TEMPERATURE-REGULATING TEXTILES USING SWITCHABLE INFRARED REFLECTIVITY

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ABSTRACT: We numerically explore the concept of switchable infrared reflectivity using electrodynamic and thermal calculations for the use of passive temperature regulating textiles. We discuss the effects of metal and shape memory polymer coated fibers on the temperature dependent reflectivity of the textile fabric.

Key Words: PHOTONIC BANDGAP, RADIATIVE TRANSFER, SHAPE MEMORY POLYMER

1. INTRODUCTION

The need for constant ambient temperature to maintain thermal comfort is a primary energy consumption in most of today's commercial and residential buildings. Modern developments show that personal cooling and heating technologies can reduce this consumption and provide a cost-effective way of energy usage. However, thermal regulation at a personal level requires a specially designed textile fabric, and a detailed understanding of the heat transfer mechanisms. The human body (with skin temperature 34 °C) emits infrared (IR) radiation centering around 9 µm with a black body spectrum. Furthermore, radiative heat transfer accounts for more than 50% of heat dissipation from the human body at rest. Therefore, with proper radiative thermal management, one can tailor and design passive temperature regulating textiles.

Recently, a number of state of the art passive temperature regulating garments have been proposed: 1) The Infrared-Transparent Visible-Opaque Fabric (ITVOF) [1], a textile that employs a photonic design in the yarn to increase radiative heat transfer through the fabric to provide passive cooling. 2) A textile fabric made out of metal coated fibers [2] staggered within a yarn for the use of thermal insulation. 3) A dual mode textile, utilizing a bi-layer thermal emitter embedded inside IR-transparent nanoporous polyethylene [3]. The dual mode textile, unlike other works, includes both cooling and heating modes within the fabric. However, it is not possible to switch between modes without flipping the textile. 4) A dynamic IR gating textile, a recent technology that uses a combination of carbon nanotubes and humidity sensitive polymers to control dynamically the emissivity of thermal radiation [4]. The drawback of this technology is that it needs humidity to start the dynamic property of the polymer, which requires moisture accumulation on the skin to some extent, leading to potential discomfort. Building upon these developments, here we numerically explore the concept of switchable infrared reflectivity using electrodynamic and thermal calculations.

2. THEORY AND DESIGN WORKING PRINCIPLE

The main idea behind a switchable IR reflectivity is to incorporate temperature responsive shape memory polymers in the photonic design of fibers and yarns. Recent studies have shown that polymers such as bio-based polylactide-urethane [5] and polyurethane [6] show thermally induced shape memory properties around the human body temperature. For smaller polymer coated dielectric fibers below an optimum diameter, the radiation reflectivity rapidly decreases, as large radiation wavelengths only weakly interact with such fibers. However, due to conductivity, polymer coated metallic-dielectric fibers act like little antennae, which scatter and absorb radiation even if the fiber diameter is far smaller than the wavelength of the radiation.

Therefore, we investigate shape memory polymer coated metallic-dielectric fibers assembled within a yarn in a specifically designed photonic geometry, with parameters such as metal coating thickness (t), diameter (df), fiber separation distance (ds), and yarn diameter (dy). At a predetermined comfort zone temperature below a critical temperature T_c, the polymer keeps a particular geometry. When the temperature rises above T_c, the polymer layer expands, thus increasing df, ds, and dy. This results in a new geometric configuration with expected decreased IR reflectivity, and an expected increase in radiative transfer to the environment. On the other hand, when the ambient temperature deviates below T_c, the polymer shrinks, thus decreasing df, ds, and dy. As a result, the initial geometric configuration will change and the IR reflectivity is expected to increase, thus reducing radiative heat loss.

