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Outdoor personal heating and cooling by a Janus textile

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Abstract

Enhancing the personal thermal comfort in outdoor environment is of substantial significance to ameliorate the health conditions of pedestrian and outdoor laborer. However, the uncontrollable sunlight, substantial radiative loss, and intense temperature change in the outdoor environment present majestic challenges to outdoor personal thermal management. To date, a wearable device with optional passive heating and cooling abilities to abet people combat extreme temperatures in outdoor spaces, is lacking. Here, we report an eco-friendly passive textile which converts the challenges into opportunities and harvests energy from the sun and the outer space for optional localized heating and cooling. Compared to conventional heating/cooling textiles like black/white cotton, its heating/cooling mode enables a skin simulator temperature increase/decrease of 11.3 °C/14.5 °C respectively under sunlight exposure. Meanwhile, the temperature gradient created between the textile and skin simulator allows a continuous electricity generation with thermoelectric modules. Owing to the exceptional outdoor thermoregulation ability, this Janus textile is promising to help maintain a comfortable microclimate for individuals in outdoor environment and provide a platform for pervasive power generation.

Outdoor space, which is an inevitable part of our daily lives, accommodate numerous human activities and industrial operations. However, extreme weather conditions and acute temperature changes in the outdoor spaces are serious threats to public health, which adversely impact the well-being and sustainability of society. In the context of climate change, the diurnal temperature variation in the outdoor space can exceed 25 °C and the figure is still elevating¹⁻³. Accompanied by the mortality burden due to the heat/cold stresses and the temperature variations has been increased and is not likely to decrease in the near future⁴. Since it is uneconomical and impractical to implement air conditioners or ventilations in the outdoor environment, a desired solution for maintaining personal thermal comfort is managing the temperature of the immediate space around human body, which is popularly known as outdoor personal thermal management.

To realize eco-friendly passive outdoor personal thermal management, there are three remarkably great challenges to be tackled (Fig. 1a). Firstly, the outdoor infrared atmospheric window allows a large fraction of body thermal emission to be transmitted to the cold outer space (~ -270 °C), resulting in much higher radiative loss for personal heating compared to the indoor scenario ($\sim 150 \text{ W}\cdot\text{m}^{-2}$ vs. $\sim 35 \text{ W}\cdot\text{m}^{-2}$ for 0.6 mm cotton). Secondly, the outdoor sunlight irradiation ($\sim 1000 \text{ W}\cdot\text{m}^{-2}$ for 1sun, AM1.5) leads to extra heat load, making it difficult to realize personal cooling. Thirdly, the outdoor temperature changes are drastic and uncontrollable, while the indoor room temperature can be controlled with air conditioners⁵. Though there have been attempts on personal management⁶⁻¹⁷, most of the studies are focused on indoor applications. The few passive outdoor textiles are demonstrated with single fixed thermal functionality of either solar heating¹³ or radiative cooling¹⁸, showing moderate localized temperature regulation ranges. An integration of the two seemingly opposite thermal functions, which can adequately protect people from excessive hot/cold outdoor environment and intense temperature changes, has not been achieved yet. Moreover, as such a textile is expected to be able to create a temperature gradient between itself and the human skin, it can also pave a sustainable and practical pathway for continuous thermoelectric power generation¹⁹⁻²³.

In this paper, we demonstrate a wearable solution towards passive all-day outdoor personal thermal management and electricity generation with a Janus textile. This textile presents several distinct advantages by converting the challenges into opportunities. (i) It functions with extra high sunlight absorptivity, low mid-infrared (MIR) emissivity for localized heating and high solar reflectivity, high MIR emissivity for cooling. (ii) Outdoor daytime measurement shows that compared to black/white cotton, this textile enables a skin simulator temperature increase/decrease of 11 °C/4.5 °C during heating/cooling modes, respectively. It is also well suitable for nighttime and indoor personal thermal management. (iii) Based on its thermoregulation abilities, the integration with the thermoelectric modules showed that a maximum power generation capacity of 5.7 mW·m⁻² at daytime and 17.1 mW·m⁻² at nighttime can be achieved. (iv) The textile is breathable and washable due to porous structure and the hydrophobic surface, it affords scalable manufacturing regarding low material costs and facile fabrication methods. Consequently, this work lays a foundation for feasible implementation of harvesting substantial outdoor energy by wearable device and explores its broad applications in thermal management and pervasive electricity generation.

