Dual-mode photonic textiles for radiative heat management

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Dual-mode photonic textiles for radiative heat management

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ABSTRACT

Personal radiative heat regulation by photonic engineered textiles can help contribute to a more sustainable cooling and heating energy consumption in buildings by expanding the range of comfortable ambient conditions. Here, we propose various dual-mode photonic fabric designs (dynamic and static) that provide thermal regulation in both cold and hot environments. In the first design, we utilize metal-coated monofilaments arranged in a hexagonal geometry within a yarn and stimuli-responsive polymer actuator beads, in this way benefiting from the infrared (IR) photonic effect (or plasmonic gap) to control the wide-band transmission of thermal radiation and to provide for a sharp, dynamic response ($\Delta\tau = 0.9$). The second design is based on metal microspheres randomly dispersed in a shape memory polymer membrane. The dynamic switching is achieved via a shape memory polymer matrix that responds to environmental changes. This design capitalizes on the strong scattering properties of metallic microspheres, leading to a strong modulation of reflectance ($\Delta\rho = 0.55$) as a function of the volume fraction. The third design is a Janus-yarn fabric composed of an asymmetric structure, leading to dual emissivity characteristics. The strong emissivity contrast ($\Delta\varepsilon = 0.72$) is achieved by utilizing metallic and dielectric fibers within the yarn; here, static switching is achieved via fabric flipping.

Keywords: radiative transfer, plasmonic-gap, metal-microparticles, setpoint-temperature, heat transfer

1. INTRODUCTION

As humanity starts to experience the consequences of climate change, natural disasters due to extreme weather conditions have become frequent events in some parts of the world. As far as humankind is concerned, global warming imposes a severe existential threat and has to be addressed.[1,2] Even though there are various human-induced factors, the imbalance between increasing energy consumption and clean energy production stands out. Due to this, the rapid switch to renewable energy sources is difficult, and solutions to significantly decrease energy consumption are crucial. Surprisingly, more than half of our energy consumption goes to the heating and cooling of large, mostly empty spaces in residential and commercial buildings. Therefore, passive personal thermal management, which creates a localized thermal regulation, can become critical to lower consumption and guarantee a sustainable future. Controlling the radiative heat transfer for personal thermal-management technologies has gained much attention due to its universality and high tunability, leading to photonic engineered textiles. At a normal skin temperature of 34 °C, to a large extent, the human body loses its metabolically generated heat by emitting infrared (IR) radiation centered near 10 μm.[3] Specifically, in an indoor setting such as an office, more than 50% of the heat loss is attributed to IR radiation. Therefore, with proper IR photon management, one can tailor and design passive temperature regulating textiles.[4–6]

2. DESIGN WORKING PRINCIPLES

Traditional textiles can only function in one mode and can only be utilized comfortably in a limited temperature window. Therefore, one must adapt the clothing to different conditions to remain comfortable: warming textiles for cold surroundings and cooling textiles in warm environments. However, both cooling and heating functionalities are needed when temperatures fluctuate, which has become more common in recent years. Our designs possess dual-mode functionality (cooling and heating), with a switching capability via shape memory polymer (dynamic) or flipping of the fabric (static). This provides an opportunity to thermoregulate for a large range of ambient temperatures.

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2.1 Dynamic transmittance switch textile (DTST)

The DTST fabric (Figure 1a) incorporates mono-filaments coated with metal, which are arranged in a photonic array geometry in a suitable combination with shape-memory polymer beads. For example, at a predetermined comfort zone temperature below a critical temperature T_c the polymer beads keep a particular geometry. When the temperature rises above T_c, the polymer beads expand, thus increasing the separation distance d between two consecutive mono-filaments. This results in a new geometric configuration with an expected increased IR transmissivity. This provides the cooling functionality needed in a hot environment. On the other hand, when the ambient temperature drops below T_c, the polymer beads shrink, thus decreasing d. As a result, the initial geometric configuration will change, and the IR transmissivity decreases, providing the desired heating function in a cold environment.

