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

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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 a Janus-yarn structure for a dual-mode thermoregulating textile that provides both passive cooling and heating functions by flipping. Using metallic and dielectric fibers within the yarn creates a strong emissivity contrast, benefitting from a plasmonic gap on the one hand, and Fabry-Pérot and multipole localized modes on the other hand. By tailoring the yarn structure, an emissivity contrast $\Delta\varepsilon = 0.72$ was achieved resulting in a significant 13.1°C setpoint temperature window, with the wearer staying comfortable between 11.3 and 24.4°C.

Introduction

To keep up with the rapidly expanding gap between clean energy production and overall energy demand, optimizing the consumption becomes a necessity. From the various major energy-loss channels in today's society, heating and cooling of mostly empty spaces in commercial and private buildings stand out. Therefore, instead of large-scale energy-demanding systems, passive thermal management at a personal scale can be a critical measure to lower consumption and guarantee a sustainable future.

For personal thermal management technologies, more specifically for textiles, controlling the radiative body heat transfer has gained more attention than other heat transfers, due to its universality and high tunability. In indoor settings such as offices, the human body loses more than 50% of its metabolically generated heat by emitting infrared (IR) radiation [1]. Several state-of-the-art fabrics based on different structures were designed and fabricated for passive (requiring no energy input), single-mode (cooling or heating) [2,3], and dual-mode (both heating and cooling) [4] thermal management. They often rely on photonic designs to regulate radiative transfer from the human body to the surroundings.

In this work, we demonstrate a promising Janus-yarn framework for a personal thermoregulating fabric [5]. The design capitalizes on numerous photonic effects that stem from the design geometry and material choice to achieve both heating and cooling functionalities, thanks to a strong emissivity contrast ($\Delta\varepsilon = 0.72$) between the two surfaces of the fabric. This contrast results in a very significant 13.1°C ambient temperature window for comfort.

Problem statement and design working principle

Traditional textiles can only function in one mode (see Fig. 1, right), and can only be utilized comfortably in a limited temperature window. One must therefore adapt the clothing they wear in 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 design for a Janus-yarn fabric possesses dual-mode

functionality, with a switching capability via flipping of the fabric (see Fig. 1). This provides an opportunity to thermoregulate for a large range of ambient temperatures.
The core working principle relies directly on the outer surface emissivity of the fabric. 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 (see Fig.1). 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. On the other hand, flipping the same fabric exposes the low emissivity side – highly reflecting metallic micro-fibers – to the ambient, acting as radiative insulation. 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.

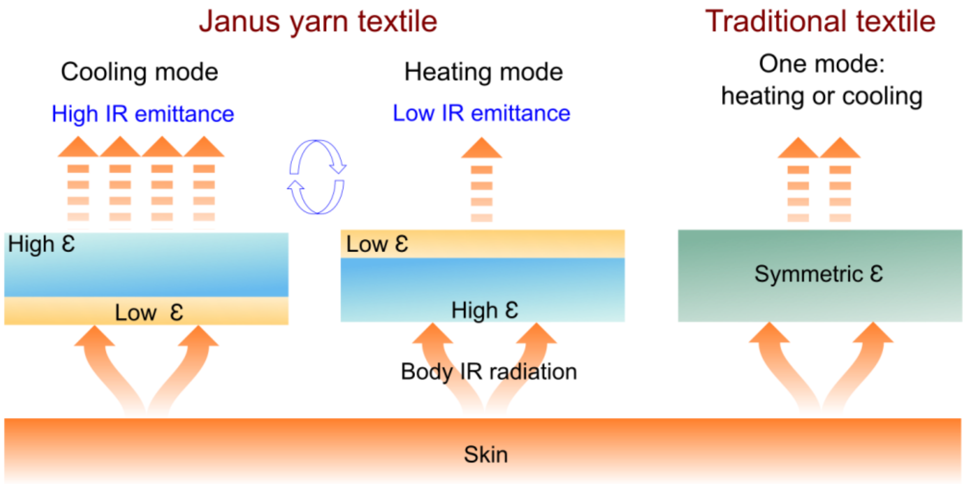

Figure 1 - Janus yarn textile working principle. When a high emissivity layer faces the ambient, the fabric is in cooling mode (left). Once the textile is flipped and the low emissivity layer faces outside, the fabric is in heating mode (center). In contrast, a traditional textile (right) only has one mode: heating or cooling.