Fig. 1. Working principle of the Janus textile. (a) Heat inflow and outflow due to radiation and solar irradiance for personal thermal management in indoor and outdoor scenario. (b) Calculated heat dissipation rate q of human body ($T_s=34$ °C) covered with textiles of different emissivity ϵ in indoor environment (blue curve) and outdoor environment (red curve, assuming $\alpha=0$) and the extra radiative heat loss rates in outdoor environment (cyan area). (c) Calculated heat dissipation rate of human skin ($T_s=34$ °C) covered with textiles (blue curve: $\epsilon=1$, red curve: $\epsilon=0$) of different sunlight absorptivity α in outdoor environment illuminated by sunlight (e) Thermal comfort zone range of bare skin ($T_s=32\sim36$ °C) covered by cotton and ideal dual-functionality Janus textile. (f) Working principle and the structure of the Janus textile.

Results

Working mechanism of the Janus textile.

To numerically anticipate the required optical properties of the Janus textile, consider the total heat dissipation rate q of the human body as^{13, 18}

$$q = q_{rad} + q_{conv} + q_{cond} - \alpha q_{sun}$$

Where q_{rad} , q_{conv} , q_{cond} are the heat loss rates due to thermal radiation, convection and conduction, respectively. q_{sun} is the solar illumination intensity and α is the sunlight absorptivity of the textile. To have a better illustration of how these heat dissipation ways and incoming heat flux from sunlight absorption work, we performed the theoretical analysis based on a steady-state heat transfer model (Fig. 1, See Supporting Information and Fig. S1 for details) with the consideration of two major challenges, yet also opportunities, for outdoor thermal management:

1) Radiative heat loss: The radiative heat loss rate in outdoor spaces can be interpreted with

$$q_{rad} = q_{rad,o} - q_{atm}$$

where $q_{rad,o}$ is the thermal radiation power emitted by the outer surface of the textile which is proportional to its emissivity ε and q_{atm} is the absorbed power due to the radiation of ambient air/objects. In indoor environment (Fig. 1a, environmental temperature $T_e=25$ °C), the human skin emits thermal radiation at around $T_s=34$ °C and meanwhile, absorbs radiation from the environment at $T_e=25$ °C. In comparison, a great amount of emission power from the human body directly passes through the atmospheric window at the wavelength range of 8 μm to 14 μm in outdoor environment (where q_{atm} is around zero)²⁴⁻³⁵, leading to a much higher radiative heat dissipation (Highlighted in Fig. 1b, cyan area). From the perspective of outdoor thermal management, this extra radiative heat loss emphasizes the importance of suppressing thermal emissivity ε for outdoor personal heating. Meanwhile, a suitable opportunity arises for outdoor cooling.

2) Outdoor sunlight: Whereas the radiative heat loss poses great challenge on personal heating in outdoor space, the outdoor solar irradiation shed light on eco-friendly localized heating. Accordingly, the solar irradiation intensity q_{sun} according to AM1.5 spectrum is $1000 \text{ W}\cdot\text{m}^{-2}$, indicating even a very slight amount of sunlight would be able to compensate the heat dissipations of human body ($q\sim 231.6 \text{ W}\cdot\text{m}^{-2}$ for $\varepsilon=1$ and $q\sim 97.1 \text{ W}\cdot\text{m}^{-2}$ for $\varepsilon=0$, Fig. 1c). For an ideal heating textile of $\varepsilon=0$, a q_{sun} of $200 \text{ W}\cdot\text{m}^{-2}$ would be able to heat up the immediate space around human body when its absorptivity α is larger than 0.3 (Fig. 1c). For the aim of outdoor thermal management, high sunlight absorptivity α substantially improves the heating ability of textiles, while high sunlight reflectivity r ($r=1-\alpha$ when textile is opaque to sunlight) is crucial for personal cooling.

