmospheric window. By employing hBN, the strong thermal absorption of the fiber was expanded to the whole atmospheric window, because hBN has hyperbolic phonon polaritons that resonance at wavelengths around the Reststrahlen band of silica. Moreover, the introduction of hBN also increases the solar reflection of SBIRA, since the scattering was enhanced by the higher refractive index of hBN in the solar range. As a result, the solar reflectivity and thermal emissivity are both enhanced using the hBN/silica core-shell fiber (Figure 1E). The experimentally measured solar-weighted reflectivity of SBIRA is 95.6%, which is higher than that of pure silica fiber fabric (89.1%). The infrared thermal emissivity of SBIRA is measured as 96.3%, corresponding to a radiative cooling power of 109.2 $W \cdot m^{-2}$.

The WIRE was made with Al alloy foil for near-unity broadband reflectance across the entire interested optical wavelength range (Figure 1C). At low temperatures, the WIRE can keep the enclosed object warm by reflecting the thermal radiation back. Furthermore, the 2.5D shallow straight-joint weave silica fabric, together with the layers and abundant interfaces in the fabric structure, results in the low out-of-plane thermal diffusivity (0.54 $mm^2 \cdot s^{-1}$) and thermal conductivity (0.083 $W \cdot m^{-1} \cdot K^{-1}$) of JTC. Such outstanding thermal insulation properties are sufficient to effectively maintain a large temperature difference between both sides, which mitigate the temperature variation in the outdoor environment across 24-h periods.

The operational robustness and resilience of the SBIRA were demonstrated with multiple tests. The flammability was tested by heating the SBIRA directly with a butane torch for 20 s and quickly cooling down to sub-ambient temperatures. The durability under cryogenic environments was tested by immersing the sample in liquid nitrogen for 10 min. The structural stability was examined by vibration at 10 gravity acceleration with frequencies ranging from 0 to 2,000 Hz, as well as other deformations such as stretching, flexing, and twisting. The sample was also immersed in strong acid (HCl) and base (NaOH) solutions for 24 h to test the corrosion resistance. After all the tests, the SBIRA maintains structural integrity with nearly unchanged solar reflectivity and infrared thermal emissivity.

The temperature regulation efficacy of the JTC was experimentally tested on EVs. In the experiment, two commercial EVs, one fully covered by the JTC and one uncovered, were parked next to each other at an outdoor site, while the weather information was taken from a weather station and a satellite. The temperatures of the passenger cabins and the battery packs in both EVs were recorded for a time period of 36 h. At hot noon, the temperature of the passenger cabin of the JTC-covered EV was 27.7°C lower than that of the uncovered EV, and 7.8°C lower than the ambient temperature. More importantly, at cold night, the JTC increased the passenger cabin temperature by 5.5°C compared to ambient temperature. Combining the cooling and keeping warm effects, the JTC significantly improves the thermal comfort in both warm and cold climates. The temperature recording of EV

