Silver coated textile for versatile personal thermal management via multi-order reflections

Xiaoyu Xie

Donghua University

Yang Liu

Donghua University

Zhao Xu

Donghua University

Dengteng Ge

Donghua University

Lili Yang (✉ liliyang@dhu.edu.cn)

Donghua University <https://orcid.org/0000-0003-3179-8214>

Research Article

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Abstract

Personal thermal management (PTM) is of paramount importance for reducing energy consumption and improving the thermal comfort of individuals. However, wearable textile via facile methods for indoor/outdoor PTM is still challenging. Here we present a novel simple yet effective method for versatile PTM via silver coated textile. Infrared transmittance of coated fabric is greatly enhanced by 150% due to the multi-order reflection of silver coating. Based on their IR radiative cooling, in indoor and outdoor, the skin surface temperature is lower by 1.1°C and 0.9°C than normal cloth, allowing the textile to be used in multiple environments. Moreover, the coated fabric is capable of active warming up under low voltage, which can be used in low-temperature conditions. These promising results exemplify the practicability of using silver coated textile as a personal thermal management cloth in versatile environments.

Introduction

The thermal balance of the human body usually interacts with the complex environment. When the body's energy metabolism and heat dissipation to the surrounding environment reach a balance, it will feel comfortable (Parsons et al. 2003). However, in extreme environmental conditions, if the heat generated by the human body is out of balance with the environment, it will feel uncomfortable, affect people's physical and mental health (Carleton et al. 2016), and even lead to serious physical therapy accidents. Space energy and cooling systems can effectively alleviate this problem, but at the same time they will consume excessive energy and cause global warming and extreme weather (Oreskes 2016; Walther et al. 2002). According to statistics, in 2016, the electricity consumption of building refrigeration systems accounted for about 20% of the total global indoor electricity consumption, and greenhouse gas emissions accounted for more than 10% of global greenhouse gas emissions (Liu et al. 2020; Pérez-Lombard et al. 2008; International 2011). "Personal thermal management" (Hu et al. 2020; Hsu et al. 2015) has become an effective solution to the current problems. Its main idea is to realize the technology of heating or cooling the human body's local environment, which can avoid wasting excess electricity on heating or cooling the entire building. Reduce energy consumption and improve energy efficiency while improving the thermal comfort of the human body. When a person is in an indoor environment, the body surface temperature is maintained at 34°C, the radiated infrared (IR) wavelength range is 7–14 μm , while traditional textiles have the characteristics of high infrared absorption and low infrared emission (Stuart 2004), which seriously inhibits heat loss in hot summer. Therefore, a kind of "radiation cooling" fabric is needed to improve the comfort of the human body in a hot environment.

Existing radiant cooling fabrics increase heat loss mainly by improving the thermal radiation transmittance or solar reflectance of the fabric. The former uses infrared transparent and visible opaque polymers to provide radiant cooling through thermal radiation emitted by the human body to the environment, including: nanoporous polyethylene (nanoPE), polydifluoride (PVDF), polyamide (PA) and other polymers. However, due to the lack of wearing comfort, such polymers are difficult to directly use as fabric materials. The second type of solutions to increase the solar reflectance of fabrics mainly includes: metal laminate or deposition (Zhu et al. 2020; Hrynyk et al. 2013; Miao et al. 2014), nanoparticle

composite (Cai et al. 2018), and fiber porosity improvement (Cai et al. 2018; Wang et al. 2020). Similarly, this type of material has shortcomings such as poor air permeability, and complex processing technology, which makes it difficult to promote and apply.

As illustrated in Scheme 1, human body emits mid-infrared radiation, however, conventional fabric (such as PA) shows low infrared transmittance which suppress the IR radiative heat dissipation. Here, we present a high infrared transmittance fabric for personal thermal management based on high thermal conductivity and multistage infrared reflection of silver coated fiber. Highly efficient heat dissipation is achieved while the original wearing comfort is maintained. We believe that this Ag@PA textile provides a new idea for "personal thermal management".