Ultimately, when we choose 32° to 36°C to be the comfortable temperature range of the skin simulator (heat dissipation rate $q = 200 \text{ W}\cdot\text{m}^{-2}$), an ideal Janus textile (Fig. 1e) under $200 \text{ W}\cdot\text{m}^{-2}$ sunlight illumination can realize a thermal comfort zone coverage of 31.2°C (Fig. 1d) and 8.2°C in outdoor and indoor environment, respectively. Apparently, it outperforms same thickness cotton in terms of both outdoor and indoor thermal management ability. As can be derived from the analysis results (Fig. 1d), the design of such an all-environment (outdoor and indoor) thermal management wearable requires critical multiband control of sunlight absorptivity α and thermal emissivity ε . Accordingly, the localized heating requires a selective solar absorbing surface (high α and low ε , Fig. 1e) and the localized cooling requires a radiative cooling surface (low α and high ε , Fig. 1e). Hence, an ideal Janus textile should be engineered with asymmetric sunlight to thermal optical properties at two surfaces to synergistically realize these two functions within itself. Moreover, to avoid the crosstalk of these two functions, the textile should be opaque for all wavelengths of interest.

Design and optical properties

Guided by the theoretical analysis results, we adopted a layered design based on

porous fibrous polymers for the dual-functional outdoor personal thermal management (Fig. 1e). In this design, nanoporous polyethylene (nPE) is chosen to be the substrate for selective solar absorbing plasmonic structures formed by copper (Cu) and zinc (Zn) nanoparticles. To enhance the mechanical stability of the solar absorbing nanostructures and avoid particle agglomeration when immersed in water, we performed graft polymerization of fluorinated acrylate monomer, 1H,1H,2H,2H-nonafluorohexyl-1-acrylate (F4) onto the nanostructure³⁶. After that, on the other surface of the nPE, a thin layer of aluminum (Al) is deposited as the metallic mirror for enhancing near-infrared (NIR) light reflection during cooling mode. Moreover, to ensure the sunlight scattering ability as well as enhancing its mid-infrared emissivity of the textile in cooling mode, a porous PMMA coated expanded polytetrafluoroethylene (ePTFE) is knitted on the top of the aluminum mirror (See methods and Fig. S2 for details of fabrication). The overall thickness of the resulting Janus textile is around 0.3 mm.

The optical properties of the Janus textile were then measured using Fourier transform infrared (FTIR) and ultraviolet–visible–near-infrared spectroscopy with an integrating sphere. The measured spectra show that the solar absorbing heating side, which consists of Cu/Zn nanoparticles sized several hundred nanometers, manifests high absorptivity ($\alpha > 0.8$) over solar spectrum and low emissivity ($\varepsilon \sim 0.16$) between 6 and 20 μm where the body thermal radiation is centralized (Fig. 2a, Fig. 2e and Fig. S3). When flipped, the cooling side shows high sunlight reflectivity ($r \sim 0.91$) and high emissivity ($\varepsilon \sim 0.87$, Fig. 2b), which satisfies the criterion for outdoor radiative cooling. The outdoor thermal management ability is then validated by wearing it on the human body and captured by optical and thermal cameras. In optical imaging, the Janus textile features dark grey color in heating mode and white color in cooling mode (Fig. 2c), which corresponds to the superior absorptivity and diffuse reflectivity for visible light, respectively. In thermal imaging, the textile shows cold color in heating mode and warm color in cooling mode (Fig. 2d), rendering low radiative heat loss and high radiative heat loss, respectively.

