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Perspective

Advanced Textiles for Personal Thermal Management and Energy

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To realize improved human body thermal comfort and reduce energy consumption on building heating and cooling, personal thermal management emphasizing energy management of human body and its local environment is emerging as a promising solution. Advanced textiles are being invented and developed to effectively regulate heat exchange between human body and its surroundings. Here, recent progress on advanced textiles for personal thermal management and its significance in energy efficiency are reviewed. We will mainly discuss textiles with engineered properties targeting at passively controlling human body heat dissipation routes, the active warming and/or cooling textiles, and the responsive textiles that offer adaptive personal thermal management ability according to the external stimuli. An outlook discussing important challenges and opportunities in this field is also presented.

Context & Scale

As the interface between human body and ambient, textiles play an important role in heat exchange between body and environment. However, for a long period of time, textile research on personal thermal management gained insufficient attention. In recent years, we are glad to witness advanced textiles that are designed to better control human body heat dissipation; these are emerging as an effective and energy-efficient way to achieve human body thermal comfort and reduce building energy consumption. This perspective discusses the recent progress in advanced textiles for personal thermal management, mainly among the academic community. The material design, textile performance, fundamental principles, and impact in energy are included. The perspectives on challenges, future directions, and guidance of advanced textiles for personal thermal management are presented.

INTRODUCTION

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment, which means that a person feels neither too cold nor too warm.[1] It is significant to maintain thermal comfort because thermal conditions of human body are crucial for physical and psychological health and even potentially life-threatening for humans if the core body temperature reaches conditions of hyperthermia, above 37.5°C–38.3°C or hypothermia below 35.0°C.[2,3] In addition, lack of thermal comfort may cause reduction in industrial labor productivity and supply, eventually resulting in decline of economy.[4,5] Maintaining human body thermal comfort wisely is important for efficient human body energy management. Furthermore, regulating human body thermal comfort wisely shows a prominent impact on saving energy consumption of building heating, ventilation, and air conditioning (HVAC) systems, which accounts for about 40% of total building energy consumption.[6] For instance, to maintain human body thermal comfort in a 2°C expanded heating/ or cooling set-point range can realize approximately 20% of HVAC energy saving.[7–9] Therefore, to develop new strategies and solutions for improved human body thermal comfort control is essential and promising.

Human body generates metabolic heat and dissipates heat to ambient all the time so as to keep homeostasis.[10] Generally, four different pathways of heat dissipation contribute to human body thermal neutrality: radiation, conduction, convection, and evaporation (Figure 1).[11] These four routes work together to realize stable body temperature, but their importance varies in diverse circumstances.[12,13] For example, human body heat loss through radiation in the mid-infrared (IR) wavelength range occupies the major part of the total heat loss when people are still in typical indoor environments,[11] whereas human body loses most of the heat via evaporation of sweat during intense exercise.[14]

Focusing on the human body and its local environment, personal thermal management based on advanced textiles is emerging as an effective and energy-efficient way to achieve human body thermal comfort.[15–20] As is all known, textile is indispensable in our daily life. To some extent, the evolution of textile usually accompanies the development of human society civilization.[21,22] Textiles not only provide body with shroud and aesthetic enjoyment but more importantly are essential for human body thermal comfort.[23,24] The integration of state-of-the-art textiles with electronics is underway.[25–27] As the interface between human body and ambient, textiles play an important role in heat exchange between the body and environment. However, for a long period of time, textile research on personal thermal management attracted insufficient attention. Fortunately, in recent years, advanced textiles that are designed to better control heat dissipation in human body are emerging, whether in industrial or academic communities (Figure 2A).

A great number of technical textile types and brands for personal thermal management have been exploited, such as Omni-heat (Columbia), CoolMax (Dupont), AeroReact (Nike), Dri-FIT (Nike), Verycool (Yonex), HeatGear (Under Armour), ForMotion (Adidas), Gore-Tex, etc. They are designed to offer improved thermal comfort for human body via various routes for assorted scenarios, such as material innovation, fiber engineering, advanced finishing technique, new structure design, and garment shape development. For instance, CoolMax utilizes a unique four-channel shape fibers to enhance the moisture transport from human body to the ambient environment; AeroReact is reported to be a moisture-responsive textile that can alter its pore size to change breathability; Verycool provides cooler feeling for human body by using xylitol in its fabric; Omni-heat is designed to reflect body heat utilizing the little silver dots inside the textile; ForMotion is capable of assisting human body control and enhance muscle activity because of its special usage of a combination of compression fabrics in sport-specific body locations; double face knitted fabrics take advantage of the difference in hydrophily of the two layers to realize improved one-way sweat transport capability.

In this article, we will review the recent progress in advanced textiles for personal thermal management portraying the latest scientific accomplishments in this field, mainly among the academic community. Passive textiles for both warming and cooling purposes via controlling human body heat radiation and conduction will be discussed. Such kinds of textiles generally utilize advanced material design and development to achieve enhancement or reduction of human body heat transport through the textiles, without consuming extra energy. Meanwhile, discussion about active warming and/or cooling textiles that employ energy conversion elements to provide additional cooling and/or warming energy will also be included. Furthermore, this perspective will encompass the smart responsive textiles with phase-change materials (PCMs) and with smart dynamic structure changes (Figure 2B). Due to the limited space, we will not discuss the moisture management textiles specially in this article. We will review the material design and performance of these textiles, emphasize on their fundamental principles, and discuss their impact in energy. Last but not least, a summary and perspective in this field will be provided.

ADVANCED TEXTILES WITH REGULATED THERMAL RADIATION PROPERTIES

Human skin is an excellent IR emitter (emissivity = 0.98), hence human body emits thermal radiation in the mid-IR wavelength range of mainly 7–14 μm with a peak intensity at 9.5 μm.[28] Radiation plays an indispensable role in human body heat dissipation, contributing to more than 50% of total heat loss in typical indoor scenarios,

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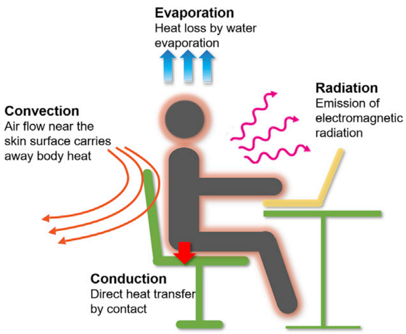

Figure 1. Heat Dissipation Routes of the Human Body

The human body generally dissipates heat via four routes: radiation, conduction, convection, and evaporation.

such as offices.[11] However, traditional textiles ignore the radiation part and are not designed for controlling the thermal radiation from human body. For novel radiative cooling/warming textiles, the IR optical property of textiles should be designed in different directions for warming and cooling purposes. The interplay of energy exchange by thermal radiation can be characterized by $\varepsilon + \tau + \rho = 1$, based on Kirchhoff's law of thermal radiation, where ε presents emissivity, τ is the spectral transmission component, and ρ refers to the spectral reflectance component. To control human body radiation via advanced textiles is, in other words, to control the optical properties of textiles and then thermal radiation exchange between human body and the textiles. In order to realize cooling effect, it is ideal for human body radiation to be dissipated as much as possible, so a mid-IR transparent textile is desired ($\tau = 1$). The next best solution is to achieve a highly emissive textile ($\varepsilon = 1$) that can greatly emit human body radiation. Both methods can effectively accelerate heat loss via radiation. On the other hand, a mid-IR reflective one ($\rho = 1$) is suitable for warming purpose. In both cooling and warming cases, textiles need to be opaque in the visible light wavelength range for practical necessity.