Modeling approach

The proposed Janus-yarn textile provides comfort over a large temperature range when design parameters are optimized. To determine this temperature range, we first utilize electromagnetic modeling to retrieve spectral and total radiative parameters, consequently implementing them in our thermal model. Details can be found in ref. [5].
To study the IR radiative response (absorptivity α, transmissivity τ and reflectivity ρ) of the design geometry, we use a finite-element-based Maxwell equations solver (COMSOL Multiphysics). The simulated geometry is constituted from metallic fibers on one side, and dielectric fibers on the other side (Fig. 2a), in a hexagonal pattern. The metallic fibers were modeled by implementing perfect reflection of their surface, which is a very good approximation for many metals in the relevant IR wavelength range – 4-25 μm in our case [6]. 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.
Simulations are performed from both sides of the structure, at normal incidence, for two light polarizations relevant to the calculation of unpolarized radiative properties. Due to computation time and resources, the design's geometric optimization (variation of amount, radii and spacing of fibers) is done using 2D parametrization. Subsequently, 3D simulation is deployed for the best-performing design with optimized geometry.

The range of comfortable ambient temperatures 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, conduction, and convection, which intervene differently in the system as shown in Figure 2b. The corresponding thermal circuit model (Fig. 2c) 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.

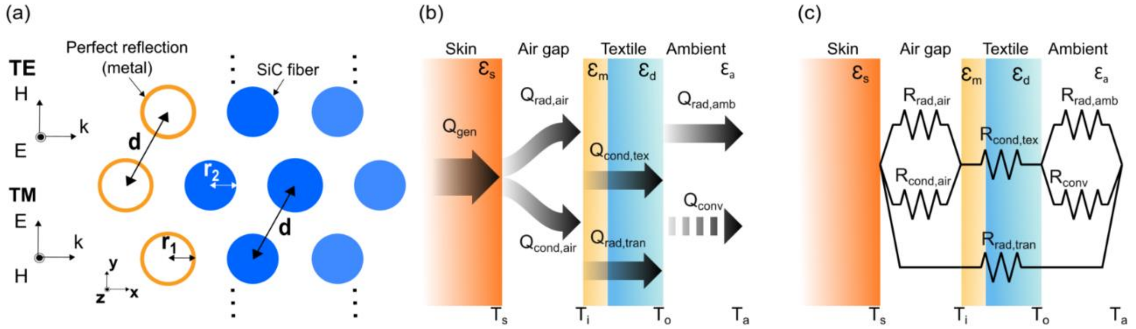

Figure 2 – (a) Electromagnetic modeling. The polarisation convention and incidence direction are indicated. The pattern is repeated in the vertical y-direction. (b) Main heat flow channels when the fabric covers skin, with an air gap in between (shown in cooling mode). (c) Thermal circuit model. $T_{s/a/i/o}$ are the temperatures of the skin, ambient, inner and outer textile layers, and $\varepsilon_{s/a/i/o}$ are their emissivities.

The requirement for a wearer's thermal comfort is the balance between metabolic heat generation (Q_{gen}) and total heat loss in dry conditions (Q_{dry}). The total heat loss is controlled by the total thermal resistance R_{tot} between skin and ambient, obtained via the circuit model. The comfort condition is thus given by $Q_{gen} = Q_{dry} = \frac{T_{skin}-T_{amb}}{R_{tot}}$.
Importantly, due to the asymmetric emissivity characteristics, the Janus-fabric possesses two different R_{tot} for heating and cooling modes, calculated using the circuit model. By considering constant metabolic heat generation and skin temperature, we then determine the comfortable ambient temperatures in cooling and heating mode.