Fig. 2. Optical properties of the textile and its morphology. (a) Sunlight absorptivity and thermal emissivity of ideal outdoor textile and the Janus textile in heating mode and (b) Sunlight reflectivity and thermal emissivity of ideal outdoor textile and the Janus textile in cooling mode. The yellow area denotes the spectra of solar irradiance and the pink area denotes the blackbody emission spectra at 34°C . (c) Thermal image (d) and optical image of human body wearing the Janus textile knitted to a white T-shirt. (e) SEM image of the Janus textile's heating side and cooling side

Outdoor thermal regulation ability measurement.

To demonstrate the thermal regulation ability of Janus textile with two thermal functions, we first built a setup for measuring the temperature of the surface which mimics the skin (termed as T_{AS}) covered by different textiles (Fig. 3a, schematic presented in Fig. S4). The setup was placed on the rooftop, facing the clear sky. To avoid the influence of the outdoor wind flows, a thin broadband transparent polyethene film was used to cover the thermal chamber. During daytime measurement when the whole setup was exposed by the sunlight (the solar irradiance was also recorded) and no power supply is applied to the skin simulator¹³. Compared to conventional heating/cooling textile like black/white cotton of 1mm/0.5mm thickness (see Fig. S5 for their optical properties), the heating/cooling mode enables a surface temperature increase/decrease of 11.3 °C/14.5 °C under mid-day sunlight exposure (12:00 am), indicating its ability in protecting people from both cold and hot environments. Throughout the measurement duration of 10:00 am-15:00 pm, the thermal regulation ability of the Janus textile (both heating and cooling modes) outperforms the conventional cottons with regard to the corresponding thermal functions.

The same setup with daytime measurement was adopted for nighttime tests and DC power was applied for simulating metabolic heat generation. In the nighttime test, we gradually increased the input power to the skin simulators to demonstrate the difference in thermoregulation abilities of two modes. The skin simulator temperature reaches 35.7 °C (Fig. 3c) at 400 W·m⁻² input power density with heating mode, while the cooling mode textile requires 500 W·m⁻² input power to reach the similar temperature (33.6 °C). This result shows that this Janus textile has the ability of enhancing (or suppressing) more than 25% of total outdoor personal heat loss rate by switching the working mode at nighttime, which is in good agreement with the calculation results (see Supporting Information for calculation details).

Thermoelectricity generation.

Subsequently, the dual-functional outdoor textile thereby provides a reliable platform for further energy-related integrations. As an example, we attached the Janus textile onto a commercial thermoelectric generator (TEG) to demonstrate the all-day electricity generation ability (Fig. S6). To mimic metabolic heat generation, we put a silicone heater and an aluminum block with multiple fins beneath the TEG (As illustrated in Fig. 3d). During daytime test under sunlight, the temperature difference between the skin simulator (T_{AS}) and the hot side (T_H , TEG covered with Janus textile in heating mode) reaches a value of around 3 °C when the T_{AS} is around 36 °C (Fig. 3e, see Fig. S7 for real-time solar irradiance power density). Correspondingly, the output voltage is around 115 mV and the calculated maximum output power density is around 5.7 mW·m⁻². We further tested the thermoelectricity generation ability of the whole device at night. By applying appropriate voltage to the silicone heater, the temperature difference between the skin simulator (T_{AS} =34.5 °C) and the cold side (T_C , TEG covered with Janus textile in cooling mode) is around 4 °C (Fig. 3f). The corresponding output voltage is around 200 mV and maximum output power density is 17.1 mW·m⁻².

Noted that there are ways to improve the power generation capacity based on the Janus textile: (1) A direct use of the Janus textile in heating mode as hot side and the Janus textile in cooling mode as cool side. We have also demonstrated that by linking these textiles with a home-made flexible thermal electricity generator (10 pairs of AZO/PEDOT:PSS as n-type and PEDOT:PSS as p-type), a temperature difference of 45 °C and an output voltage of 26 mV is achievable (Fig. S8); (2) A combination with stacked TEGs or TEG with lower thermal conductivity to further increase the temperature of the hot side (Fig. S9), thereby improve the overall performance of the whole device.