Mid-IR Transparent Radiative Cooling Textiles

For cooling purpose, Tong et al. theoretically designed an IR-transparent visibly opaque fabric (ITVOF) utilizing synthetic polyethylene fibers that are intrinsically low IR-absorptive. These fibers were structured to minimize IR reflection via weak Rayleigh scattering while maintaining visible opaqueness via strong Mie scattering.[19] The first radiative cooling textile based on nanoporous polyethylene (NanoPE) was experimentally demonstrated by Hsu et al. (Figure 3A).[29] The interconnected pores that are 50–1,000 nm in diameter are embedded in the polyethylene film. The pores scatter visible light strongly via Mie scattering and render the NanoPE film opaque to human eyes because the pore size range is comparable with the wavelength range of visible light (400–700 nm), while the intrinsic mid-IR transparency of polyethylene is maintained due to the mismatch between mid-IR light wavelength range and the pore size range.[29] The tactful combination of intrinsic mid-IR transparent material and nanoscale pores for selectively spectral control make NanoPE a promising material for human body radiative cooling and building cooling energy saving, even though the nonwoven properties of the film are not ideal for practical wearing.

To go a step further, Peng et al. reported the large-scale extrusion of uniform and continuous NanoPE microfibers with cotton-like softness for industrial fabric production (Figures 3B and 3C) and first demonstrated the radiative cooling fabric knitted and woven with NanoPE microfibers (Figure 3D).[30] The knitted/woven fabric containing NanoPE microfibers exhibit a decent radiative cooling effect (~2.3°C lower

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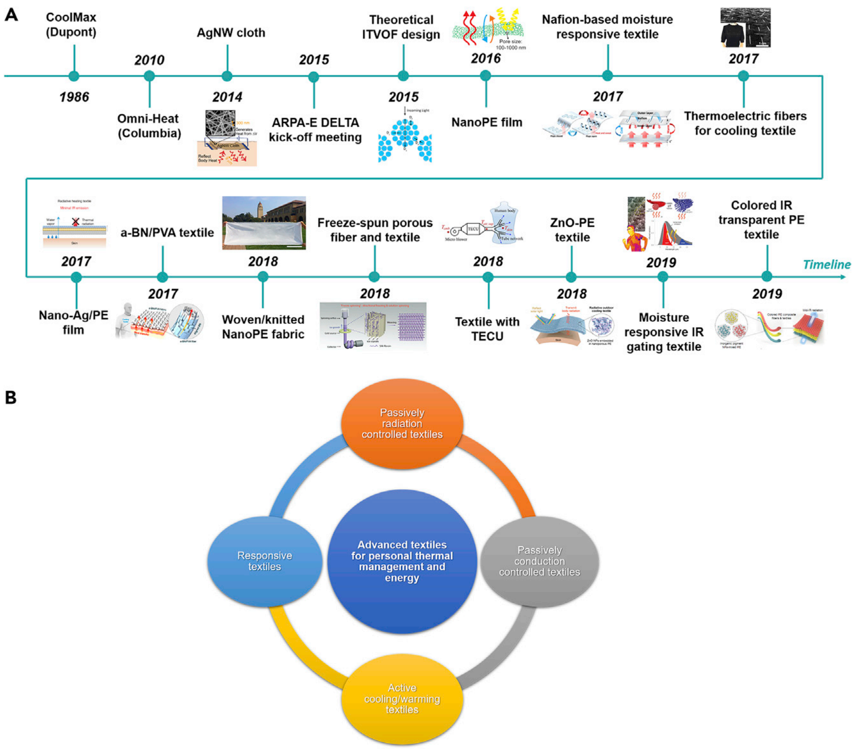

Figure 2. Development of Advanced Textiles for Personal Thermal Management and the Design Strategies

(A) Roadmap of advanced textiles for personal thermal management and energy.

(B) A diagram showing the different approaches reviewed in this article.

skin temperature than conventional cotton fabric), together with improved wearability and durability.[30] The set-point increase of indoor temperature corresponds to the decrease of skin temperature, indicating that people who wear the NanoPE fabric can increase the set point by 2.3°C but still feel as thermally comfortable as the ones who wear cotton clothes. The 2.3°C set-point decrease can help save about 20.1% of the building cooling energy. Furthermore, inorganic nanoparticles as coloring components were utilized to realize scalable colored, mid-IR transparent textiles.[31]

Based on the intrinsic mid-IR transparency of polyethylene, researchers are also developing composite textiles combing polyethylene and other conventional textile materials to achieve better wearability, such as hydrophilicity and mechanical strength.[32] In addition to utilizing the intrinsic mid-IR transparent materials such as polyethylene, photonic structure design approach can help realize desired IR transparency based on blending of IR-opaque fibers and largely IR-transparent fibers.[33,34] For instance, Catrysse et al. theoretically designed a photonic structure textile for localized thermal cooling using cotton and nylon fibers.[35] From their calculation, the textile containing up to one-third cotton and two-thirds nylon allows 2.2°C cooling ability compared with cotton-only textiles, which can result in obvious energy saving.[35]

Mid-IR Emissive Radiative Cooling Textiles

Apart from mid-IR transparent textiles for radiative cooling, tuning the surface emissivity of textiles has also been demonstrated as an efficient route to realize thermal regulation.[36] It is worthwhile to mention that the emissivity of the outer surface of

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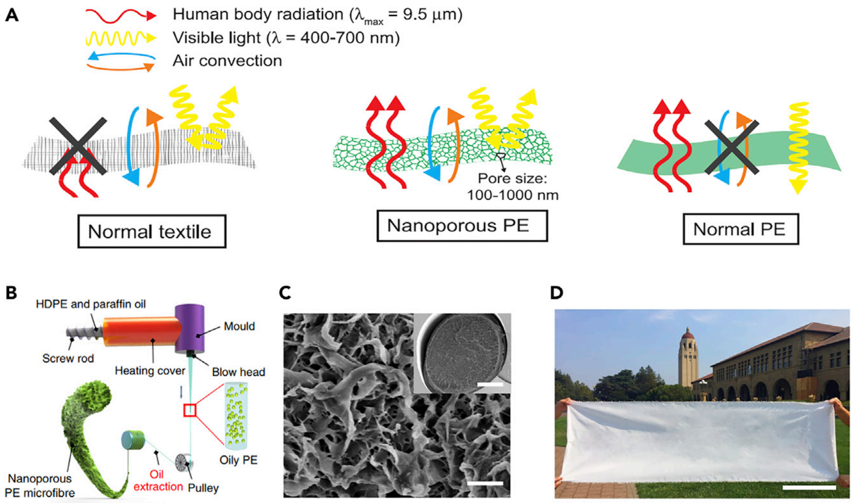

Figure 3. Mid-IR Transparent Textiles Based on NanoPE for Radiative Cooling

(A) Schematics of comparison among normal textile, NanoPE, and normal PE. Only NanoPE satisfies IR transparency and visible light opacity at the same time. Adapted from Hsu et al.[29] with permission from the American Association for the Advancement of Science.

