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Hierarchical textiles with optical design and fiber nanomanufacturing: breakthrough innovation in personal thermal management

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Abstract

Against the backdrop of intensified urban heat island effect, adopting proactive personal thermal management (PTM) measures is crucial for maintaining health in modern societies. A hierarchical textile with optical design and fiber nanomanufacturing has been recently reported to show efficient radiative cooling ability in all-weather conditions and exhibit outstanding wearability. The above-mentioned study paves the way for its application in PTM in urban heat islands.

Keywords: Urban heat island effect, radiative cooling textiles, hybrid fibrous structure, wearability

As global warming and energy issues intensify, there is a growing demand for low-energy personal thermal management (PTM) approaches. In contrast to air conditioners, which consume high amounts of energy and are not controllable outdoors, high-performance textiles for personal thermal comfort demonstrate increasing potential with their portability and low cost[1]. Among the design strategies for PTM textiles (such as phase change materials, thermally conductive materials, thermal insulators, sweat evaporation and radiative cooling)[2-5], radiative cooling has received widespread attention recently due to its great heat transfer efficiency, ease of regulation and environmental friendliness.

By means of material selection and optical design, radiative cooling textiles are capable of achieving a sub-ambient temperature decrease of more than 6 °C during the daytime by the conduction of thermal radiation into outer space through an atmospheric transmission window (ATW, 8-13 μm) while reflecting sunlight (0.3-2.5 μm)[6-8]. However, when studying daytime radiative cooling materials, researchers tend to ignore the heat gains generated by the heated ground and urban buildings, which has a significant impact on the cooling efficiency of textiles in urban heat island areas. Additionally, radiative cooling textiles typically have broadband emissivity in the mid-infrared (MIR) region and are described by a horizontal geometry. From the perspective of practical application, about 97% of the textiles on the human body are used vertically on standing[9], indicating that large amounts of radiation from the heated ground or urban buildings will be absorbed by the textiles, particularly in urban areas.

To address these problems, the challenge of achieving desirable cooling performance lies in the precise modulation of the spectral selectivity of textiles; that is, emission only dominates in the ATW while suppressing all other parasitic heat from the surroundings[10]. Recently, Wu *et al.* exhibited a hierarchical textile with optical design targeting urban heat islands[11]. Through multilayer structural design and spectral engineering, the textiles exhibited precise spectral selectivity and excellent optical performance in the MIR region.

As shown in Figure 1, a hierarchical textile [spectrally selective hierarchical fabric (SSHF)], comprising an emission layer composed of wool fabric, a reflection layer built of silver nanowires (AgNWs) and a polymethylpentene (PMP) nano-micro hybrid fiber layer, was designed with a solar reflectance of 0.97 and an average emissivity of 0.85 in ATW. With its selective and asymmetric design principles[12], the SSHF efficiently radiated heat into outer space while significantly curbing radiative heat absorption and promoting the loss of body heat from humans.

Owing to its low MIR reflectivity and low MIR transmittance, the AgNW layer effectively shields the environmental thermal radiation within the MIR spectrum from reaching the wool fabric. Therefore, it can significantly curtail all other parasitic heat from the surroundings[13]. Simultaneously, the AgNW layer leverages its high thermal conductivity to facilitate the conduction of heat from the wool fabric to the surface, thereby enhancing the overall radiative cooling effect. Moreover, the mechanical strength and durability of the textiles were enhanced by embedding AgNWs within a layer of poly(ethylene-ran-butylene)-block-polystyrene (SEBS). Additionally, the breathability of SSHF was enhanced by its porous structure. Given that both the PMP fabric and the AgNW layer exhibit isotropic properties, the SSHF demonstrated superior mechanical performance during tensile tests.

The researchers tested the outdoor cooling performance of SSHF via thermal measurement under different conditions. The temperature of SSHF was 12.6 °C lower than the environment during the nighttime and 6.2 °C lower under the solar irradiance of 1,010 $W \cdot m^{-2}$. Even in conditions of high relative humidity (RH), the textile still achieved a sub-ambient temperature reduction of approximately 2.5 °C during the daytime. Furthermore, the cooling effects were assessed using wallpaper to simulate an urban setting, with the temperatures recorded for cotton, rubber, silk, and SSHF being 44.1, 44.6, 42.5, and 40.9 °C, respectively. Beyond its exceptional radiative cooling capabilities, the novel textile also excelled in terms of wearability,