Experimental Section

PA fiber bundles (Nylon-66, 280 D) are purchased from Qingdao Tianyin Textile Technology Co., Ltd. Ag@PA fiber bundles (280 D) are prepared from the electroless plating on PA fiber bundles using a solution of 7 g/L silver nitrate, 3 g/L ammonia, 15 g/L glucose and 2 g/L catalyst hexamethylenetetramine for 40 min. Silver nanowires dispersion (AgNWs with a diameter of 30 nm and a length of 30 μm , anhydrous ethanol with a concentration of 3 mg/mL) is purchased from Shanghai Bohan Chemical Technology Co., LTD. PA fabric (58 g/m²) and Ag@PA fabric (66 g/m²) are directly woven from PA bundles and Ag@PA fiber bundles on Stoll ADF 530W. AgNW-PA cloth (60 g/m²) is achieved from dip-coating of PA cloth in Ag NWs solution and vacuum drying for 6 h. Infrared transparent and visible light opaque (nanoPE) film (thickness of 16 μm) is purchased from Asahi Kasei Company, Japan.

IR transmittance (τ) is measured by FT-IR spectrometer (Thermo Scientific Nicolet iS 50). The infrared photo is taken by an infrared thermal imager (Flir T62101). The infrared transmission energy is measured by an infrared thermal imager and ResearchIR 4 software. A fiber optic spectrometer (USB2000 spectrometer, Ocean Optics, USA) is used to measure the visible light reflectance and transmittance of fabrics. Scanning electron microscope (SEM) images are taken by TESCAN (MAIA3, Czech Republic). The thermal conductivity of the fiber bundle is measured by a thermal constant analyzer (HOTDISK TPS2500S).

IR reflection of fiber bundle

The fiber bundles are tightly twined side by side on a white paper-made cardboard. The temperature of surface heat source (10×20 cm²) is set to 70°C. The distance between bottom of the substrate and the heat source is maintained 2 cm. The effective reflection area is changed via the rotation angle α between the substrate and the heat source. An infrared thermal imager was placed horizontally to measure the IR reflected energy.

IR transmission of fiber bundle

The fiber bundles are arranged closely on the PE substrate in a single and three layers. The surface heat source is set at 70°C, and the relative height of the substrate and heat source is maintained at 6 cm. The IR thermal imager is perpendicular to the horizontal plane of the substrate, and IR transmittance energy of fiber bundles along the vertical direction was measured by ResearchIR 4 software.

IR emission of fiber bundle

The fiber bundles are tightly twined side by side on a white cardboard, and the surface heat source temperature is set to 50°C. The cardboard is attached to the heat source and keep the temperature constant after 5 min. The infrared thermal imager is set to the temperature measurement mode, and three different measurement points were taken to measure the temperature for three times. The ambient temperature and the actual fiber bundle temperature are generated by the heat of the contact thermocouple. The emissivity of the two fiber bundles can be calculated by:

$$\varepsilon = \frac{(T'_0)^n - T_u^n}{T_0^n - T_u^n} \quad (1)$$

where T'_0 is the temperature displayed by the infrared camera, T_u is the ambient temperature, T_0 is the actual temperature of the fiber bundle, and the value of n is related to the working band of the thermal imager, for the band range of 8-13μm, the value of n is 4.09.

Joule Heating tests

The cloth sample is cut into 3 cm×3 cm, and copper tape is pasted on both ends of the sample for electrical contact. The voltage is provided by Mestek DP152 DC stabilized power supply. Temperatures are monitored by a thermocouple (diameter 0.3 mm, type K) connected to a temperature controller.

IR transmission simulation

COMSOL Multiphysics software was used to simulate the infrared energy transmission. Two-dimensional model was chosen, and ray optics → geometric optics (GOP) for the physical field was selected. The geometry model was circular and formed into an array (double layer). The materials were set to Ag and PA respectively. The wavelength of ray was set to 9.5 μm.

Results And Discussion

Morphologies of silver coated fiber

As a typical commercial fiber, PA fiber is here presented in Figure 1A-i with a diameter of 20 μm. After the electroless plating, fibers remain their original morphologies, i.e. Ag@PA fiber (Figure 1A-ii). The diameter of Ag@PA fiber is almost unchanged, indicating the uniform and very thin silver layer. The EDS element

distribution images of Ag@PA fiber (Figure 1B) confirm the full coverage of Ag on the PA fiber surface. The XRD patterns of PA fibers and Ag@PA fibers are also shown in Fig. S1. The two diffraction peaks at 20° and 24° or merged 22.4° correspond to the characteristic peaks of PA fiber. The XRD peaks appearing at 38.22° , 43.51° , 65.34° and 76.40° indicate the (111), (200), (220) and (311) planes of face centered cubic structure (JCPDS No. 87-0719). The XRD results also demonstrate that silver is successfully coated on the surface of PA fiber.