(B) A schematic diagram of the manufacturing process for the NanoPE microfiber.

(C) Scanning electron microscope (SEM) image of the cross-section view of a nanoPE microfiber. Scale bar, 2 μm. The inset shows a lower-magnification SEM image of the well-preserved cross section of the microfiber. Scale bar, 50 μm.

(D) A photograph of a large woven NanoPE fabric. Scale bar, 0.35 m.

(B–D) Adapted from Peng et al.[30] with permission from Nature Publishing Group.

textiles matters more than the inner one because radiation is more dominant in heat exchange between textile outer surface and ambient than that between human body and textile inner surface.[37] A dual-mode textile was shown to perform both passive radiative cooling and warming utilizing the very different emissivity of its two surfaces. The surface with high emissivity facing outside brings about 3.1°C radiative cooling effect, whereas the low-emissivity surface facing outside leads to 3.4°C radiative warming effect. An expansion of thermal comfort zone by 6.5°C was demonstrated.[36] Textiles showing improved wearability based on this concept will be attractive for drastic temperature change cases in practical usage.

Solar-Reflecting Radiative Cooling Textiles

Controlling the mid-IR thermal radiation from human body is adequate for indoor situations because there is almost no other intense thermal radiation source. However, avoiding thermal radiation energy from sun in outdoor environments becomes highly important as well for radiative cooling purpose.[38–40] Solar spectrum is mainly composed of visible light (400–700 nm) and near IR (NIR) light (700–2,500 nm), which together constitute around 93.4% of solar irradiance (~1,000 W/m^2).[41] To cut off the heat energy gain from sun is, in other words, to cut off the NIR light and visible light passing through our clothes.

Various types of reflective materials including transition metals (e.g., Ag, Ti, and Al), inorganic or organic compounds (e.g., TiO_2, Fe_2CO_3, antimony doped tin oxide, and AZO pigments) and natural compounds (e.g., chlorophyll) have been used to develop cool coatings on textiles to increase sunlight reflection.[42–44] It is shown that coating of irregular-shaped TiO_2 particles with size of 293–618 nm in a mixture of anatase and rutile phase on a cotton fabric can realize 3.91°C lower surface

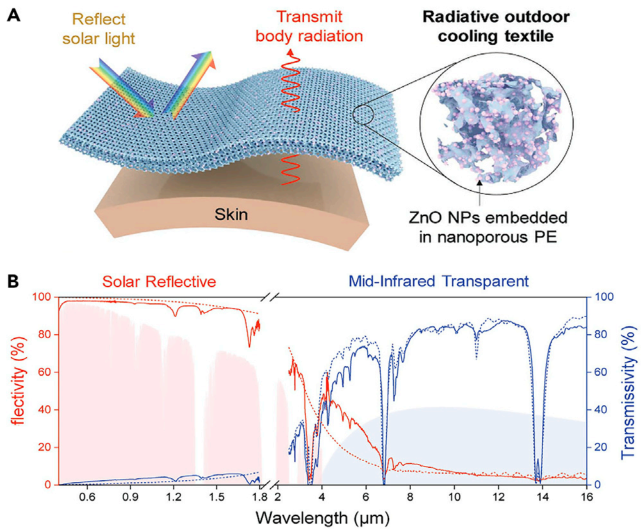

Figure 4. Spectrally Selective Nanocomposite Textile Utilizing Zinc Oxide Nanoparticle-Embedded NanoPE for Outdoor Personal Cooling

(A) Schematic of the ZnO nanoparticle-embedded NanoPE textile. Its spectrum was designed to be transparent for human body thermal radiation and reflective for sunlight.

(B) Reflectivity and transmissivity spectra of ZnO-PE from ultraviolet to mid-IR range (0.3–16 μm) from measurement (solid lines) and simulation (dashed lines). The shaded areas show the AM 1.5 G solar spectrum (pink) and human body radiation spectrum (blue).

(A and B) Adapted from Cai et al.[47] with permission from Wiley-VCH.

temperature.[43] Nanostructured materials and photonic structure were reported to improve visible reflectance as well.[45,46]

It is more effective for realizing prominent cooling effect if both the whole solar spectrum and human body radiation spectrum can be manipulated. The textile that is capable of reflecting visible and NIR light greatly while maintaining the mid-IR transparency for human body radiation is promising. Cai et al. proposed a novel spectrally selective nanocomposite textile for radiative outdoor cooling using zinc oxide nanoparticle-embedded NanoPE (ZnO-PE) (Figure 4A).[47] By reflecting more than 90% of solar irradiance and selectively transmitting out human body thermal radiation (Figure 4B), this textile can enable simulated skin to avoid overheating by 5°C–13°C compared with normal textile such as cotton under peak daylight condition.[47] The authors also demonstrated the feasibility of manufacturing ZnO-PE fibers that can be potentially knitted/woven into practical textiles with improved wearability.[47]

Low-Mid-IR Emissive Radiative-Warming Textiles

For radiative-warming purposes, textiles with engineered high-mid-IR reflectance are in demand. Textiles made of pure metallic fibers were reported by Larciprete et al.[48] Even though good thermal reflection was realized, this type of textile is heavy, stiff, and fragile. Metal-polymer composite yarns (e.g., core spun yarns and blended yarns) were also reported for IR-reflective textiles with improved flexibility.[49] In addition, surface modification on conventional textiles using metallic nanomaterials were proposed to endow the textile with high IR reflectance.[18,37,50,51] Hsu et al. demonstrated a silver nanowire embedded cloth (AgNW cloth) for personal thermal management (Figure 5A).[18] The metallic nanowires form a conductive network that can not only reflect human body IR radiation but also allows Joule heating to complement the passive insulation.[18] However, perhaps because of roughness of the cloth and the insufficient connection between nanowires, the mid-IR