2.2 A dynamic passive thermoregulation fabric using metallic microparticles (MMDF)

The MMDF (Figure 1b) incorporates metallic microparticles in a stimuli-responsive shape memory polymer matrix. The operation relies on two concepts: the strong scattering of micro-scale metallic particles in the IR and the swelling and shrinking capabilities of specific polymers as a function of temperature or humidity. For the heating mode, at lower temperatures, the polymer matrix shrinks, which increases the volume fraction (f_{v}) of the particles, leading to increased reflectance. This directly blocks the radiative heat flux emitted from the human body to the ambient, leading to enhanced thermal comfort at low temperatures. On the other hand, for the cooling mode, at higher temperatures, expanding the polymer matrix decreases the particle volume fraction and reflectance, so the radiative heat flux of the body escapes to the ambient, leading to enhanced comfort at higher temperatures.

2.3 Janus-yarn fabric for dual-mode radiative heat management

The core working principle of the Janus-yarn fabric (Figure 1c) relies directly on the outer surface emissivity. This stems from the Stefan-Boltzmann radiative emission law, stating that the total power radiated from an object is proportional to its emissivity ε. Changing this emissivity from high to low strongly reduces the radiative heat transfer to the ambient. Therefore, when the highly emissive layer of the fabric – dielectric micro-fibers – faces the ambient, the surface acts as an infrared radiator creating a cooling effect in a hot environment. On the other hand, when it is cold, flipping the same fabric exposes the low emissivity side – highly reflecting metallic micro-fibers – to the ambient, acting as radiative insulation, thus delivering a heating function. Furthermore, because the fabric is constituted out of yarns, which are bundles of fibers, it provides the required air permeability and water-vapor transmission for standard thermal comfort.

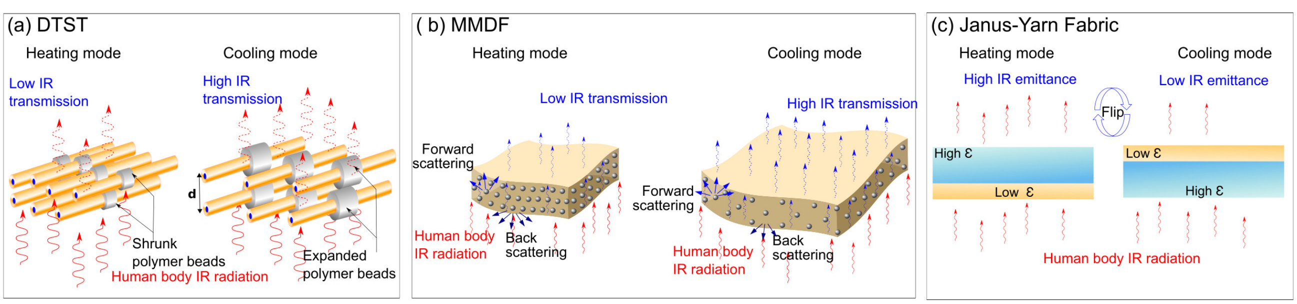

Figure 1. Schematic illustration of the working principle behind (a) Dynamic Transmittance Switch Textile (DTST), (b) Metallic Microparticle-based Dynamic Fabric (MMDF), (c) Janus-yarn fabric.

3. METHODS

To understand the IR optical responses of the designs, we implemented various numerical study approaches accordingly. We employ the finite-element method for the DTST and Janus-yarn fabrics to calculate rigorous solutions of Maxwell's equations, using commercial software (COMSOL Multiphysics). On the other hand, for the MMDF design, we combined extended Lorenz-Mie solutions with the radiative transfer equation using the collision-based Monte Carlo method. The thermal performance of the designs is investigated using heat transfer analysis.

For DTST, since the metal-coated mono-filaments are considered infinitely long, parallel cylinders, the geometry is two-dimensional, consisting of an array of circular, metal-coated mono-filaments (Perfect electric conductor), hexagonally arranged and surrounded by air (Fig. 2a). We use air as the background medium, as the shape-memory polymer beads take only a very small volume in the structure. Moreover, the refractive index of such polymers, typically below 1.5, would only slightly increase the effective index. Simulations are performed at normal incidence for two light polarizations relevant to the calculation of unpolarized radiative properties.