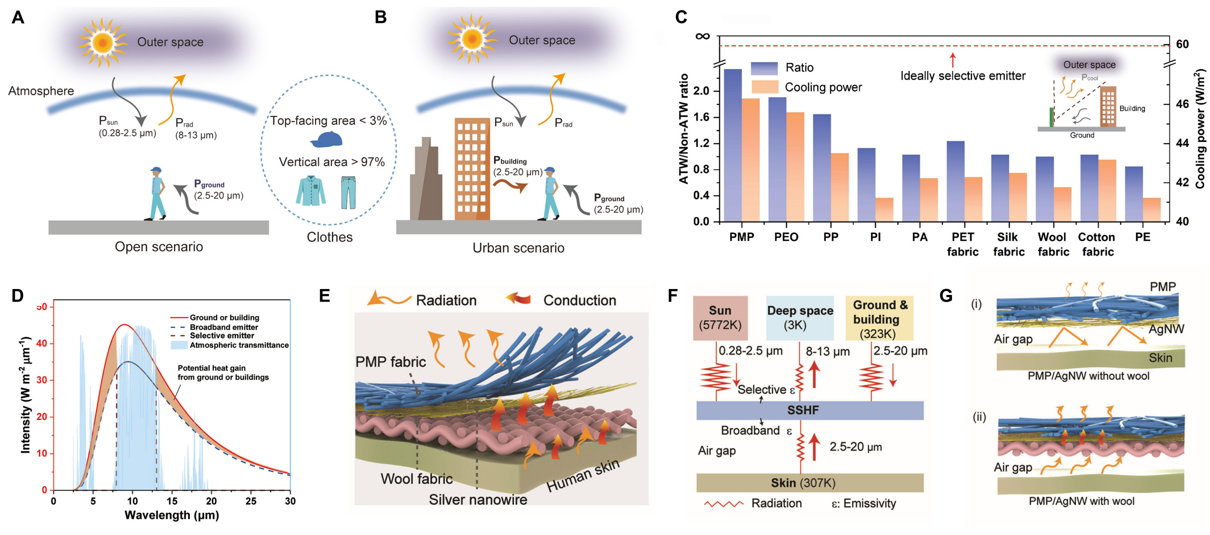

Figure 1. (A and B) Schematic representation of textiles in the (A) open environments and (B) urban environments; (C) The theoretical cooling power and emissivity selective ratio for PMP, common polymer films, and textile materials; (D) The radiated power from a perfect broadband or spectrum-selective textile emitter at T_{skin} of 34 °C and hemispherical irradiances from the terrestrial features at T_{terr} of 50 °C; (E) Structure of the hierarchical SSHF; (F) Radiative heat transfer networks of SSHF in open scenario; (G) Schematic representation of the effect of wool fabrics on the absorption of thermal radiation from human skin. From Ref.[11]. Reprinted with permission from AAAS. PMP: Polymethylpentene; SSHF: spectrally selective hierarchical fabric.

featuring durability, washability, breathability, and robust resistance to mechanical stress and anti-UV aging properties.

In summary, the study by Wu *et al.* provides a strategic approach to textile design, featuring an upper layer that emits heat selectively through the ATW, an AgNW layer for repelling undesired thermal radiation, and a wool base layer that facilitates heat transfer from the skin to the intermediate layer[11]. This design yields a textile that offers passive cooling even in the presence of urban heat islands, while also exhibiting excellent durability, mechanical strength, and washability.

Building upon the existing progress in PTMs [Table 1], it is evident that further improvements in wearability, breathability, flexibility, and meticulous optical engineering are essential to address the complexities of the microclimates between the human body and textiles[14]. To advance this field, several comprehensive strategies for enhancing radiative cooling textiles have been proposed and are discussed in detail:

(1) Great optical properties are fundamental for radiative cooling textile applications; thus, developing materials with high solar spectrum reflectivity and high ATW emissivity is vital.

(2) For composite textiles, the cooling mechanism of the textiles and the interaction of the different materials need to be further investigated explicitly.

(3) The creation of textiles with both color and excellent cooling effects is a topic that needs further exploration.