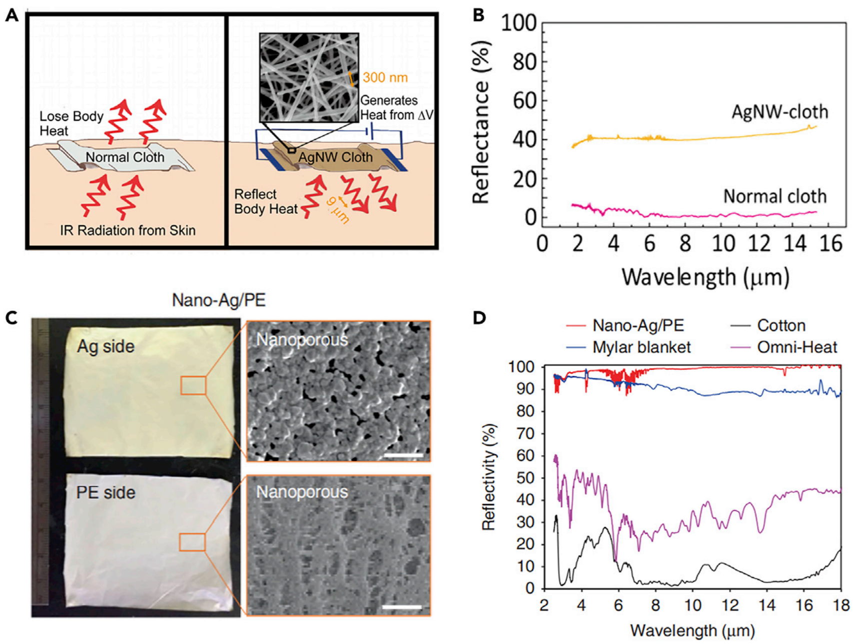

Figure 5. Radiative-Warming Textiles with Enhanced IR Reflectance

(A) Concept illustration of Ag nanowire cloth with thermal radiation insulation and active warming.
(B) Reflectance measurement of normal cloth and AgNW cloth.
(A and B) Adapted from Hsu et al.[18] with permission from American Chemical Society.
(C) Photographs and SEM images of the silver side and PE side of Nano-Ag/PE. Scale bar, 1 μm.
(D) Measured total Fourier transform infrared (FTIR) spectroscopy reflectance of the Ag side of Nano-Ag/PE, cotton, Mylar blanket, and Omni-Heat.
(C and D) Adapted from Cai et al.[37] with permission from Nature Publishing Group.

reflectance was not very high (Figure 5B). Later research reported nanoPE film coated with nanostructured metal can gain further enhanced mid-IR reflectance and improved passive warming effect.[15,36,37] Cai et al. developed nanoporous silver textiles based on NanoPE (Nano-Ag/PE) with strong reflectivity in the inner surface to reflect human body thermal radiation and strongly suppressed thermal emissivity of the outer surface to minimize the radiative heat loss from the textile (Figures 5C and 5D).[37] This kind of textile can enable 7.1°C decrease of the set point compared with normal textile, which illustrated great thermal insulation property. The low-emissivity layer added via surface modification should be considered if it is tough and durable enough during the use process. Compared with exposure on the outer surface, making the modified surface an interlayer may be a better choice. In addition to the surface modification strategy, Hazarika et al. demonstrated composites based on woven Kevlar fiber, metallic nanowires, reduced graphene oxide (rGO), and polydimethylsiloxane (PDMS), which show high IR reflectivity and localized warming effect.[52,53]

ADVANCED TEXTILES WITH REGULATED HEAT CONDUCTION PROPERTIES

As one of the main pathways for human body heat dissipation, heat conduction control is worthwhile to be studied in order to enhance or reduce human body heat loss for effective personal thermal management. For IR-opaque textiles, at the interface between human body skin and the inner surface of textiles, heat conduction instead of heat radiation is the dominant heat-transport route. Moreover, heat conduction is the only way of heat dissipation inside the textile itself. Therefore, designing and developing novel textiles with regulated heat conduction properties is valuable for efficient personal thermal management. The design principle for advanced textiles that are engineered for conductive cooling purpose is to increase the thermal conductivity of textiles as much as possible. On the contrary, textiles for conductive warming purpose ought to be highly thermal insulative.

Conductive Cooling Textiles with Enhanced Thermal Conductivity

One way to introduce conductive cooling effect to textiles is to apply thermally conductive materials as coatings on the fiber surface.[54–58] Suitable materials should be able to offer great thermal conductivity and do not show adverse effect on radiative heat dissipation at the same time. Carbon-based materials, such as multi-walled carbon nanotubes (MWCNTs),[56] single-walled carbon nanotubes (SWCNTs),[57] and graphene[58] have been utilized for thermally conductive coating for textiles. These materials exhibit both high thermal conductivity and emissivity. Applying a resin coating containing MWCNTs onto the surface of cotton fabrics was reported to lead to obvious improvement of the thermal conductivity. Only 11.1% of MWCNTs in the coating increases the thermal conductivity of cotton fabrics by up to 78%. Furthermore, MWCNT content increase to 50% enhanced the thermal conductivity by 1.5 times.[56] Coated fabric that had 50% MWCNTs in the coating layer was demonstrated a 3.9°C lower equilibrium surface temperature than the untreated fabric on contact with a 50°C surface.[56]

In addition, thermally conductive materials can be embedded into the fiber structures of textiles to offer improved heat conduction for human body. Compared with the surface coating method, the composite fibers provide a more durable alternative for human body conductive cooling.[59–61] Gao et al. reported a personal thermal regulated textile using thermally conductive and highly aligned boron nitride (BN)/poly (vinyl alcohol) (PVA) composite (a-BN/PVA) fibers to improve the thermal transport properties of textiles for personal cooling (Figure 6A).[59] The enhanced thermal conductivity of a BN/PVA composite fibers can transport the heat generated by human body to the outer surface of textile more efficiently, thus realizing conductive cooling effect and personal energy management (Figure 6B).

Conductive Warming Textiles with Reduced Thermal Conductivity

To achieve good thermal insulation for textiles, one popular method is to trap a mass of air into the textile to increase its thermal resistance, such as the down jacket.[63] In order to store plenty of air in the fabric, one way is to mimic the natural property of down fibers. A commercial product of 3M, called Thinsulate, was invented for thermal insulation clothing. The 15-μm-diameter fibers are much thinner than normal fibers, and thus, heat flow can be effectively reduced compared to conventional textiles.[64] Besides, shaped fibers with special cross-section shapes have been recognized as a useful strategy to hold more air. In contrast to round fibers, profiled fibers tend to trap more air inside the textiles because they cannot be packed as compact as the round ones.[65]

In addition to holding air among the fibers serving as heat dissipation barrier, hollow fibers can further prevent heat loss efficiently. The fibers with high porosity can effectively trap enough air inside fiber itself and meanwhile reduce the weight of the textile.[62,66] Recently, Cui et al. demonstrated the continuous and large-scale fabrication of fibers with aligned porous structure, mimicking polar bear hairs via a "freeze-spinning" technique (Figure 6C).[62] The fibers produced through this method possessed around 87% porosity and had axially aligned porous structures, which

