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Polymer Nanocomposites for Lowering Heating and Cooling Loads in Buildings †

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Abstract: Worldwide, buildings consume over 40% of the total commercial energy, and 36% of this amount is dedicated to heating and cooling of buildings. Therefore, building environment control systems require efficient thermal management (Ürge-Vorsatz et al., 2015). An ideal thermal management that could lower the energy load for cooling and heating respectively would combine passive strategies for thermal control, which are characterized by low cost, straightforward implementation, and energy efficiency, with the on-demand control of heating and cooling, specific for active thermal management strategies. The scientific challenge of building an efficient platform for thermal control was addressed by using block copolymer materials in the development of nanocomposites with dynamically tunable thermal infrared properties. The polymer nanocomposites manage 60–70% of the metabolic heat flux from sedentary individuals and can modulate changes in the individual body temperature within a setpoint temperature range of 8 °C. This increase in the setpoint temperature translates into use of air conditioning for cooling/heating with a significantly lowered load, which would further translate into a 4.3% decrease of global energy consumption.

Keywords: nanocomposite; polymer; thermal comfort; infrared radiation

1. Introduction

Energy consumption for building operation accounts for ~40% of global energy consumption, and their heating and cooling requires ~36% of this amount [1]. This is an opportunity to diminish energy use worldwide [2] through the development of novel personal (localized or wearable) thermoregulatory clothing. For example, the US Department of Defense (DoD) is one of the largest energy consumers worldwide, and the 300,000 buildings spread across >1000 DoD installations worldwide account for ~30% of DoD and ~21% of USA federal government energy consumption, corresponding to an annual resource commitment of ~2.1×10^{14} Joules at a cost of $12.5 billion [3,4]. Worldwide, the total energy cost are >6400 billion US dollars [5]. There are multiple measures that can be pursued for lowering energy costs with a high return on investment, such as the retrofitting of lighting fixtures; incorporation of upgraded heating, ventilation, and air conditioning system components; adoption of novel energy distribution strategies; modification of building thermal envelopes via improved roofs and windows; and implementation of behavior-based solutions for personnel. In essence, such measures represent a strategy for transforming the resilience, reliability, and efficiency of installation energy consumption into a strong reliable method for cost saving and efficiency improvements within the next decades. Consequently, the development of novel and improved approaches to energy management (which will facilitate the aforementioned sustainment and recapitalization projects) remains of critical importance both for improving the energy efficiency and for enhancing the quality of life of consumers worldwide while maintaining affordable costs for energy.

Currently, almost all buildings, whether permanent or temporary, employ traditional systems based on decades-old thermal management methodologies, which are categorized either as "passive" or "active" depending on their mode of operation [6–9]. On the one hand, passive thermal management systems and technologies, such as building insulation and reflective coatings, leverage the intrinsic properties of their constituent materials to facilitate heat transfer via conduction, convection, and/or radiation, thereby making them static but low cost, energy efficient, and straightforward to implement [6–9]. On the other hand, active thermal management systems and technologies, such as building air conditioning and heat pumps, require the input of energy from an external source to facilitate heat transfer (via the same mechanisms), thereby making them costly, relatively inefficient, and complex, but precisely and directly controllable by a user [6–9]. Within this context, the "ideal" thermal management technology for buildings would simultaneously feature the key advantageous characteristics of both passive and active systems, i.e., a reasonable cost, little-to-no energy input requirement, straightforward implementation, and user-controlled adaptability to changing conditions.

Among passive systems, "space blankets," such as the one shown in Figure 1A, have emerged as one of the famous known thermal management technologies [10–12]. Space blankets were initially developed by NASA in the 1960's to mitigate the effect of extreme temperature fluctuations on personnel, equipment, and spacecraft, and in their most basic configuration, consist of a thin layer of metal on a transparent plastic sheet [10]. This material configuration, while highly effective at reflecting infrared radiation, features static properties and cannot be dynamically reconfigured on demand. Nonetheless, due to a favorable combination of low weight, compactness, and manufacturability, various incarnations of the space blanket have found both military and civilian applications as food packaging, emergency portable shelters, medical warming devices, protective clothing, building insulation, and solar concentrators [11,13,14]. Specifically, space blankets have proven particularly invaluable as emergency portable shelter components and medical warming technologies, helping to save countless lives in the field [14,15]. More generally, space blankets have made a global impact by facilitating space exploration, improving food storage, and reducing energy consumption. Despite their technological significance, space blankets have remained essentially unchanged as passive thermal management technologies and still function in much the same way as they did over fifty years ago.