3. RESULTS AND DISCUSSION

We performed numerical finite-element electromagnetic simulations for a silica core fiber coated with 200 nm thick gold staggered as a bundle in a specific geometry to form a single yarn. The reflectivity spectra for two different yarn designs based on this particular geometry for two different ds values is shown in Fig. 1, along with the human body emissivity spectrum. From this plot one can observe that the IR reflectivity for the geometry with ds = 8 µm is close to unity in the wavelength range from 8.5µm to 10.5µm. On the other hand, the IR reflectivity for the geometry with ds = 16 µm has a peak close to unity in the wavelength range of 19 µm to 22 µm.

In both cases, the situation can be interpreted that in some specific wavelength range, the IR propagation through the yarn is forbidden to some extent. In general, the situation where electromagnetic waves cannot propagate through a periodic structure for a certain wavelength range is called a Photonic Band Gap (PBG) effect. Thus, one can conclude that we are observing a PBG in the yarn, for both cases (ds = 8 µm and ds = 16 µm).

However, it is important to assess in which wavelength range it falls compared to the peak of human body emissivity. From the two reflectivity curves, it is clear that the PBG effect of the IR reflectivity for the geometry with ds = 8 µm (Fig. 1, red solid line) is in the same wavelength range as the human body emission. Consequently, this translates to higher reflectivity of thermal radiation back to the human body, thus losing less heat to the environment and keeping the human body warm. However, for the case where ds = 16 µm, the PBG is outside the main wavelength range of human body emissivity. As a result, the reflectivity for this yarn is low, which promotes radiative heat transfer to the environment, and cools the human body.

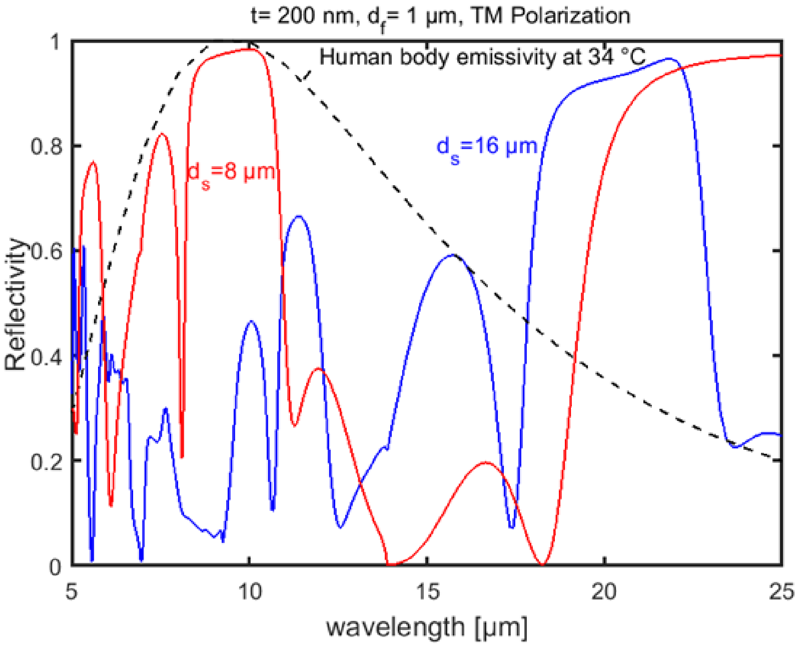

Figure 1. Numerical simulation results for the IR radiation reflectivity of a 200 nm gold coated silica fiber staggered in a specific geometry to form a yarn with ds = 8 µm (red solid curve) and with ds = 16 µm (blue solid curve). We also display the emissivity spectra of the human body at a skin temperature of 34 °C (black dashed line).

4. CONCLUSION

The results obtained above show that switchable IR reflectivity can be achieved by exploiting the geometry-dependent PBG phenomenon. Therefore, by tailoring this PBG effect we can have a suitable reflectivity in or out of the human emissivity main wavelength range. Consequently, this results in a warming or a cooling mode of the textile, depending on the ambient temperature. Overall, the concept of a tailorable IR reflectivity has the potential to achieve a dynamic passive temperature regulating textile.

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