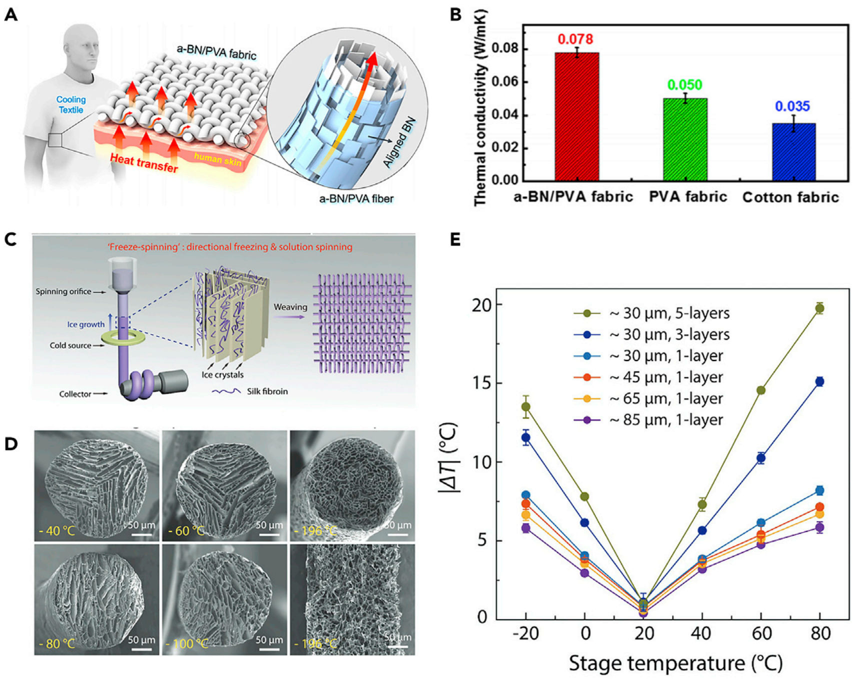

Figure 6. Advanced Textiles with Enhanced Thermal Conductivity and Thermal Insulation Property

(A) Schematic illustration of the a-BN/PVA thermal regulation textile. The embedment of the well-aligned and interconnected BNNSs in the PVA polymer matrix improves thermal conductivity of the textile.

(B) Measured thermal conductivities of the cotton, PVA fabric, and a-BN/PVA fabrics.

(A and B) Adapted from Gao et al.[59] with permission from American Chemical Society.

(C) Schematic illustration of the "freeze-spinning" technique. Highly porous biomimetic fibers with aligned porous structure was realized by combining "directional freezing" with "solution spinning" techniques.

(D) Radial cross-sectional SEM images showing different porous structures of biomimetic fibers prepared at different freezing temperatures: −40°C, −60°C, −80°C, and −100°C, respectively.

(E) Temperature difference (|ΔT|) between the textile surface and the stage against the stage temperature for different textiles (various pore size and the number of layers).

(D and E) Adapted from Cui et al.[62] with permission from Wiley-VCH.

were helpful for the mechanical strength of fibers (Figure 6D). A woven textile made of such biomimetic fibers exhibits excellent thermal insulation performance as well as good breathability and wearability (Figure 6E).[62] Approximately 4°C temperature difference was reported for the one-layer 30-μm-pore-size sample on a 0°C and 40°C stage. High porosity contributes to low thermal conduction, and thermal convection of the fiber is also greatly restricted as air is blocked within individual micropores, which largely reduces energy loss from human body.[62]

Research focusing on improving thermal insulation property of textiles via surface coating has also been reported. As an excellent thermal insulation material category, aerogels are applied on textiles as thermal barrier, such as aluminum hydroxide aerogel and silica aerogel.[67,68] Jabbari et al. reported that a type of lightweight and highly thermal insulative aerogel-doped poly(vinyl chloride)-coated fabric composites was prepared on woven fabrics made of polyester fibers. It was revealed that the thermal insulation capability of the fabrics was enhanced by ∼26% (thermal conductivity decreased from 205 to 152 mW/m·K).[67] Nevertheless, aerogel coatings show some drawbacks in practical application. For example, its mechanical brittleness causes cracks during washing and wearing and health issue due to the inhalation of aerogel granules.

ACTIVE COOLING/WARMING TEXTILES

The advanced textiles with regulated radiation and conduction properties are categorized as passive cooling/warming textiles because no energy input is required. This strategy is energy efficient, but the extent of cooling/warming effect is limited.[69,70] Aiming at delivering extra cooling/warming power to human body, active cooling/warming textiles are developed. Joule heating that utilizes the electro-thermal conversion is widely reported for active warming textiles. It is often realized via modification or the embedment of electrically conductive materials onto textile surface or its fibers. Carbon-based materials (such as carbon nanotube and graphene),[71,72] metallic (nano)materials,[51,73,74] and conductive polymers[75] have all been reported as feasible solutions for Joule-heating textiles. With applied voltage, the decreased electrical resistance achieved by introduced materials make the textiles generate suitable Joule-heating power for human body warming. For instance, the nanowire percolation network embedded in polymer can provide robust electrothermal effect under mechanical deformations.[74] For metallic materials, they are usually reported to exhibit not only capability for Joule heating but also supply good thermal radiation reflectance.[18,52,53,76]

Combined with smart warming control systems, the active Joule-heating textiles can work as smarter integrated personal thermal management devices. Huang et al. reported a novel sandwich-structural textile (Ag nanofibers/silk fabric/Pt nanofibers) in which Joule-heating elements and temperature sensors are incorporated.[73] The Ag nanofiber network film attached on the fabric functioned as a wearable heater and the Pt nanofiber network array served as wearable temperature sensors (Figure 7A). Displaying high thermostability, thermal resistance of the heater and temperature sensitivity, and accuracy of the temperature sensors, this sandwich-structural textile showed potential in interactive control by a smartphone.[73] Figure 7B illustrates the schematic diagram of a textile-based thermal controller system including a heater, temperature sensor, microcontroller unit (MCU), and Bluetooth module. Desired temperature can be set by a mobile application, then the digital output signal sent from the smartphone via Bluetooth can control the output of the energy module, which can alter power input for the Ag nanofibers to adjust their temperature.[73] Even though the complete application of textile with the smart temperature controller has not been fully demonstrated, this work provides useful inspiration for future development direction of the integrated and interactive advanced textiles.

Apart from Joule-heating mechanism for active warming, Li et al. demonstrated a stretchable solar and electric dual-heaters on textiles based on the biomimetic MXene textures.[77] Inspired by the black scales of *Bitis rhinoceros*, they developed a sequential thermal actuation approach to construct biomimetic MXene nanocoating (Figure 7C). The constructed highly hierarchical structure resulted in broadband light absorption (up to 93.2%) and realized improved light-to-heat conversion performance. Stretchable and wearable heaters dual powered by sunlight and electricity were fabricated using mechanically deformed MXene structures, and the light-to-heat conversion contributed obvious supplement to the electrical heating (Figures 7D and 7E).[77] New insight of active warming textiles was provided by this work. More integrated solar and electric dual-heated textile may be realized if the coating process of the MXene nanocoating onto individual fibers can be developed.