For MMDF, we first use electromagnetic wave theory (i.e., extended Lorenz-Mie solutions) to calculate the optical properties of a single metallic microsphere, which includes scattering, extinction, and absorption efficiencies, and the scattering phase function. Second, we study the effective radiative properties of a microsphere cloud uniformly dispersed in a polymer matrix (such as asymmetry factor, scattering albedo, effective absorption, scattering, and extinction coefficients). Third, we investigate the radiative transfer analysis of a semitransparent particulate medium using a collision-based forward Monte Carlo method (Fig. 2b).

For the Janus yarn, the simulated geometry is constituted from metallic fibers on one side and dielectric fibers on the other side (Fig. 2c), in a hexagonal pattern. The metallic fibers were modeled by implementing perfect reflection of their surfaces, which is a very good approximation for many metals in the relevant IR wavelength range of 4 - 25 µm in our case. Due to its strong IR absorbing (and thus emitting – see Kirchhoff's law) property in the 4 - 25 µm region, silicon carbide (SiC) is used as the dielectric. Again, simulations are performed from both sides of the structure, at normal incidence, for two light polarizations to calculate the unpolarized radiative properties.

The overall performance of the designs is examined by modeling the heat transfer from the skin to the ambient. The main objective is to determine the maximum and minimum surrounding environment temperatures that the proposed fabric can maintain without affecting the wearer's thermal comfort: the setpoint temperature. The setpoint temperature is determined from a heat transfer analysis using thermal circuit models: heat transfer represents the electric current, and the temperature in each layer of the system represents the electric potential. The three heat transfer channels, when the fabric covers the skin with an air gap in between, are radiation,

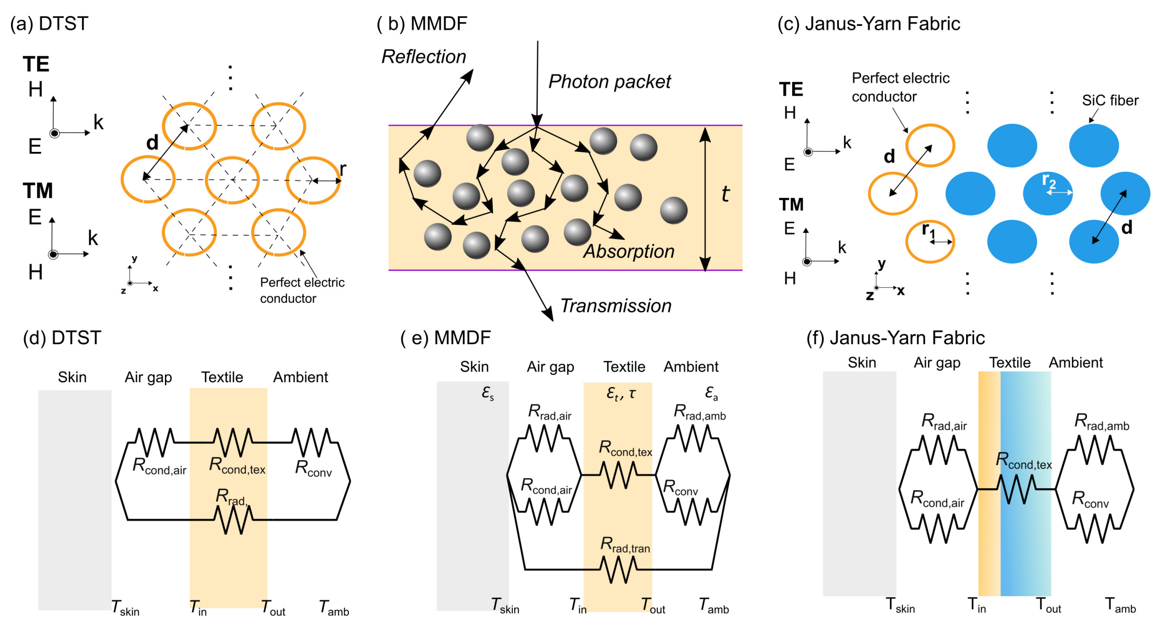

Figure 2. The schematic of simulated model for the IR response: (a) DTST, (b) MMDF and (C) Janus-yarn fabric; and for heat transfer (d) DTST, (e) MMDF, and (f) Janus-yarn fabric, respectively.

conduction, and convection. The thermal circuit model is constructed with thermal resistances R involving the conductivity of the textile and its radiative properties – obtained from the simulations – as well as properties of the air gap and ambient (see Figure 2d, e, and f).

