Nanostructured Materials for Radiative Cooling Textiles

Francis Alcorn Literature Seminar October 31, 2019

Indoor space cooling is an energy-intensive process, accounting for nearly 12% of energy consumption by the residential sector in the US in 2015[1]. Studies have suggested that this energy consumption could be reduced by approximately 10% per 1°C increase in indoor cooling temperature setpoints[2]. Aiming to relax the cooling requirements for comfortable indoor environments, several groups have investigated nanostructured materials as radiative cooling textiles, for passive personal cooling.

Radiative cooling relies upon minimizing the absorption of incident radiation on an object, while allowing for outgoing thermal (i.e. blackbody) radiation from the object to escape into a cold reservoir. In the case where the radiative power output from an object is larger than the absorptive power input to an object, there is a net energy flow out of the object, resulting in cooling until the incident and outgoing radiation powers reach a steady state. The steady state temperature of a radiatively cooled object is consequently lower than an object which is not radiatively cooled. Radiative cooling below ambient temperatures in sunny conditions has been demonstrated using a HfO_2/SiO_2 heterostructure which effectively reflects 97% of incident solar radiation while improving emittance radiation in the atmospheric transparency window, thereby using the vacuum of space as a cold reservoir for cooling[3].

As with other radiative cooling materials, a radiative cooling textile should scatter or reflect all incident (external) radiation, while transmitting all outgoing radiation. In the case of textiles for clothing, the outgoing radiation corresponds to the human blackbody spectrum, which is maximum around ~8-12 µm[4]. Toward this goal, several candidate materials have been investigated. Namely, works by Dr. Yi Cui and colleagues[4-7] at Stanford University as well as Dr. Zhong-Ming Li and colleagues[8] at Sichuan University have investigated nanoporous polyethylene (NanoPE) and a work by Dr. YuHuang Wang and Dr. Min Ouyang and colleagues[9] at the University of Maryland has investigated a carbon nanotube coated commercial textile as candidates for viable radiative cooling textiles.

NanoPE films were the first material investigated as candidates for radiative cooling textiles[4]. The simple chemical structure of polyethylene, extended aliphatic chains, results in very few infrared (IR) absorbance peaks(Figure 1A, green), especially in the peak of the human blackbody spectrum[4] (Figure 1A, yellow shadow), making the material effectively transparent to human blackbody radiation. Simultaneously, nanoscale features, 50-1000 nm wide pores, result in Mie scattering of visible light, making the material visibly opaque[4] (Figure 1B, green). In

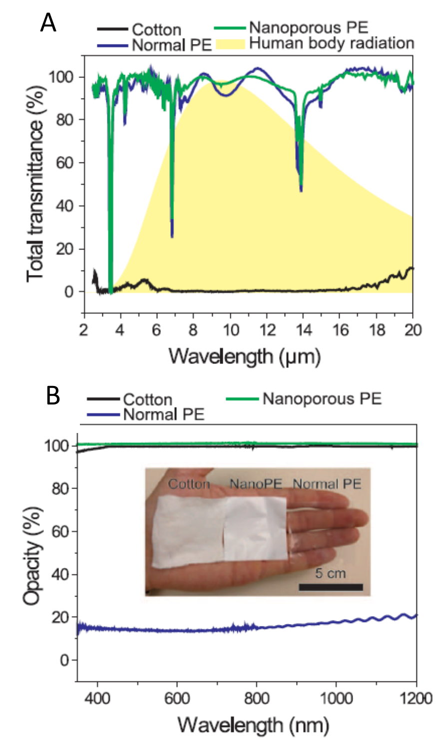

Figure 1: A) IR spectra and B) UV-vis spectra of cotton (black), polyethylene and NanoPE (blue). Human blackbody spectrum is shown in yellow in A Photographs of the material are inset in B.[4]

comparison, normal polyethylene has similar IR transparency to NanoPE but is also visibly transparent (Figure 1, blue curves), while cotton is as visibly opaque as NanoPE but does not transmit IR radiation (Figure 1, black curves)[4]. The combination of visible opacity and IR transparency of NanoPE result in radiative cooling abilities. Using a home built heating device, it was further demonstrated that NanoPE does provide superior cooling than traditional textile materials, cotton and Tyvek, even when processed for improved breathability and water-wicking for textile comfort[4].

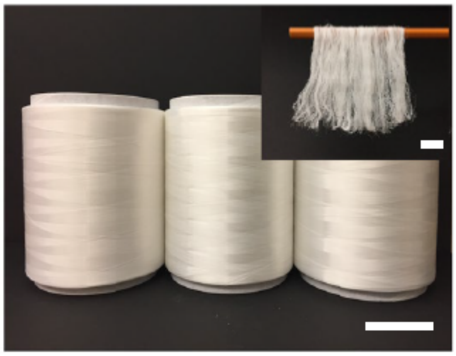

Figure 2: Spools of NanoPE thread (scale bar, 9 cm). Inset: NanoPE threads (scale bar, 1.5 cm)[5].

In later work, Cui and co-workers demonstrated production of NanoPE threads at a large scale for producing fabrics[5]. By extruding molten polyethylene with paraffin oil and subsequently extracting the oil, they could produce strands of porous polyethylene with a cotton-like appearance[5] (Figure 2, inset). In figure 2 are several spools of these NanoPE threads, depicting the scalability of producing this material. As with NanoPE film, fabrics produced by knitting the NanoPE display superior capabilities for cooling than conventional textiles[5].