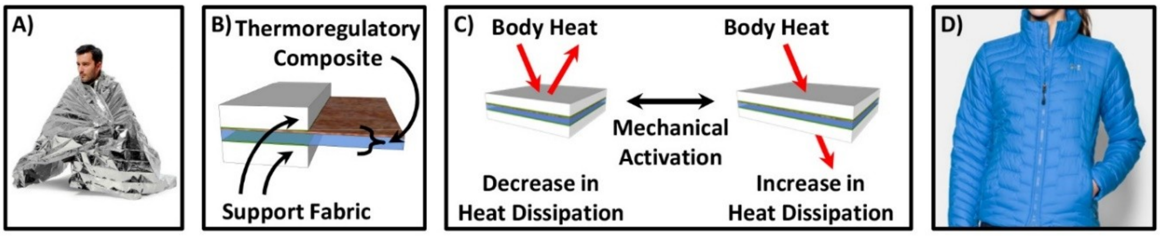

Figure 1. (**A**) A picture of a space blanket. (**B**) A schematic illustration of the proposed thermal comfort and efficiency garment. (**C**) A schematic of the activation mechanism for thermal efficiency nanocomposite, which shows switching between two heat dissipation states. (**D**) A picture of integrated thermal efficiency nanocomposite with garment.

This paper presents a laboratory technology for making wearable, clothing-integrated dual-mode (heating and cooling) polymer nanocomposites for providing thermal comfort to consumers in a passive way and benefitting the environment by lowering the energy consumption. These materials are based on thermoplastic elastomers (TPEs) coated on one side with nanometer-thick metal layer and integrated with the clothing made of well-known textile materials (such as cotton, polyester)[1]. The working principle of these materials is showed in Figure 1B,C. This material brings an opportunity to diminish energy use worldwide through the development of novel personal (localized or wearable) thermoregulatory clothing.

The nanocomposites can be integrated in novel adaptive thermoregulatory textile as comfort garment with a multi-layer structure, similar to a dynamically adaptive space blanket-like material is sandwiched between two fabrics, as illustrated in Figure 1B. In it, the cloth would have mechanical properties similar to spandex, and wearers will induce changes in its thermoregulatory properties through mechanical activation (stretching or similar, which is easily achieved in clothing via zippering, buttoning, drawstrings, etc.). Before mechanical activation, the cloth traps infrared radiation emitted by the wearer, leading to a decrease in heat dissipation and a heating effect, and after activation, the cloth releases infrared radiation emitted by the wearer, leading to an increase in heat dissipation and a cooling effect, as illustrated in Figure 1C. Thus, garments that integrate such thermoregulating materials, such as the jacket in Figure 1D, will maintain the skin of person wearing it at a constant temperature even when the external one varies by >10 °C, representing a significant advance with regard to the current state-of-the-art.

The development of advanced thermal management textiles that dynamically regulate the energy exchanged by the human body with its environment is a grand challenge in the clothing industry [16,17]. Such technologies would allow wearers to trap or release the energy produced by their bodies via evaporation, conduction/convection, and/or radiation, and thus, would enable them to directly maintain a consistent temperature in changing thermal settings [16,17]. Within this context, the space blanket shown in Figure 1A represents the simplest incarnation of a wearable thermoregulatory technology, as it efficiently traps the body's emitted infrared radiation and lets users maintain their thermal comfort in cold environments.

2. Experiments

Materials and Methods

To prepare the nanosized metal layer, a ~20 nm planar metal film (aluminium, copper, zinc, nickel) was electron beam evaporated onto a 6-inch diameter silicon wafer (University Wafer) by using electron beam evaporation technique (Figure 2A).

