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Dynamic emissivity modulating thermoregulating fabric using metallic particles

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Abstract: Maintaining comfort using photonic thermal management textiles can potentially decrease the energy cost for heating and cooling in residential and office buildings. We propose a thermoregulating fabric comprised of a high emissivity bottom layer and a metal-particle polymer composite on top to modulate emissivity and provide dynamic and passive thermal comfort. With detailed numerical modeling we demonstrate a wide dynamic ambient setpoint temperature window of ∼7.25 °C, with the wearer staying comfortable in the range between 18.5 and 25.75 °C. This thermoregulating performance indicates a vital energy-saving potential and paves the way to a more sustainable society.

As humanity starts to experience the consequences of climate change, addressing the global energy crisis provides us with a significant challenge. Surprisingly, more than half of our energy consumption goes to the heating and cooling of large empty spaces in residential and commercial buildings [1]. Therefore, passive personal thermal management, which creates a localized thermal regulation, can become critical to lower consumption and guarantee a sustainable future. Recently, micro-photonic driven local thermal management in textiles has captivated attention. Since radiative transfer accounts for around 50% of heat dissipation from the human body, a proper photonic thermal management strategy allows one to design passive temperature-regulating textiles. Previously we have shown a static state-of-the-art emissivity switch fabric design based on the Janus-yarn concept [2]. However, this fabric requires mechanical flipping to switch between cooling and heating modes.

Here we propose a metal-particle dynamic emissivity switch textile for dual-mode temperature regulation, using the fabrics' outer surface emissivity modulation. The fabric is constituted of a highly emissive bottom layer and a low emissive composite layer on top, which is thermo-mechanically dynamic (Fig. 1a). The top layer is made from a temperature-sensitive shape-memory polymer matrix with equal-sized metal particles (copper) uniformly dispersed, while the bottom layer is composed of carbon black. The proposed design operates in two modes, heating and cooling. When the ambient is cold, the fabric is in heating mode, and the polymer shrinks; thus, the volume fraction of the metal particles increases, resulting in high scattering and reflection, leading to a low effective emissivity of the fabric's surface [see Fig. 1a (I)]—subsequently, strong radiative heat emission to the ambient. When the ambient is hot, the fabric is in cooling mode; the polymer expands, allowing the low-emissive shape-memory polymer based top layer to stretch; as a result, the volume fraction of metal particles decreases [see Fig. 1a (II)]. This decrease substantially lowers radiation scattering and increases the fabric's emissivity, therefore facilitating more radiative heat transfer from the human body to the ambient. By introducing an optimized copper particle, one can achieve an effective emissivity contrast of about 0.65, which translates to a wide ambient setpoint window.

To model the fabric design, we first use electromagnetic wave theory (i.e., extended Lorenz-Mie solutions) to calculate the optical properties of a single metallic microsphere, such as scattering phase function, scattering efficiency, and absorption efficiency. Second, we calculate the effective radiative properties of a particle cloud uniformly dispersed in a polymer matrix (effective scattering and absorption coefficients). Third, we investigate the radiative transfer analysis of a particulate medium using a collision-based forward Monte Carlo method. Finally, we implement the radiative parameters (emissivity) retrieved from the Monte Carlo calculations in the thermal model to retrieve the ambient setpoint temperature [3].

Figure 1b plots spectral emissivity for two specific cases, volume fraction f_v = 0.01 and 0.1, respectively, which we associate with the cooling and heating mode. In cooling mode (f_v = 0.01, blue line), we observe a very high spectral emissivity; therefore, the fabric is almost a perfect emitter for all the interesting wavelengths. In heating mode (f_v = 0.1, dark red line), the spectral emissivity is low over the entire human body emissivity spectral range (light blue background surface plot). It is clear that a low volume fraction results in high emissivity, and high volume fraction results in substantially decreased emissivity. This result is directly related to the metal particle cloud's effective scattering coefficient, which increases with volume fraction. The emissivity dependence on the volume fraction delivers the expected dynamic temperature regulation property of the proposed fabric. Heat transfer analysis shows that the design achieves a minimum setpoint of 18.5 °C to provide heating and the highest setpoint of 25.75 °C to provide cooling (Fig. 1c). The minimum setpoint corresponds to the emissivity of 0.27, where f_v = 0.1. On the other hand, the highest setpoint corresponds to an emissivity of 0.93, where f_v < 0.01.

Overall, we propose a dual-mode fabric design for personal thermal management using a multilayer approach by incorporating metallic particles to deliver emissivity modulation. The dynamic switching is achieved via a shape memory polymer matrix that responds to environmental changes. This design provides thermal comfort in a setpoint window of about 7.25°C.

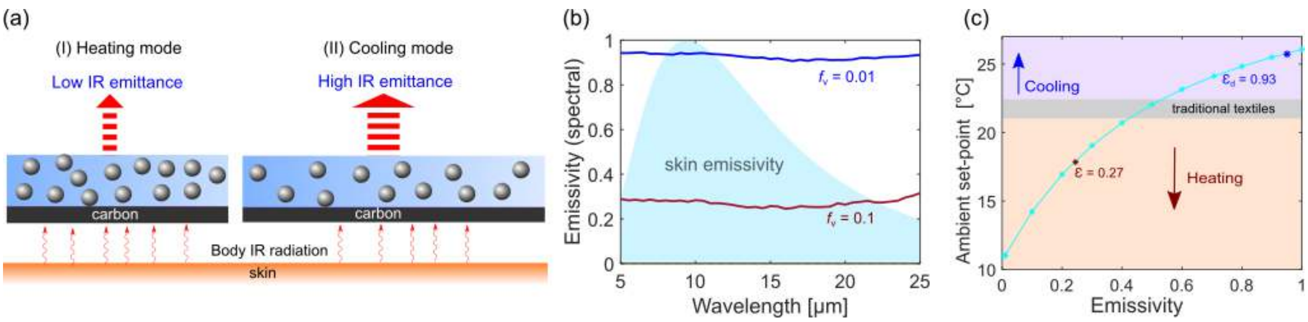

Figure 1. (a) Schematic illustration of fabric design working principle with dual mode operation. (b) Spectral emissivity for f_v = 0.01 and 0.1. (c) Ambient setpoint temperature of the design as a function of emissivity.

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