Table 1. Performance comparison of different PTM materials

Textiles	Solar spectrum reflectivity	Emissivity	Cooling performance	Stability assessment	Ref.
Metafabric (2023)	0.92	0.97	6.5 °C lower than the ambient environment (750 $W \cdot m^{-2}$)	Metafabric presented a high breaking strength of 1.34 MPa at 1,179%	[6]
Metafabric (2024)	0.92	0.83	14.5 °C lower than the ambient environment (800 $W \cdot m^{-2}$)	The mass of the heating and cooling sides was decreased by 2.69% and 1.02% after 100 friction cycles	[7]
Metafabric (2024)	0.88	0.87	2.23 °C lower than the ambient environment (830 $W \cdot m^{-2}$)	The mass reduction of metafabric was by 5.3% after 10,000 friction cycles, while the mass loss was 1.9% after 50 washing cycles	[8]
Metafabric (2023)	0.88	0.94	6.5 °C lower than the temperature of cotton (800 $W \cdot m^{-2}$)	The mass loss was less than 1.7% after 120 cycles, while R_{solar} and ε_{LWIR} remained stable	[14]
RCCF (2024)	0.90	0.98	6.5 °C lower than the temperature of cotton (728 $W \cdot m^{-2}$)	The R_{solar} and ε_{LWIR} remained stable after 20 washing cycles	[17]

PTM: Personal thermal management; RCCF: radiative cooling cellulose-based fabric.

(4) Unidirectional cooling methods may result in excessively low temperatures, compromising human comfort in cold environments; thus, it is essential to explore radiant heat transfer textiles with dual cooling and heating modulation capabilities to address personal radiant heat management in all-weather conditions.

(5) The application of radiative cooling materials to vertical surfaces is a recent research hotspot. Notably, the Ag layer, known for its robust reflection in the visible and near-infrared range, demonstrates an undeniable potential that cannot be overlooked in suppressing non-ATW parasitic heat[15].

(6) The application of wearable electronics via radiative coolers is an important direction in the development of radiative cooling textiles[16].

(7) Further improvements in wearability, breathability, and flexibility are essential; methods such as constructing Janus structures to orient humidity, incorporating PCM for temperature control, and applying abrasion-resistant coatings can be used to enhance their wearability[14,17,18].

DECLARATIONS

Authors' contributions

Wrote and revised the manuscript: Chen, Y., Gao, F., Zhan, X., Zhang, Q.

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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Feng Gao

Feng Gao is an Associate Researcher and Master's Supervisor at the Quzhou Research Institute/School of Chemical Engineering, Zhejiang University. His primary research areas are polymer/inorganic functional micro-nano composite materials and silicon-based interface protective coatings.

As the first or corresponding author, he has published over 30 papers in prestigious international journals, including *Advanced Materials*, *Advanced Functional Materials*, *Small*, *Chemical Engineering Journal*, *Materials Horizons*, and *Carbohydrate Polymers*. His groundbreaking research has led to the granting of 5 authorized invention patents, with an additional 10 patents currently under application. Dr. Gao has been instrumental in several high-impact projects, including sub-projects funded by the National Natural Science Foundation of China, Zhejiang Provincial Natural Science Foundation, and Key R&D Program. His exceptional contributions have earned him multiple accolades, including recognition in the Quzhou High Level Talent Plan, Quzhou "Nankong Elite" Innovation and Entrepreneurship Talent Award, China Textile Industry Federation Science and Technology Progress First Prize, Light Industry Federation Technology Invention First Prize, and National Innovation and Entrepreneurship Excellent Postdoctoral Fellow award.

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Qinghua Zhang is a distinguished professor at the School of Chemical Engineering, Zhejiang University, where he also serves as a doctoral advisor. Additionally, he holds leadership roles as the Deputy Director of the Joint Institute of Chemical Reaction Engineering and the Director of the New Energy Materials Research Institute at the Zhejiang University Quzhou Research Institute. His exceptional contributions to research and academia have earned him recognition as a leading talent under Zhejiang University's Long-term Basic Research Plan, the Zhejiang Province Special Talent Support Program (Ten Thousand Talents Program), and the Jiangxi Province "Double Thousand Plan" Innovation and Entrepreneurship Leading Talent Program. Professor Zhang's primary research focuses on the design, preparation, and application of interface functional materials and new energy materials. He has developed a series of novel biomimetic interface functional materials and lithium battery materials, and established the relationship between the surface properties of interface functional materials and their structure and chemical composition. With over 200 publications in globally renowned journals, including *Nature Water*, *Nature Communications*, *Angewandte Chemie*, *Journal of the American Chemical Society*, *AIChE Journal*, *Advanced Materials*, *Advanced Functional Materials*, *etc.*, Professor Zhang's research has been widely acclaimed. His work has garnered more than 6,500 citations, with an impressive H-index of 52.

In addition to his academic accomplishments, Professor Zhang holds more than 70 authorized invention patents, including multiple PCT patents. His innovations have been recognized with numerous prestigious awards, including the First Prize of the Jiangsu Provincial Science and Technology Award and the First Prize of the China Chemical Society Technology Invention Award. Notably, he has also received four accolades for patent achievements, including the China Patent Excellence Award and the Geneva International Invention Award.