IR properties of Ag@PA fiber bundle

In order to study the infrared properties of Ag@PA fabric, the infrared properties of Ag@PA fiber bundle are firstly investigated, including IR reflection, transmission and emission. Figure 2A presents a schematic diagram for the infrared reflection tests. The fiber bundles are tightly twined side by side on the white cardboard (as a low IR reflective material). Figure 2B shows the IR images of two bundles at rotation angle α between the cardboard and heat source of 90° and 30° . Ag@PA fiber bundle seems brighter than PA fiber. When the rotation angle α gradually decreases from 90° , the reflection energy increases (as shown in Figure 2C). The reflection energy of Ag@PA bundle remains higher than that of PA bundle, indicating the high reflection of silver coating. Figure 2D shows a schematic diagram for testing infrared transmission performance. The fiber bundles are twined on the PE substrate with single and three layers respectively. Figure 2E and 2F exhibit the infrared transmission energy curve in the vertical direction of fiber arrangement. Figure 2G shows the Fourier infrared spectra of the two fiber bundles arranged in a single layer. It can be seen that the PA fiber bundle maintains low transmission energy in both monolayer and three-layer condition. In contrast, the IR transmission energy of Ag@PA fiber bundle demonstrates high-low values alternately. Comparing with the bundle image, it is obvious that high IR transmission comes from the edge of the Ag@PA fiber bundle, which is probably due to the high IR reflectivity of the silver coating. Using the experimental setup shown in Fig. S2 and based on the equation (1), the emissivity ε of Ag@PA fiber bundle and PA fiber bundle is calculated to be 0.69 and 0.87, respectively, indicating the lower IR absorption of Ag@PA fiber bundle.

In order to further describe the IR penetration path of fiber bundles and understand the difference of IR transmittance between different fiber bundles, the infrared transmittance process is simulated via COMSOL Multiphysics. Figure 2H and 2I show the paths of IR lights after the incidence on Ag@PA fiber bundle and PA bundle, respectively. The incident infrared light is absorbed greatly in the PA fiber bundle, and almost no transmission is observed. Ag@PA fiber bundles greatly increase the transmitted infrared beams due to the multi-level reflection of infrared rays on the multilayer silver-plated fiber.

PA fabric and Ag@PA fabric are woven using bundles under the same condition. Figure 3A and 3C demonstrate the same weave structure of two fabrics. IR thermal images of one-layered or double-layered fabric are taken in order to compare the IT transmission visually. Figure 3D shows that PA fabric have high infrared transmission energy only at the cavity of fiber bundle edge. On the contrary, the infrared transmission energy of Ag@PA fabric (Figure 3B) is greatly enhanced whether it is in a single-layer or double-layer state. Figure 3E summarizes the IR energy flux at different temperatures of heat source

(40°C, 60°C and 80°C). It's indicated the IR transmission radiance of Ag@PA fabric is greater by 20-50% than that of PA fabric. The IR transmission using a Fourier Transform infrared (FTIR) spectrometer with diffuse gold integrating sphere and IR radiance at different heat sources are also studied. Figure 3F shows that the infrared transmittance of Ag@PA fabric in the 2.5-12 μm infrared band is around 40%, about 2.5 times of that of PA fabric.

IR adaptive applications of Ag@PA textile

Personal thermal management includes the applications of IR adaptive textile in indoor and outdoor environments. In order to compare the IR adaptive properties, here PA cloth doped with silver nanowires (AgNW-PA cloth) was prepared and tested. As shown in Figure 4A, three different fabrics are wrapped on the forearm in double layers, which are then exposed in lab. The thermal images are also taken and all samples are in thermal equilibrium before imaging. Moreover, the infrared radiation energy penetrating the fabric is also tested. Compared with three fabrics, the skin surface temperature beneath the PA cloth is the highest, and the temperature difference between two sides of PA cloth is the greatest, suggesting the excellent thermal insulation of PA cloth. In contrast, the thermal images show that the area covered by Ag@PA cloth is in a "hot" state, indicating that the infrared transmission energy value in this area is large, which is beneficial to the heat dissipation of human body. In the indoor environment, the temperature of the Ag@PA cloth covered skin only increased by 0.4°C compared with the bare skin (34.1°C), which achieved a 1.1°C drop in temperature compared to the traditional PA cloth.