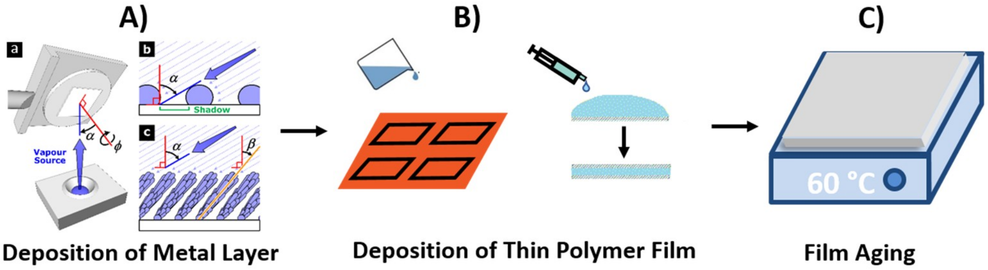

Figure 2. (**A**) Deposition of nanometer thick metal layer, (**B**) Embedding of metal layer within an infrared-transparent elastomer, (**C**) Maturation of nanocomposite on hot plate.

Next, to embed the nanosized metal layer within an infrared-transparent elastomer, a 10–100 micron thick film from commercially-available hydrogenated styrene-based block copolymer (Kraton Polymers LLC) was deposited directly onto the metal-modified substrate either by spin coating, doctor blading or dip coating (Figure 2B).

Then the composite was maturated on a hot plate at 60–70 °C for 10–15 min and then delaminated from the substrate (Figure 2C). The resulting nanocomposite films were used for physical, mechanical (Instron 3365 Universal Testing System), morphological (SEM), and infrared (FLIR C2 infrared video camera) characterization experiments as needed.

3. Results

The experiment began by fabricating the desired composite material according to the scheme in Figure 2A. The samples have areas of > ~160 cm^2 by using common laboratory techniques: spin coating, dip coating, doctor blading. The infrared-reflecting nanostructured metal film was electron-beam evaporated onto a support substrate (Figure 2A) *(33)*, obtaining an underlying continuous metal coating, as confirmed by top-down scanning electron microscopy (SEM). Next, the metal layer was embedded in an infrared-transparent styrene-based copolymer (Figure 2B). Subsequently, the nanocomposite was aged on a hot plate and delaminated from the substrate to obtain a free-standing material, which featured a multi-domain metal layer on one side, as confirmed by top-down SEM analysis. Overall, this is a robust procedure suitable for scaling for large area nanocomposite materials.

The nanocomposites were characterized in terms of mechanical properties via tensile testing and the engineering stress versus engineering strain data shows such materials are soft and stretchable elastomers, with an average elastic modulus of 2–3 MPa and an elongation at break of ~700% (Figure 3). In initial state, the nanocomposite samples are opaque and highly reflective, with irregularly-shaped metal domains. Applying a mechanical strain of only 30%, the composites became partially transparent and less reflective. The soft elastomer behaviour of the nanocomposites leads to no hysteresis, with fully reversible mechanical loading/unloading in < 1 under multiple mechanical cycles. Such characteristics make this nanocomposite a thermal switch with a fairly rapid response time.

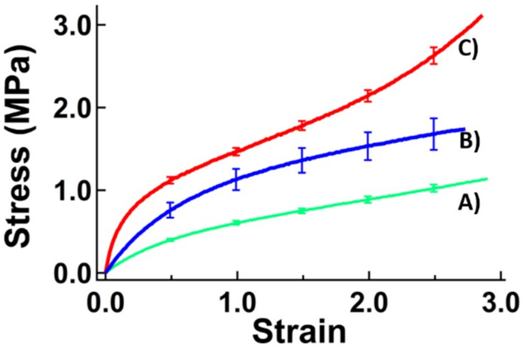

Figure 3. (**A**) Stress-strain curve for film of pure block copolymer with 15% styrene content, (**B**) Stress-strain curve for film of pure block copolymer with 30% styrene content, (**C**) Stress-strain curve for film made of nanocomposite material.

4. Discussion

The nanocomposites can modulate infrared reflectance and transmittance on demand under applied mechanical strain. In initial unstrained state (Figure 4 left), it demonstrates infrared reflectance of ~100% and a low average total transmittance of <1%, since the metal domains cover completely the infrared-transparent polymer matrix. When mechanical strain is applied the infrared reflectance decreases with an increased infrared transmittance (Figure 4 right), since the polymer matrix is only partially covered by reflecting metal nanolayer. Both the reflectance and transmittance of infrared light of the nanocomposite show linear dependence up to 50% linear mechanical strain of the samples. The ratio of infrared transmittance at strains of 0% and 100% is >30 showcasing the reversible thermal switching behavior.