Fig. 3. Thermal measurement and thermoelectricity generation tests. (a) The setup for measuring the outdoor thermal management ability of the Janus textile. (b) The setup for measuring the outdoor thermoelectric generation ability of the Janus textile combined with commercial thermoelectric modules. (c) Daytime thermal measurement results. The recorded data corresponds to the real-time temperature of the skin simulator covered with different textiles (red line: Janus textile in heating mode, blue line: Janus textile in cooling mode, purple line: black cotton, black line: white cotton, yellow line: ambient temperature, yellow dashed line: solar irradiance power density). (d) Nighttime thermal measurement results. The input power to the silicone heater is

gradually increased to mimic metabolic heat generation for maintaining constant healthy skin temperature. Every stair in the figure corresponds to a power density increase of $100 \text{ W}\cdot\text{m}^{-2}$. Daytime (e) and nighttime (f) thermoelectricity generation test of the Janus textile combined with commercial thermoelectric modules. The black line corresponds to the temperature difference between skin simulator and the hot side (e) and cold side (f) of the thermoelectric modules which is covered by the Janus textile in heating mode. The yellow line is the measured output voltage of the thermoelectric modules.

Wearability tests.

We further characterized the wearability of the Janus textile and these tests are mainly focused on washability and breathability of the resulting textile. The washability of the Janus textile is tested through clear water stirring of different duration time. It can be inferred that with the help of the grafted fluorinated groups, the resulting textile retains super-hydrophobicity which makes the laundry induced deterioration negligible. The sunlight absorptivity of the heating side witnesses almost no change and its emissivity show only around 0.01 increment after 60 minutes washing (Fig. 4a). The solar reflectivity and emissivity of the cooling side decreases by 0.02 and 0.09 after 60 minutes washing, respectively (Fig. 4b). Apart from the laundry durability, the treatment by F4 also contributes to various advantages in terms of multifunctional smart textile. At heating mode, such a waterproof heating side also prevent water droplets adhesion in outdoor environment and thereby reduce the heat loss due to evaporation (Fig. 4c). At cooling mode, the hydrophobicity difference of two surfaces has great potential to be combined with engineered micropores to accelerate sweat transportation process and further enhance the cooling ability¹¹. The breathability test shows that with the well-distributed nanopores (Fig. 2e and Fig. S10), the water vapor transmission rate (termed as WVTR in Fig. 4d) of the Janus textile is comparable to traditional textile such as cotton, being much better than the Mylar blanket (aluminum coated polyethylene terephthalate film), which is a commercial radiative textile to prevent radiative heat loss.

Fig. 4. Washability and breathability characterization. The absorptivity and emissivity change of the (a) heating side (b) and cooling side) after F4 treatment and washing cycles. (c) The water contact angle of the two sides of the Janus textile and the optical image of the F4 treated and untreated Janus textile after washing. (d) The water vapor transmission rate (WVTR) of different textiles.

Discussion

In summary, we develop a Janus textile with remarkable localized heating/cooling performance in outdoor environment. First, from the perspective of wearables devices, this work offers an unprecedented solution for harvesting energy from the sun, cold space for passive thermal management. Second, the Janus textile is able to implement two modes both day and night, thereby exceeds or matches the state of art for all-day and all-environment thermal management. Third, the perceptible temperature differences between the skin and the textile surface created when the textile works in

different modes makes the textile a reliable building block for continuous thermoelectric generation. Last, the facile fabrication method of the flexible textile and its low material costs makes it suitable for scalable fabrication, facilitating potential applications such as multi-functional camouflage, sensing, anti-freezing, anti-fogging, and powering on-body electronics. Ultimately, the described flexible material affords new possibilities for various modern technologies where spatial temperature regulation and continuous green energy solution is needed.