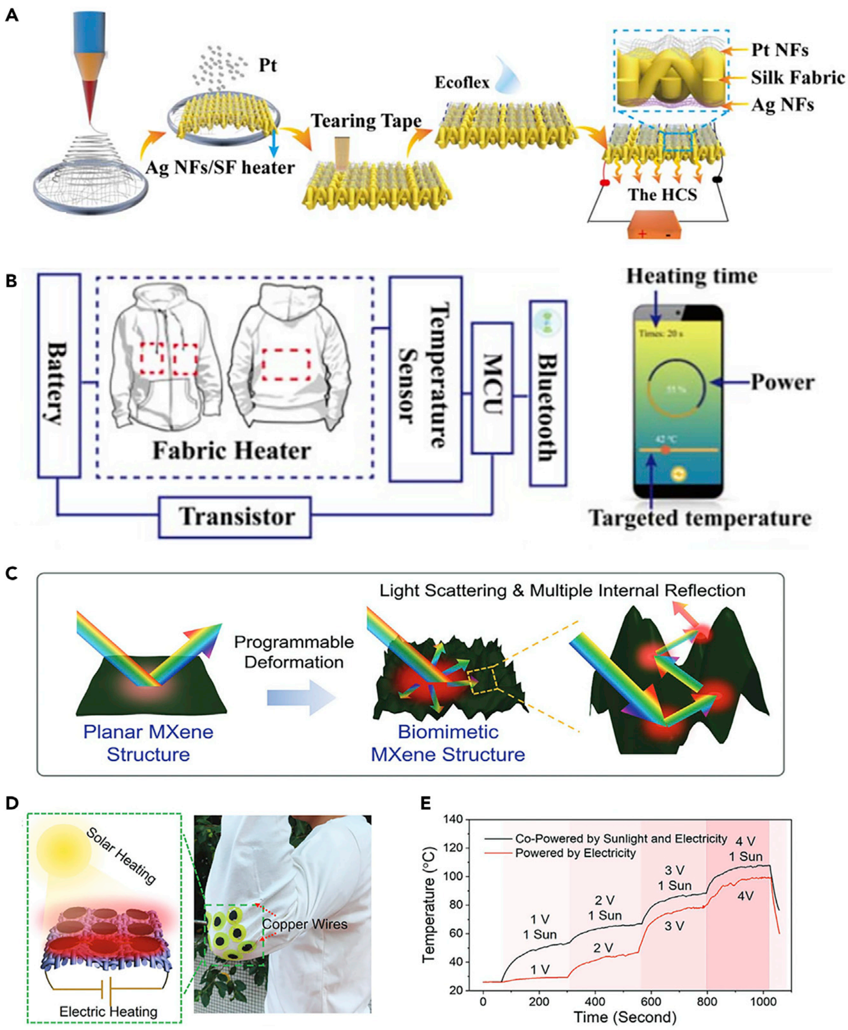

Figure 7. Active Warming Textiles Based on Joule-Heating and Light-to-Heat Conversion

(A) Schematic illustration of the preparation process of the sandwich-structural textile (Ag NFs/fabric/Pt NFs), in which Joule-heating elements and temperature sensors are incorporated.

(B) Schematic shows the circuit diagram of the smart thermal controlling system.

(A and B) Adapted from Huang et al.[73] with permission from IOP Publishing.

(C) Schematic illustration of the biomimetic MXene nanocoating with broadband light absorption and enhanced light-to-heat performance.

(D) Schematic illustration (left) and digital photograph (right) showing that the stretchable solar/electric MXene heaters were integrated on a T-shirt for thermal management.

(E) Measured surface temperature of the stretchable solar/electric MXene heaters co-powered by one-sun illumination and different voltages.

(C–E) Adapted from Li et al.[77] with permission from Wiley-VCH.

In addition, portable energy conversion devices added onto textiles are reported to supply warming/cooling power for human body.[16,78–80] A portable thermoelectric (TE) energy conversion unit (TECU) that converts electricity into cooling and energy was developed by Zhao et al.[16] In the cooling mode, the TECU supplies cool air for human body, and vice versa. The cool or warm air was transported through a tree-like rubber tube network, which was knitted into the garment (Figure 8A).[16] Zhang et al. fabricated crystalline TE microwires and nanowires by thermally drawing hermetically sealed high-quality inorganic TE materials in a flexible fiber-like substrate (Figure 8B). As-fabricated fibers were woven into a fabric, yielding up to 5°C Peltier

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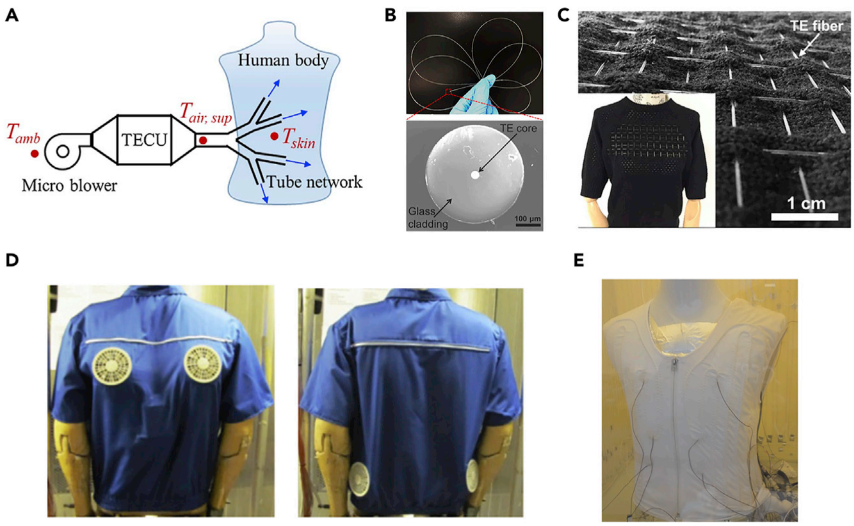

Figure 8. Active Warming/Cooling Textiles with Portable Energy Conversion Devices

(A) Schematic of TECU. Ambient air is cooled down or heated up by the TECU and then supplied to the human body through a tree-like tube network by using a micro-blower to exchange heat with skin. Adapted from Zhao et al. [16] with permission from Elsevier.

(B) Photograph of single TE fiber with a length of 1 m showing a good flexibility and its cross-sectional SEM image.

(C) TE fibers are woven into a large-area fabric to construct a wearable TE device.

(B and C) Adapted from Zhang et al.[80] with permission from Elsevier.

(D) Ventilated jackets with small fans and openings located at different torso sites. Adapted from Zhao et al.[78] with permission from Elsevier.