Results and discussion

First, in 2D simulations, we characterized different structure configurations to evaluate the best performing yarn geometry. We varied the metallic and dielectric fibers radii and their spacing, as well as the number of layers of dielectric fibers.
On the one hand, we found 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.
On the other hand, increasing the size and amount of dielectric fibers mainly improves the absorbing/emitting properties of the yarn from this side. Depending on the fiber size and spacing compared to the radiation wavelength, some photonic resonances such as Fabry-Pérot modes and multipoles inside the fibers can further enhance the absorption/emission of the dielectric side. A detailed analysis can be found in ref. [5].
In the end, the best 2D yarn structure (taking advantage of the plasmonic gap reflection and dielectric absorption) was identified and then simulated in 3D to confirm our results.

The A, T and R spectra from the metallic and dielectric sides of the 3D structure are presented in Figures 3a and c respectively. This yarn geometry achieves an integrated transmissivity of $\tau = 0.004$, an integrated emissivity of $\varepsilon_m = 0.02$ from the metallic side and $\varepsilon_d = 0.74$ from the dielectric side, thanks to the aforementioned plasmonic gap, Fabry-Pérot modes and multipole resonances (field profiles in Fig. 3b).

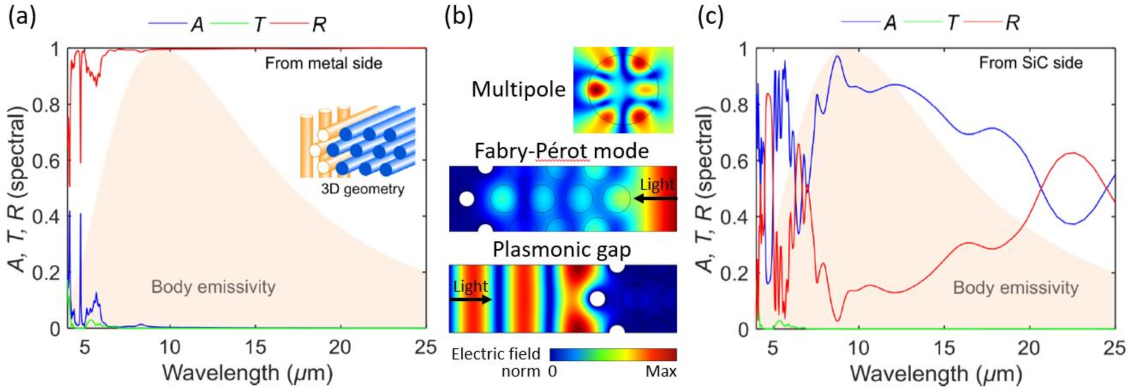

Figure 3 - Unpolarized absorptivity, transmissivity and reflectivity of the best (3D) Janus-yarn structure ($r_1 = 0.6\mu m$, $r_2 = 1.125\ \mu m$, $d = 3\mu m$, 3 layers of SiC fibers), from the metallic (a) and dielectric (c) sides. (b) Field profile examples of the plasmonic gap, a Fabry-Pérot mode and a multipole resonance.

This huge emissivity contrast of $\Delta\varepsilon = 0.72$ and small transmission results in a strong duality of our textile: the minimum and maximum comfortable ambient temperatures calculated through our thermal model, for the cooling and heating modes are respectively 11.3°C and 24.4°C: a comfort range of 13.1°C. This range is far larger than that of traditional textiles, which is usually limited between 19°C and 23°C.

Conclusion

We design and optimize a dual-mode yarn structure for personal thermal management. It achieves an outstanding emissivity contrast between the two sides of the textile, leading to highly efficient cooling and heating modes and a comfortable ambient temperature range from 11.3°C to 24°C. This enlarged comfort range can participate to the reduction of energy consumption for heating and cooling of commercial and private buildings, thereby contributing to a more sustainable society.

Acknowledgements

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