Methods

Fabrication of the Cu/Zn NPs selective solar absorbing coating. The nanoporous PE was bought from SK Innovation. The Zn and Al were separately deposited onto two sides of the nPE film with a high-vacuum magnetic sputtering system (DISCOVERY-365, Denton) and the sputtering parameters were set to be 90 W(DC), 800 s for Zn, and 100 W(DC), 600 s for Al. After sputtering, the Zn/Al nPE films were immersed into CuSO₄ solution (5 mM) for 5 s for Cu nanoparticles to form. The samples were then blow-dried in high-purity nitrogen. The coating of Zn and Cu nanoparticles was then treated with F4 solution to enhance hydrophobicity. This F4 solution was prepared by dissolving 1H,1H,2H,2H-Perfluorodecanethiol (Rhawn) in absolute ethyl alcohol with a ratio of 1:1000.

Fabrication of the PMMA coated ePTFE/Al radiative cooling structure. The ePTFE of 300 μ m thickness was bought from Baoxin Microfiltration, China. To form PMMA coatings on ePTFE, the PMMA (average Mw ~120,000 by GPC) purchased from Sigma Aldrich was dissolved in acetone, after then water is added to make a PMMA-acetone-water solution with a 1:8:1 mass ratio. The solution was then spray-coated on ePTFE in the ventilated cupboard. The desired thickness was obtained by controlling the amount of solution that put into the spray gun and the area size of ePTFE film.

Emissivity measurement. Emissivities of different textiles were measured with a Fourier transform infrared spectrometer (Bruker, Vertex 70) equipped with a room-

temperature doped triglycine sulfate (DTGS) detector. The black soot deposited onto a gold-coated silicon wafer using a burning candle was used as a reference. Different samples were fixed on the same heater controlled by a temperature controller. The temperature for measurement was set as 60 °C.

Sunlight absorptivity measurement. Transmission and reflection spectra were measured using a universal measurement spectrophotometer (Agilent, Cary7000) equipped with an integrate sphere. The incident angle of light source onto the samples was about 8°. For the measurement of diffuse reflectance, a thick white paint coating was used as a reference.

Thermal measurement. All thermal measurements were performed with thermocouples (Omega, SA-1K) and a Keithley 2700 multimeter was used to acquire the real-time temperature. The optical images are shot with Fujifilm X-E3 camera and XF50 f/2 lens. The thickness of tested black cotton is 1mm and the thickness of tested white cotton is 500µm. The skin simulator consists of a copper plate and a silicone heater underneath. A 6-mm-thick aerogel was used to hold the skin simulator which acted as a heat insulator. The whole thermal chamber was covered with Mylar blanket and aluminum foils to reduce heat transfer through conduction and radiation from the ambient. A thin layer of broadband transparent polyethylene film was attached to the upper surface of the thermal chamber in order to avoid the influence of wind flows. The thermocouples were attached to the upper surfaces of the copper plates for measuring the temperature. During daytime measurement, the thermal chamber was placed facing the clear sky without any tilt and a pyranometer was used for measuring the solar irradiance power density. During nighttime measurement, a DC power supply was connected to the silicone heater to mimic metabolic heat generation.

Thermal electricity measurement. Four commercial thermoelectric modules (TGM-287-1.4-1.5) were connected in series and put together in a 2x2 array (11cm×11cm), and had aluminum tapes on both sides to improve the temperature consistency of the four module surfaces. The TED was put on to the skin simulator (AS) with its top side covered by different tested textiles. The thermal electricity output voltages were then

measured by the Keithley 2700 multimeter. The skin simulator was placed onto an aluminum block with multipole fins and the whole thermoelectricity generation device was put on an acrylic chamber covered by Mylar blanket. The maximum output power density is calculated by $P_{\max} = nS^2(T_h - T_c)^2 / 4R / A$, the number of thermocouples n in the thermoelectric generator is 1148, the measured Seebeck coefficient S is 43.5 $\mu\text{V/K}$, the measured resistance per thermocouple is 0.042 Ω and area size A is 11 cm $\times$ 11 cm.

Water vapor transmission rate measurement. The test was performed using ASTM E96 with modification. Petri dishes filled with 10 ml distilled water were sealed by the textile samples using rubber bands. These sealed dishes were then put into an environmental chamber whose temperature was kept at 30°C and relative humidity at 40%. The dishes were weighed periodically with an electronic balance (OHAUS, AR1502CN). The water vapor transmission rates were calculated from the mass loss, which was equal to the mass of evaporated water.