(E) The photograph of the prototype of LCG. Cooling tubes were sewed to the lightweight basic garment. Adapted from Guo et al.[79] with permission from Elsevier.

cooling effect (Figure 8C).[80] Garments with attached lightweight battery-powered fans were fabricated to increase forced ventilation for human body cooling (Figure 8D).[78] In addition, liquid cooling garments (LCG) were designed to provide cooling effect through liquid coolant circulation in the flexible tubes embedded in the textiles (Figure 8E).[79] Despite the effect for personal thermal management, factors such as portability, noise, and contact comfort of such textiles should be considered for daily applications.

RESPONSIVE TEXTILES FOR PERSONAL THERMAL MANAGEMENT

Different from conventional textiles and advanced textiles introduced above, responsive textiles interact with human body or environment by responding to it. The changes of human body, environment or itself can trigger changes in the responsive textiles.[81] Textiles responsive to temperature, moisture, pH, light, etc., have been reported exploiting abundant stimuli-responsive materials, which can alter their configuration or physical properties responding to small changes.[81–83] Assorted types of responsive textiles for various applications have been reported, but we will only focus on the responsive textiles for personal thermal management in this part.

Responsive Textiles with Phase-Change Materials

Textiles incorporated with phase-change materials (PCMs) to realize thermal regulation has been attracting researchers. PCMs take advantage of latent heat, which can be stored and released over a narrow temperature range.[84,85] Generally, the PCMs utilized in textiles exhibit high enthalpy of fusion, which are capable of absorbing and releasing thermal energy through the phase-change process. When exposed to high temperature, PCMs undergo the liquification process accompanied with a huge amount of energy adsorption when they reach their melting points. In reverse, solidification process happens releasing latent heat when temperature of PCMs arrives at the crystallization point as temperature decreases.[86] By absorbing or releasing latent heat, textiles with PCM are capable of providing thermoregulating and temperature buffering effects for human body.[87–94] Diverse types of PCM whose melting point are typically in the range of 15°C to 35°C have been applied in textile field, such as hydrated inorganic salt, linear long chain hydrocarbons, polyethylene glycol, and their eutectic mixtures.[89,91]

Responsive Textiles with Dynamic Structure Changes

Responsive structure changes in advanced textiles also play an important role in dynamic thermoregulation. The active control in radiation, conduction, and convection properties result from the variation of textile structure including thickness change, pore switch, fiber and/or yarn structure change, etc. Such type of textiles affords adaptive thermal comfort and dynamic energy management in varied occasions.

Zhong et al. designed and demonstrated two kinds of humidity-induced smart clothing that can reversibly adapt their thermal insulation functionality.[95] Both designs were based on the successful application of the Nafion film from DuPont, which will bend toward the lower humidity side very fast when subjected to a humidity difference between the opposing faces. The first one was proposed to mimic the pores in human skin, in which pre-cut flaps open to produce pores in Nafion sheets when humidity increases, such as perspiration, thus permitting air flow with enhanced air convection and reducing both the humidity level and the apparent temperature. The flaps can close automatically as humidity decreases to keep the wearer warm (Figure 9A).[95] The second design involves thickness adjustable clothes by inserting the bent polymer sheets between two fabrics. As the humidity increases, the sheets become thinner, thus reducing the gap between the two fabrics to alleviate the thermal insulation. The insulation layer can recover its original thickness upon humidity reduction to restore its warmth-preservation function (Figure 9B).[95] Similarly to the first design mimicking human skin pores described above, Mu et al. reported an ambient-driven actuator that takes advantage of inherent nanoscale molecular channels with a commercial perfluorosulfonic acid ionomer (PFSA) film (Figure 9C) and developed a kirigami-inspired single-layer actuator for personal humidity and heat management.[96] A bilayer-structured biohybrid film was demonstrated by Wang et al. by depositing genetically tractable microbes on a humidity-inert latex material to form a heterogeneous multilayered structure; they obtained biohybrid films that can reversibly change shape within a few seconds in response to environmental humidity gradients. A running suit prototype that can automatically adjust the moisture transfer and heat resistance based on such material was also fabricated (Figure 9D).[97] These works exhibit useful design concept for humidity sensitive smart textiles. Plus, shape memory polyurethane has been demonstrated to show water vapor permeability change around its glass transition temperature that is close to human body temperature, thus maintain stable body temperature.[99,100] Moreover, thermal-responsive hydrogels, such as PNIPAAm have also been applied to thermal and humidity management of the human body in water environments.[82,101]

The above works mainly focus on control of enhanced and/or reduced air convection induced by varied humidity, or the thermal induced structure change of materials resulting in water vapor permeability ability change, which can in reverse tune the heat dissipation through convection. The work below we would like to highlight was the first demonstration of dynamic gating of IR radiation in a responsive textile. Zhang et al. successfully realized the modulation of IR radiation as the relative humidity

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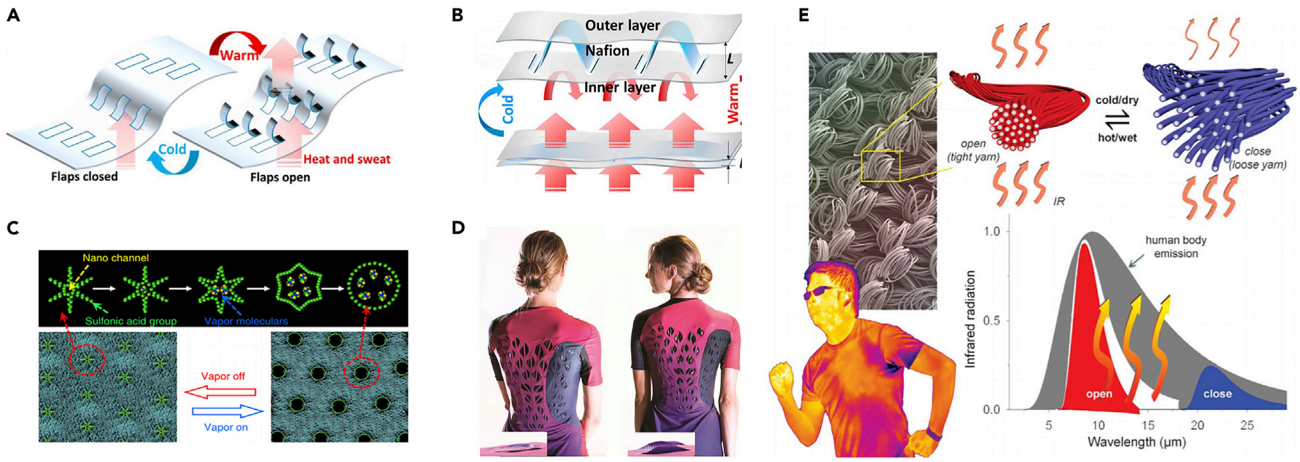

Figure 9. Smart Responsive Textiles with Dynamic Structure Changes

(A) Nafion sheet schematics with openable flaps mimicking thermo-adaptive functionality of human skin.