People inevitably need to be exposed to high-temperature outdoor environments during daily life, while the outer high temperature will cause the heating up of Ag@PA cloth quickly. In order to decrease the sunlight radiation in visible band, as shown in Figure 4C and 4E, an infrared transparent and visible light opaque (nanoPE) film is knitted on the surface of Ag@PA cloth, i.e. PE/Ag@PA cloth. This new fabric can not only maintain the high infrared transmittance of the original fabric, but also reflect visible light efficiently (as shown in Fig. S4). The IR thermal images of different fabrics under sunlight are taken and the surface temperatures are tested. From the results in Figure 4D, the skin temperature beneath the PE/Ag@PA cloth is lower by 0.9°C than that of traditional PA cloth with the outdoor sunlight radiation. The skin temperature beneath the Ag@PA cloth is close to that of PA cloth due to the great visible radiation absorption. These results prove that our fabric can be used both in indoor and outdoor environments.

This Ag@PA cloth is not only capable of passive heat dissipation but also active warming up in cold environments. One piece of Ag@PA cloth with area of 3 cm×3 cm is clamped and copper electrodes are pasted on both ends. The temperature is measured by a thermal couple in close contact with the sample. As shown in Figure 4F, when only 1.5V is applied, the temperature of the fabric can rise frequently. Figure 4G indicates the temperature change versus time when the cloth is applied with different voltages. The function of Joule heating in cold weather further complements the high radiation cooling described previously.

Conclusion

In summary, we have demonstrated a design for versatile personal thermal management fabric based on IR radiation cooling and electrical Joule heating. Uniform silver layer is coated on PA fiber via electroless plating method. The IR properties of coated bundles through experiments and simulations confirm that Ag@PA fiber bundle has higher infrared reflectance and lower infrared absorption rate than PA fiber bundle. The knitted fabric from Ag@PA fiber bundle shows enhanced IR transmittance by 150% due to the multi-order reflection of silver coating on the surface. Compared with traditional PA textiles, the skin temperature can be lowered by up to 1.1°C indoor and 0.9°C outdoor, realizing the "passive cooling" of the human body. In the cold winter, Joule heating can also be used to obtain additional heat to achieve "active heat preservation". In addition, compared with ordinary textiles, Ag@PA cloth remains the advantages of light weight, breathability, and durability. We believe that this excellent high-infrared permeable textile can reduce people's demand for indoor refrigeration, reduce fossil energy consumption, and provide an idea for alleviating global climate problems.

Declarations

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

Figure 1

(A) SEM images of (i) PA fiber and (ii) Ag@PA fiber. (B) EDS element distribution image of Ag@PA fiber.

Figure 2

(A) Schematic diagram of infrared energy reflection test of fiber bundle. (B) Thermal images of PA bundle and Ag@PA bundle at 90° (left) and 30° (right) between bundle and heat source. (C) Infrared reflected energy comparison of two fiber bundles. (D) Schematic diagram of infrared energy transmission test of fiber bundle. (E-F) Infrared transmittance energy change versus location of single-layer fiber bundle (E) and three-layer tiled fiber bundle (F). (G) Fourier infrared spectroscopy of Ag@PA fiber bundles and PA fiber bundles. (H-I) IR light transmission simulation of PA fiber bundle (H) and Ag@PA fiber bundle (I).

Figure 3

(A-B) Optical, SEM and IR thermal pictures of Ag@PA fabric. (C-D) Optical, SEM and IR thermal pictures of PA fabric. (E) IR radiance energy of two fabrics at different heat sources. (F) IR transmission of two kinds of tiled fabrics.

Figure 4

(A) Optical and IR thermal images of three kinds of fabrics wrapped around forearm in indoor and (B) their radiant energies, surface temperatures comparison. (C) Optical and IR thermal images of three kinds of fabrics wrapped around forearm outdoor and (D) their radiant energy, surface temperatures comparison. (E) Schematic diagram for the passive cooling of PE/Ag@PA cloth in hot environment. (F) IR photos of Ag@PA fiber bundle at 0 s, 5 s, 10 s, and 15 s after applying 1.5V voltage. (G) The temperature change versus time after applying different voltages to Ag@PA cloth.

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