Water contact angle measurement. The static water contact angles were measured by a DropMeter A-200 contact angle system (MAIST Vision Inspection & Measurement Co. Ltd., China) in the ambient environment to evaluate the wettability of the textile.

Data Availability

The authors declare that the data supporting the findings of this study are available within the paper and its supplementary information files.

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Author Contributions

These authors contributed equally: Hao Luo, Yining Zhu. Q.L. conceived the idea and supervised the project together with M.Q.. H. L and Y. Z. performed the calculations and experiments. P.G. performed part of the calculation. Z.X., Y.H., M.W., and C.Y. performed part of the characterization. H.L., Q.L. and M.Q. wrote the manuscript. All authors discussed the results and contributed to the final version of the manuscript.

Competing interests

The authors declare no competing financial interests.

Figures

Figure 1

Working principle of the Janus textile. (a) Heat inflow and outflow due to radiation and solar irradiance for personal thermal management in indoor and outdoor scenario. (b) Calculated heat dissipation rate q of human body ($T_s=34^{\circ}\text{C}$) covered with textiles of different emissivity ϵ in indoor environment (blue curve)

and outdoor environment (red curve, assuming $\alpha=0$) and the extra radiative heat loss rates in outdoor environment (cyan area). (c) Calculated heat dissipation rate of human skin ($T_s=34^\circ\text{C}$) covered with textiles (blue curve: $\varepsilon=1$, red curve: $\varepsilon=0$) of different sunlight absorptivity α in outdoor environment illuminated by sunlight (e) Thermal comfort zone range of bare skin ($T_s=32\sim36^\circ\text{C}$) covered by cotton and ideal dual-functionality Janus textile. (f) Working principle and the structure of the Janus textile.

Figure 2

Optical properties of the textile and its morphology. (a) Sunlight absorptivity and thermal emissivity of ideal outdoor textile and the Janus textile in heating mode and (b) Sunlight reflectivity and thermal emissivity of ideal outdoor textile and the Janus textile in cooling mode. The yellow area denotes the spectra of solar irradiance and the pink area denotes the blackbody emission spectra at 34 °C. (c) Thermal image (d) and optical image of human body wearing the Janus textile knitted to a white T-shirt. (e) SEM image of the Janus textile's heating side and cooling side

Figure 3

Thermal measurement and thermoelectricity generation tests. (a) The setup for measuring the outdoor thermal management ability of the Janus textile. (b) The setup for measuring the outdoor thermoelectric generation ability of the Janus textile combined with commercial thermoelectric modules. (c) Daytime thermal measurement results. The recorded data corresponds to the real-time temperature of the skin simulator covered with different textiles (red line: Janus textile in heating mode, blue line: Janus textile in cooling mode, purple line: black cotton, black line: white cotton, yellow line: ambient temperature, yellow dashed line: solar irradiance power density). (d) Nighttime thermal measurement results. The input power to the silicone heater is gradually increased to mimic metabolic heat generation for maintaining constant healthy skin temperature. Every stair in the figure corresponds to a power density increase of $100 \text{ W}\cdot\text{m}^{-2}$. Daytime (e) and nighttime (f) thermoelectricity generation test of the Janus textile combined with commercial thermoelectric modules. The black line corresponds to the temperature difference between skin simulator and the hot side (e) and cold side (f) of the thermoelectric modules which is covered by the Janus textile in heating mode. The yellow line is the measured output voltage of the thermoelectric modules.

Figure 4

Washability and breathability characterization. The absorptivity and emissivity change of the (a) heating side (b) and cooling side) after F4 treatment and washing cycles. (c) The water contact angle of the two sides of the Janus textile and the optical image of the F4 treated and untreated Janus textile after washing. (d) The water vapor transmission rate (WVTR) of different textiles.

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