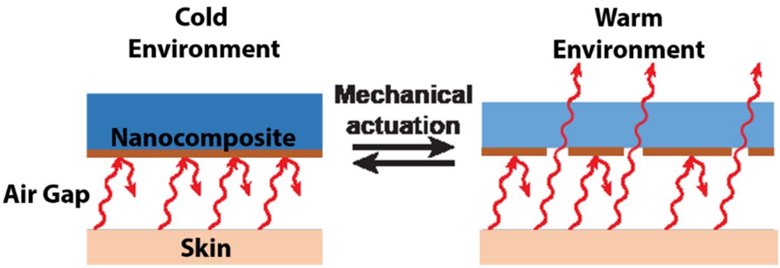

Figure 4. Schematic of the heat flux (red arrows) from human skin, relative to outside environment with a variable temperature, shown without (**left**) and with (**right**) mechanical actuation. After actuation, the heat flux from the skin to the environment increases, and the skin maintains a constant temperature between cooler (**left**) and warmer (**right**) environment temperatures.

In order to assess the reversible dynamic thermal switch capability, sleeves integrating nanocomposite and cloth were tested under mechanical actuation (Figure 5). An infrared video camera was used to record the change in temperature and the outgoing heat flux of the skin on forearms fitted which such sleeves. The sleeve was actuated mechanically by uniaxial strain (Figure 5 left). The sleeve made with space blanket strips trapped and reflected back the heat emitted by the covered forearm, raising the skin temperature by 1.0 ± 0.1 °C more than the bare forearm of the same person (Figure 5G and Figure S7). The unactuated reflective nanocomposite-based sleeve reflected the heat emitted by the covered forearm and raised its temperature by ~0.9 ± 0.1 °C more than the same person's bare forearm Under an applied strain of 50%, the nanocomposite-based sleeve raised the temperature of the forearm by only 0.1 °C more than the same person's bare forearm (10-fold reduction in the temperature change measured for the space blanket). Thus, the nanocomposite-based sleeves could be adjusted to modulate the consumers' local changes in body temperature by nearly an order of magnitude, more than the reported temperature perception thresholds for a variety of human subjects [18]. Such data opens the way for research on development of nanocomposite materials that regulate the local temperature across the different parts of human body.

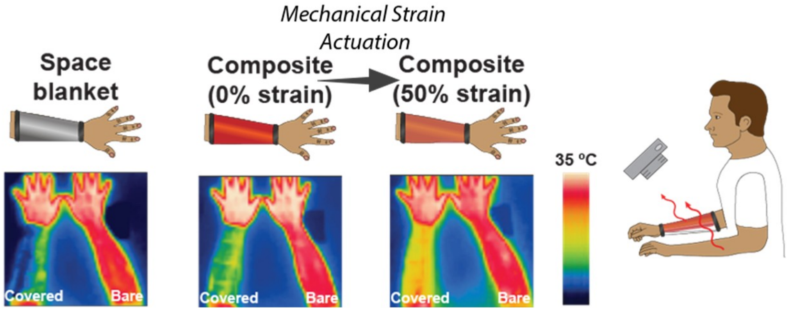

Figure 5. Test of nanocomposite cloth sleeve with infrared FLIR C2 video camera.

Left: Forearm covered with a space blanket sleeve (top) and infrared camera image of a forearm covered with a space blanket-based sleeve (left) and a bare forearm (right); forearm covered with nanocomposite sleeve under a mechanical actuation of 0% (top) and infrared camera image of a forearm covered with a composite-based sleeve (left) and a bare forearm (right); forearm covered with nanocomposite sleeve under a strain of 50% (top). Infrared camera image of a forearm covered with a composite-based sleeve under a strain of 50% (left) and a bare forearm (right) (bottom); -Right: Experimental visualization with infrared camera of the outgoing heat flux and local temperature for a human subject with one sleeve-covered forearm and another bare forearm.

The next step involved the evaluation of the nanocomposites' capability for adaptive thermal management, for possible application in clothing. The data from experimental measurements taken with the infrared camera (Figure 5) was used to model heat transfer between human skin and the surrounding environment with an air gap similar with real clothes (Figure 4). The setpoint temperatures (the ones at which the body's skin temperature and outgoing heat flux remain constant, and humans maintain their thermal comfort) were calculated for multiple textile materials. The unactuated nanocomposite has a setpoint temperature of 14.5 °C similar to a space blanket (14.3 °C) (Figure 6). Applying increasingly larger mechanical actuation to the nanocomposite leads to increasing the setpoint temperature of the nanocomposite, similar to multiple common textile materials (Figure 6) and thus the nanocomposite mimics the capabilities of such fabrics and textiles.