Several other studies have investigated further control over the optical properties NanoPE using composite-materials[6-8]. A recent work from Cui and co-workers demonstrated that NanoPE fabrics can be colored by mixing several inorganic dyes with molten polyethylene during the extrusion process[6]. Specifically, they investigated Prussian blue (blue dye), iron oxide (red dye), and silicon (yellow) nanoparticles[6]. Importantly, these dyes are IR transparent in comparison to traditional organic dyes. Consequently, the coloration is not at the expense of IR transparency in the resulting fabrics. Figure 3 shows photographs of dyed NanoPE fabrics (left) and IR camera images (right) of these fabric over a human forearm[6]. The bright red coloration through the textiles in the IR camera images is a result of human blackbody radiation, which passes through the textile without attenuation.

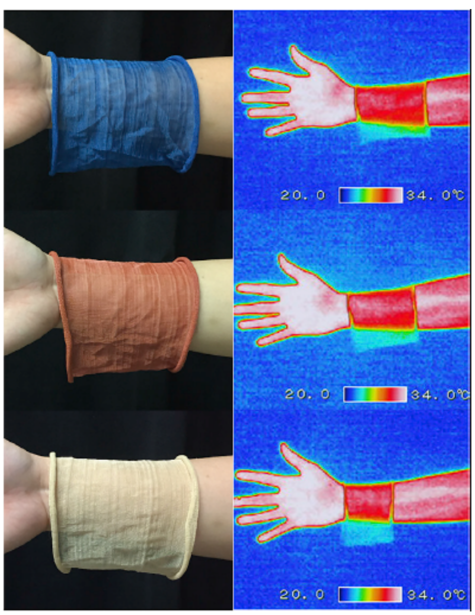

Figure 3: Images of dyed NanoPE fabrics (visible, left and IR, right). From top to bottom: blue, red, yellow[6].

Several studies have shown that NanoPE-based composite materials have enhanced reflectivity over the solar spectrum for further increased cooling abilities compared to traditional textiles in sunny conditions (i.e. outdoors)[7-8]. Cui and co-workers accomplished this by adding ZnO nanoparticles to their NanoPE threads[7]. Similarly, Li and co-workers added nanoscale polyamide (Nylon) fibers to NanoPE films[8]. Both studies demonstrated improved radiative cooling abilities in sunny environments.

While most of the research in radiative cooling textiles has been based around nanoporous polyethylene, a recent work by the Wang/Ouyang groups has sought an alternative route to producing radiative cooling textiles. Specifically, they demonstrated that the IR transmissivity of a commercially-available textile material can be enhanced by adding carbon nanotubes (CNTs) to make the polymer fibers act as conductors[8]. This resulted in an inter-fiber distance-dependent gating of IR radiation. Using environmentally responsive biomorphic fibers, in which hot/humid environments cause the fibers to aggregate and decrease inter-fiber spacing and cold/dry environments increase fiber-spacing, they were able to dynamically control the IR transmissivity of the CNT-coated metatextile over the atmospheric transparency window, as shown in figure 4[8]. The dynamic IR gating increases the radiative cooling in warmer environments where it is favored and decreases it in cooler environments.

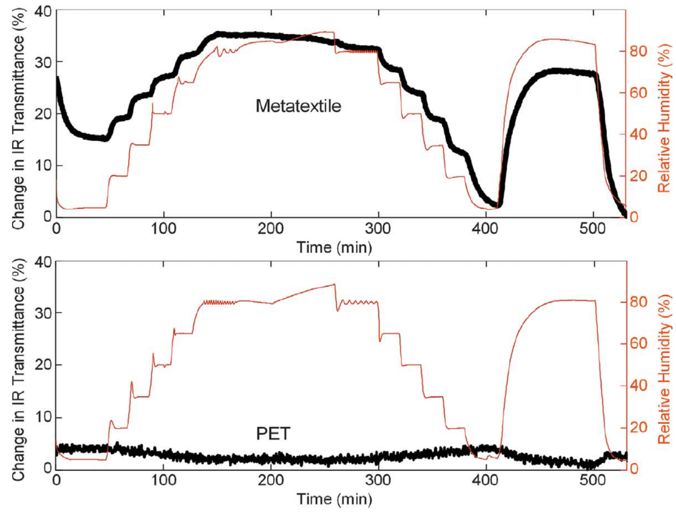

Figure 4: Change in IR transmittance (black line) due to changes in relative humidity (red line) over time for the CNT metatextile (top) and a conventional PET textile (bottom).

The works in the field of radiative cooling textiles have thus far been largely fundamental, investigating either unconventional textile materials (polyethylene[4-8]) or commercial textile materials with an unconventional additives (CNTs[9]). They have been largely proof-of-concept and have not yet fully addressed other parameters necessary for these materials to be commercially viable and useful. Specifically, these materials will need to be sufficiently strong, durable, and comfortable to compete with conventional textile materials. Additionally, as clothing has a role in protection from mechanical, chemical, and ultraviolet hazards, these radiative cooling textiles will need to be studied in this regard. A few studies have demonstrated mechanical strength comparable to some textile materials[4] and durability to washing[6], but these studies are very limited and incomplete. Additionally, several comfort metrics, breathability and water-wicking, have been studied, but comfort to the wearer has not been assessed, and is likely experimentally challenging, due to the subjective nature of comfort. As of yet, no studies have attempted to study if the protection these materials provide compared to conventional fabrics.

In conclusion, several materials, nanoporous polyethylene and carbon-nanotube coated environmentally-responsive textiles, have been shown to possess properties necessary for usage as radiative cooling textiles, but there remain many questions related to their practicality for such applications. These questions will need to be addressed in order for radiative cooling textiles to become viable materials for fabrics and clothing.

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