4. RESULTS AND DISCUSSION

The spectral transmittance for the DTST is presented in Fig. 3a for two different separation distances d and a filling factor of 0.15. For $d = 2$ μm, starting from a cut-off wavelength of 5 μm, there is a wide stopband called the plasmonic gap. On the other hand, for $d = 10$ μm, the first and second transmission bands are visible, while the plasmonic gap is shifted to a higher wavelength (not visible on the graph). The above photonic effects are present in all spectral curves, so we can assess the influence of changing d in the process of IR transmittance. When d increases, the spectral curve shifts to a longer wavelength region and vice versa, thus shifting the plasmonic gap and the first transmission band. As a result, for larger d (but not too large), the transmission band is underneath the maximum of the human body emissivity curve, leading to more transmission of IR thermal radiation from the skin to the environment. This allows the DTST to operate in a cooling mode. On the other hand, for smaller d, the plasmonic gap is underneath the human body emissivity curve. Consequently, a very low IR transfer from the skin to the environment is realized; in this case, DTST is operating in a heating mode. The DTST achieves a minimum setpoint of 9.5 °C, and a maximum setpoint of 25.7 °C, which correspond to τ close to zero and $\tau = 0.9$, respectively (Fig. 3d).

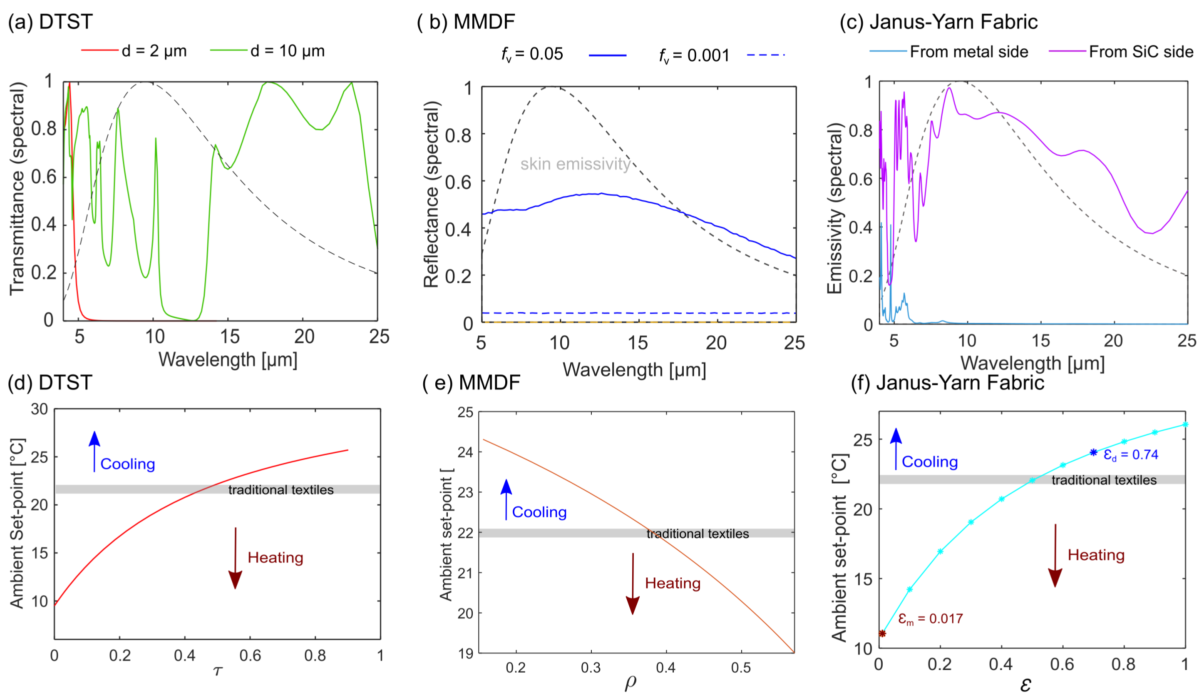

Figure 3. (a) Spectral transmittance of DTST. (b) Spectral reflectance of MMDF. Spectral emissivity of Janus-yarn fabric.(d) Ambient setpoint temperature of DTST as a function of transmittance τ. (e) Ambient setpoint temperature of MMDF as a function of reflectance ρ. (f) Ambient setpoint temperature of Janus-yarn fabric as a function of transmittance ε.