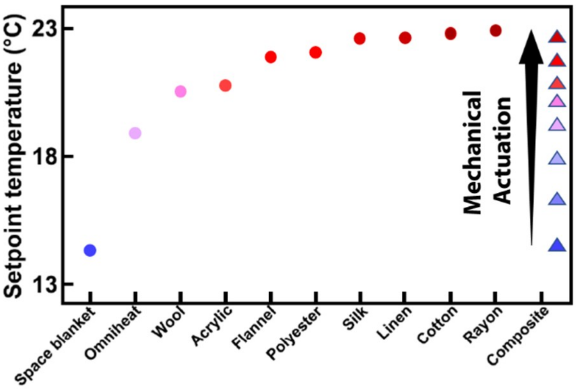

Figure 6. Environmental setpoint temperatures at which a human would maintain a constant skin temperature and unchanged outgoing heat flux while wearing various common types of cloth (circles) or the nanocomposite mechanically actuated (triangles).

Any structure, either temporary or permanent, is exchanging heat with the environment (Figure 7A). The energy consumption for buildings represents 40% of worldwide energy consumed annually, and from this 36% is used for heating and cooling (Figure 7B). The use of clothing integrating the nanocomposite would allow an expansion of the set point, similar to consumers wearing traditional thick warm clothing (Figure 6).

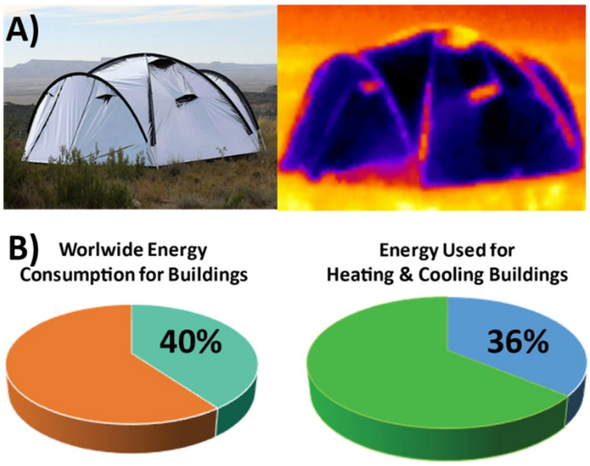

Figure 7. (**A**) Left: visible image of tent. Right: infrared camera of same tent, showing heat losses, (**B**) Ratio of worldwide energy consumed for buildings, and ratio of energy consumed for heating and cooling buildings [1].

It is well-known that expanding the cooling and heating set-points by 4 °C each can lead to large energy savings up to 45 and 35%, respectively [19]. Thus, the expansion of the heating set-point by 4 °C (22 °C to 18 °C) leads to energy savings of 35% and consequent theoretical energy savings (Figure 7B) of 0.35 * 0.36 * 0.40 = 5%. Experimental implementation of decrease in setpoint temperature in a building lead to a significant 5% decrease in energy consumption for every degree the setpoint temperature was dropped [20]. Therefore, a calculation of the global impact of decreasing the setpoint temperature from 22 °C to 16 °C (6 °C difference) would yield 5%/°C * 6 °C = 30% reduction in energy consumption in building. Therefore, personal clothing with integrated nanocomposite which provides an expanded range of thermal comfort temperatures and thermal efficiency for users holds the potential to reduce global energy consumption by up to 0.30 * 0.36 * 0.40 = **4.3%**.

5. Conclusions

The nanocomposite described here can be integrated with textile cloth for development of an artificial thermo-regulatory platform. The nanocomposite function via a unique mechanism that relies on reversible and mechanically-actuated changes in surface microstructure. Such materials change their reflectance and transmittance in the infrared region of the electromagnetic spectrum and their thermoregulatory properties resemble those of common materials, such as the space blanket, fleece lining, wool, and cotton. The nanocomposite behaves like radiative thermal switch with straightforward mechanical actuation method without hysteresis, and can regulate skin temperature changes for consumers in real time. Even more, such nanocomposites can be manufactured from low-cost commercially available starting materials using scalable processes.

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Conflicts of Interest: The author declares no conflict of interest.

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