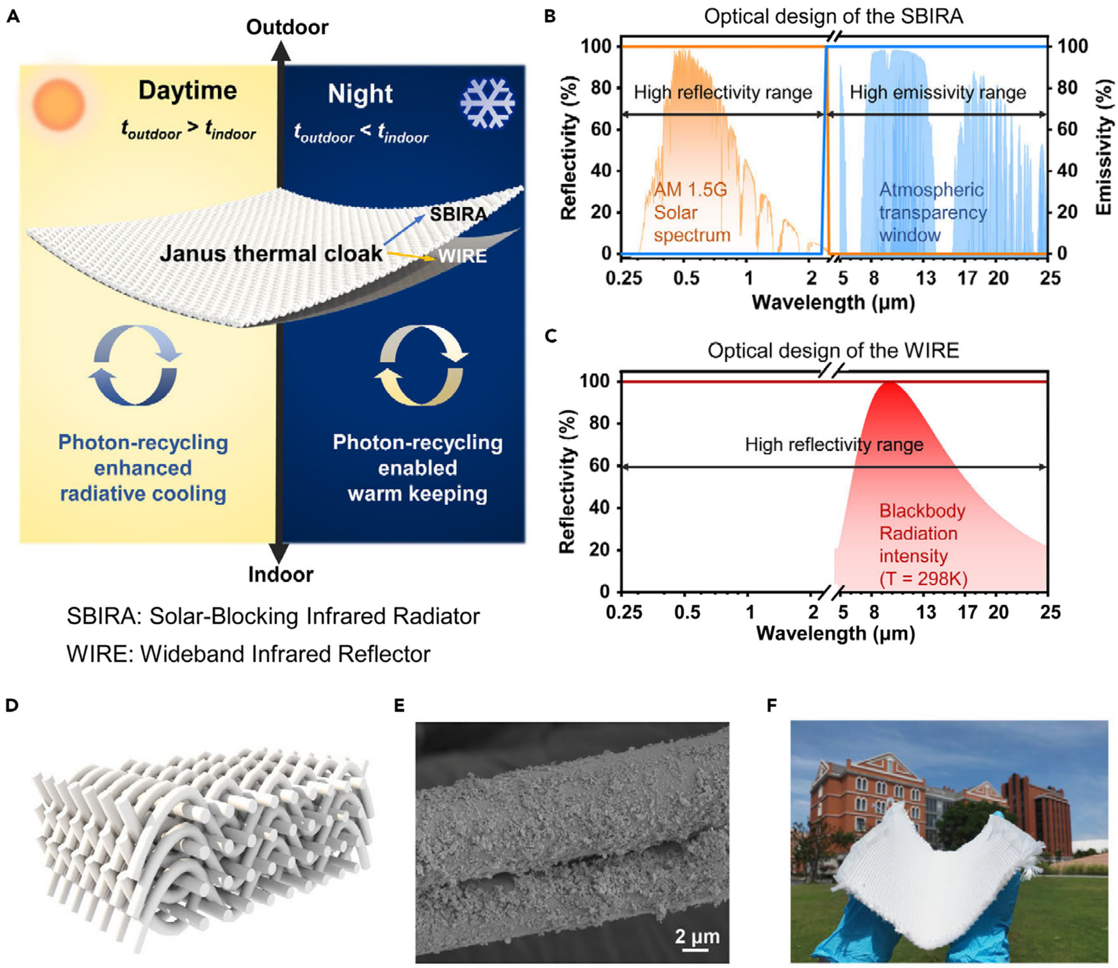

Figure 1. The design and characterization of the Janus thermal cloak (JTC)

(A) Schematic of the JTC and the temperature regulation mechanism.

(B) The optical design of the SBIRA, which is desired to have near-unity reflectance in the solar range and thermal emittance in the atmospheric window.

(C) The optical design of the WIRE, which is desired to have near-unity broadband reflectance in both the solar range and the atmospheric window.

(D) Schematic of the 2.5D shallow straight-joint weave silica fabric.

(E) SEM image of the hBN/silica core-shell fibers.

(F) Photo of a SBIRA sheet.

Adapted from Qiao et al.[10]

battery packs also justifies the fact that the JTC could regulate the battery temperature below 25°C at hot noon and over 0°C at cold night during the experiment time in Shanghai, China. The stabilized battery pack temperature of the EV covered with the JTC can mitigate the thermal aging effect at high temperatures and the energy loss at low temperatures.

We conclude that Qiao and co-workers developed a Janus thermal cloak that realizes both sub-ambient radiative cooling in hot daytime and super-ambient warming in cold nighttime, with low costs, scalability, and excellent durability. Meanwhile, environmental sustainability of the materials remains a future research direction for this work since the silica fiber is related to potential environmental and human health hazards, such as toxicity to wild species, soil contamination, and lung diseases of human. Moreover, considering the aesthetic demands of building and EV owners, the commercialization and application of the JTC would benefit from the development of variations with non-white colors.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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Opportunities for battery aging mode diagnosis of renewable energy storage

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Lithium-ion batteries are key energy storage technologies to promote the global clean energy process, particularly in power grids and electrified transportation. However, complex usage conditions and lack of precise measurement make it difficult for battery health estimation under field applications, especially for aging mode diagnosis. In a recent issue of *Nature Communications*, Dubarry et al. shed light on this issue by investigating the solution based on machine learning and battery digital twins. They achieved aging modes diagnosis of photovoltaics-connected batteries working for 2 years with more than 10,000 degradation paths under different seasons and cloud shading conditions.

The promotion of renewable energy sources has facilitated the large-scale use of lithium-ion batteries in electric vehicles and power grids.[1] However, in addition to the primary charging and discharging reactions, side reactions also take place, causing the batteries to age. This is reflected in the capacity loss and internal resistance increase brought on by the loss of active materials (LAM) and lithium inventory (LLI). Different combinations of aging mechanisms and influencing factors cause different aging patterns in practical applications. Readers seeking a thorough understanding of aging modes and mechanisms and health prognostic techniques can consult the most recent review.[2] The majority of methods work well in lab settings where precise measurements are being made. However, when it comes to field applications, the complex working conditions and poor quality of the obtained data are still challenging for the implementation of existing methods.[3] The lengthy maintenance cycles required by conventional diagnosis techniques result in device downtime, which reduces productivity and efficiency. In addition, various degradation patterns are caused by different combinations of LAM and LLI, and pure estimation of the battery capacity or resistance is a black box that cannot offer important physical insights into aging.[4] The desire for interpretable machine learning methods for battery health prognostics is growing, and the battery digital twin can provide more physical insights for the prognostic methods.[5]

A recent work presented by Dubarry et al.[6] proposed an appropriate approach for the onboard health diagnosis of photovoltaics (PVs)-connected lithium-ion batteries. Three main issues are studied in this work, which are the most focused and urgently required in this area, including the synthetic voltage data generation with battery digital twins, aging mode scale diagnosis of battery health, and machine learning for lithium-ion battery health diagnosis under field applications. A

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https://doi.org/10.1016/j.joule.2023.06.014