(B) The schematic of the thickness reversible structure using nafion as a thermally adaptive interlayer.

(A and B) Adapted from Zhong et al.[95] with permission from Nature Publishing Group.

(C) Schematic representation of the molecular channel expansion process in the PFSA film. Adapted from Mu et al.[96] with permission from Nature Publishing Group.

(D) Images of garment prototype before exercise with flat ventilation flaps (left) and after exercise with curved ventilation flaps (right), based on the moisture sensitive biohybrid two-layer film. Adapted from Wang et al.[97] with permission from the American Association for the Advancement of Science.

(E) Design principle illustration of an IR gating textile. Each yarn knitted into the textile is composed of multiple metafibers that contain IR-active nanostructures. When hot and wet, the yarn collapses into a tight bundle, resulting in resonant electromagnetic coupling that shifts the IR emissivity to spectrally overlap with that of human body and facilitate radiative cooling effect. When cold and dry, the reverse effect occurs. Adapted from Zhang et al.[98] with permission from the American Association for the Advancement of Science.

of underlying skin changed (Figure 9E).[98] They engineered triacetate-cellulose bimorph fibers with a thin layer of carbon nanotubes to turn polymer fibers into electrically conductive. Then a metatextile with smart and dynamically adaptive IR optical properties was produced incorporating tunable electromagnetic interactions at the fiber level. In a humid condition, the yarn formed by the modified bimorph fibers collapses, bringing the metal elements on neighboring fibers closer together to induce resonant electromagnetic coupling. The coupling effect can shift the emissivity of the textile to better match the human body's thermal radiation, which effectively enhances heat exchange between human body and the ambient. Conversely, the yarn responds in an opposite manner to reduce heat dissipation as humidity decreases. This makes it possible to effectively gate (i.e., "open" and "close") the IR radiation through the textile in response to environmental change. The IR transmittance change by more than 35% in response to humidity change was demonstrated.[98] This work opens a new pathway for developing IR-transmittance-responsive textiles. Optimized responsive change and response mechanism relying on other stimuli, such as temperature, will be possibly developed and draw more attention.

CONCLUSIONS AND PERSPECTIVE

With the development of society, individual comfort is drawing increasing attention on diverse occasions. Because of its importance in not only human body comfort, health, and productivity but also building energy saving, personal thermal management is being taken seriously and undergoing prosperous development. We are glad to witness the emerging works in this field offering novel and reasonable solutions for personal thermal management. In this article, we provided a concise review on recent research on advanced textiles for personal thermal management and categorized the advanced textiles mainly based on their working mechanisms. Considering the pathways of human body heat dissipation, passive textiles regulating the thermal radiation properties and conduction properties for both warming and cooling purposes were demonstrated. To supply extra warming/cooling energy for human body, active warming textiles mostly based on Joule heating and active cooling textiles utilizing enhanced convection and liquid cooling were launched. Moreover, smart responsive textiles, which can adjust the microclimate of human body through latent heat or altering its macroscale and/or microscale structures as environmental parameters change, have also been reported. The advanced textiles provide promising solutions for human body thermal comfort and offer new insights for building energy saving. Compared with achieving building thermal management and improving the energy efficiency via novel building materials, personal thermal management through textiles is more flexible, cost effective, and energy efficient because focus is only on human body and its local ambient. Together with the development of building technology, we believe advanced textiles can play increasingly important role in building energy saving and benefiting the sustainable development of society.

Despite the rapid development, both challenges and opportunities still exist. First, the gap between lab-scale proof-of-concept demonstration and practical application and commercialization needs to be filled. The wearability of textiles should be taken into account besides thermal management capability: Can they provide comfortable air permeability for human body? Can they satisfy the desirable wicking and moisture management performance? Can they achieve suitable mechanical strength and tactile feeling for wearing comfort during practical usage? Are the materials applied in novel textiles biocompatible and safe enough to human body? Can they sustain their performance in all aspects after the normal washing process for multiple times? The scalability of the as-demonstrated textiles should be considered as well: Are the materials accessible enough and cost-effective for large-scale industrial production? Are the manufacture processes easy and suitable for currently available manufacture facility? Can they be colored and styled according to manufacturer and costumers at will for fashion purpose? Are the newly developed materials eco-friendly and easy to be recycled?

Second, more universal test methods for demonstrating cooling/warming effects of textiles are to be established and acknowledged. Some works only reported the improvement in specific thermal properties (e.g., thermal conductivity) instead of reporting the direct cooling/warming effects for human body, which is not sufficient because the final cooling/warming effect of textiles is the comprehensive result of the interplay among human body, the textile, and the ambient involving many factors. In addition, the demonstration methods used in published papers are different and sort of flexible, even though they are self-supportive. However, this flexibility leads to the difficulty in comparing different works due to the different experimental apparatus, parameters, and control samples. The consistency may perhaps bring about the more rapid development of this field. Moreover, test methods need to be modified or changed in order to adapt to the transition from lab-scale demonstration to large-scale production. For example, manikin tests and opinion poll in simulated and/or actual environment are necessary before the launch of products.

Furthermore, advanced textiles based on new thermoregulation mechanisms may be demonstrated. For instance, mixed strategies mentioned above can be applied to render textiles with improved performance: textiles with tailored properties in multiple heat dissipation directions rather than only one may realize enhanced thermal management function due to the synergetic effects; researchers can look for different energy conversion routes, such as the light-to-heat energy supplement described above, for active warming textiles; responsive textiles can be developed to respond to more types of ambient parameter change and change their own properties in various ways; PCMs that can alter their thermal radiation properties due to the crystalline structure change at certain temperature (e.g., VO_2) may be explored for textile application, but the high critical temperature remains as the key problem; textiles specially designed for perspiration scenarios combining excellent water and/or moisture management and meanwhile thermal effect are also attractive. Additionally, technical textiles used in unique situations (such as extreme hot and/or cold conditions, outer space, fire, strong wind, etc.) are in ever-increasing demand and high standard. For instance, in extreme hot environment (e.g., Sahara Desert, Middle East), extreme cold conditions (e.g., polar regions), fire scenes, and outer space, how to insulate human body with the ambient hotness and/or coldness more efficiently is worth studying; in strong wind, how to push the limit of wind resistance of textiles meanwhile reserve the decent wearability deserves research as well. To expand the thermal comfort capability of human body in harsh environments is actually to improve the adaptivity limit of human body, which is significant. Biomimetic approaches perhaps provide inspiring solutions.

Moreover, advanced textiles for personal thermal management can be integrated with flexible electronics and energy-harvesting devices to realize the next-generation smart textile that achieves multiple functions encompassing thermal comfort, sensing, computing, electronic control, and self-powering. The advanced textiles for personal thermal management can probably provide enhanced heat dissipation solutions for working electronics as well, which benefits the stable and efficient operation of the whole system. We expect this perspective can help researchers gain a comprehensive picture of the recent progress in this area and motivate more remarkable breakthroughs in the near future.

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