For the MMDF, the effective scattering coefficient of the microparticle cloud increases with f_v (near the relevant 10 μm wavelength), showing potential for dynamic modulation. This stems from the large scattering efficiency of a single Ag microsphere (radius of about 1.5 μm) in the same wavelength region. As an important result, for $t = 150$ μm, Figure 3b shows the spectral reflectance of the MMDF for two specific cases, $f_v = 0.001$ and 0.05, respectively, which we associate with the cooling and heating mode. In cooling mode ($f_v = 0.001$, bottom dashed line), we observe a very low reflectance, so the fabric is almost perfectly transparent for all wavelengths, and this facilitates the dissipation of radiative flux from the skin to the ambient. In heating mode ($f_v = 0.05$, solid line), the reflectance increased substantially, thus returning an important fraction of the body radiation back to the skin. The MMDF achieves a minimum setpoint of 18 °C, and the highest setpoint of 26 °C (Fig. 3e). The minimum setpoint corresponds to $\rho = 0.55$, where $f_v = 0.05$. On the other hand, the highest setpoint corresponds to ρ close to zero, where $f_v < 0.001$, hence the fabric is highly transparent to the body thermal radiation.

For the Janus-yarn, similar to DTST, we find that the array of metallic fibers creates a plasmonic gap, which results in total reflection above a certain wavelength whose value depends on the spacing of the fibers. This high reflection leads to almost zero transmission through the textile, improving its dual radiative properties. Absorptance/emissivity values from the metallic side also remain extremely low due to this gap, achieving the low radiation emission required for a heating mode (see Fig. 3c). From the dielectric side, depending on the fiber size and spacing, various photonic resonances, such as Fabry-Pérot modes and multipolar resonances inside the fibers, enhance the absorption and thus the emission. In the end, this yarn geometry achieves an integrated transmissivity of τ=0.004 from both sides, an integrated emissivity of ε_m=0.02 from the metallic side, and ε_d=0.74 from the dielectric side, thanks to the aforementioned gap and resonances. This large emissivity contrast of $\Delta\epsilon = 0.72$ and small transmission results in a strong duality of the Janus-yarn fabric: the minimum and maximum comfortable ambient temperatures calculated for the cooling and heating modes are respectively 11.3 °C and 24.4 °C (see Fig. 3f).

5. CONCLUSION

We demonstrated dual-mode fabrics for personal thermal management using multiple photonic designs. We proposed a dynamic transmittance switch textile (DTST), a metallic microparticle-based dynamic fabric (MMDF), and a Janus-yarn fabric. The DTST uses metal-coated monofilaments arranged in hexagonal geometry within a yarn, and stimuli-responsive polymer actuator beads to provide a sharp, dynamic response ($\Delta\tau = 0.9$) and a setpoint window of 13.1°C. The MMDF is based on metal microspheres randomly dispersed in a shape memory polymer membrane. The dynamic switching is achieved via a shape memory polymer matrix that responds to environmental changes. This design capitalizes on the strong scattering properties of metallic microspheres, leading to a strong modulation of reflectance ($\Delta\rho = 0.55$) as a function of the volume fraction, thus delivering a setpoint window of 8°C. The Janus-yarn fabric is composed of an asymmetric yarn, leading to dual emissivity characteristics. The strong emissivity contrast ($\Delta\varepsilon = 0.72$) is achieved by utilizing metallic and dielectric fibers within the yarn; thus, static switching is achieved via fabric flipping. Consequently, providing thermal comfort within a setpoint window of 11°C.

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