In recent years, personal cooling technologies have been developed to provide local environmental control to ensure the user remains thermally comfortable when in extreme environmental conditions such as those faced by athletes, the military, or EMS personnel.[1] However, there remains a distinct lack of such technologies for everyday use by the average end user who spends the majority of the time in a sedentary state. This is especially important for indoor environments where incorporation of such technologies can offset energy consumed by HVAC systems for cooling while maintaining sufficient levels of thermal comfort. For instance, recent studies have shown that in the United States alone, residential and commercial buildings consume nearly 41% of total energy use each year with 37% of that energy devoted solely to heating and cooling.[2,3] To reduce energy usage, buildings have incorporated more renewable energy sources such as solar power, implemented advanced HVAC systems, utilized higher performing thermal insulation, and phase change materials for thermal storage all of which requires significant financial investment.[4–6] Instead, personal thermal comfort technologies offer a potentially low cost solution towards mitigating energy use by HVAC systems. Although these technologies can be used in a variety of indoor and outdoor environments, the focus of this work is to provide personal cooling in temperature regulated indoor environments.

At present, several technologies are commercially available which provide varying degrees of personal cooling. However, these technologies are typically tailored as high performance products, such as sportswear, body armor, and personal protection equipment, thus limiting functionality for everyday use. Arguably the most prevalent personal comfort technology used in industry today is moisture wicking where sensible perspiration is drawn away from the skin to the outer surface of the fabric and evaporated to ambient air thus cooling the wearer passively.[7–9] The drawback of this technology is that it is activated only when the wearer is sufficiently perspiring so that moisture accumulates on skin; thus, moisture wicking is not suitable to provide cooling for sedentary individuals. Other technologies utilize phase change materials in the form of cold packs which can effectively draw heat from the human body due to the high latent heat of melting associated with water and other refrigerants.[10–13] However this technology tends to be bulky in size and requires frequent replacement of the cold packs over time rendering this technology inconvenient and expensive to the end user. And finally, several technologies provide active cooling through use portable air conditioning units or liquid cooling.[14–18] These systems not only consume power, but also tend to be prohibitively expensive.

To overcome these limitations, we introduce the concept of an infrared-transparent visible-opaque fabric (ITVOF) which utilizes the human body's innate ability to thermally radiate heat as a cooling mechanism during the summer season when environmental temperatures are high. A heat transfer model was developed in order to determine the required IR optical properties of the ITVOF to ensure thermal comfort is maintained for environmental temperatures exceeding the neutral band. From this analysis, it was experimentally observed that existing textiles fail to meet these requirements due to a combination of intrinsic material absorption and structural backscattering in the IR wavelength range. In lieu of these loss mechanisms, a design for an ITVOF was developed using a combination of optimal material composition and structural photonic engineering. Specifically, synthetic polymers which support few vibrational modes were identified as candidate materials to reduce intrinsic material absorption in the IR wavelength range. To reduce backscattering losses, individual fibers were designed to be comparable in size to visible wavelengths in order to minimize reflection in the IR by virtue of weak Rayleigh scattering while remaining optically opaque in the visible wavelength range due to strong Mie scattering. By additionally reducing the size of the yarn, which is defined as a collection of fibers, less material is used thus decreasing volumetric absorption in the IR wavelength range even further. The ITVOF design is numerically demonstrated to exhibit a high transmittance and a low reflectance in the IR wavelength range while remaining optically opaque in the visible wavelength range. Compared to conventional technologies, an ITVOF can be manufactured into simple form factors while providing a fully passive means to cool the human body regardless of the physical activity level of the user.

ambient temperature as a function of the cloth's total reflectance and transmittance for different combinations of the air gap thickness, t_a, and the convective heat transfer coefficient, h, which represent a typical range of ambient environmental conditions where natural convection is dominant. In order to properly compare the impact of the cloth's optical properties on cooling for different environmental conditions, t_a and h are coupled such that at an ambient temperature of 23.9°C (75°F) and assuming typical optical properties for clothing ($\rho_c \sim 0.3$ and $\tau_c \sim 0.03$), the total cooling power is always equal to the total heat generation rate thus ensuring a consistent baseline neutral temperature band is used.[27]

In both cases, a reflective cloth is more detrimental to cooling performance than an absorptive cloth since a high absorptance implies a high emittance, which would allow clothing to radiate thermal radiation to the environment albeit at a lower temperature. It can also be observed in Fig. 2a that in the limit of high absorption, the maximum ambient temperature is higher for the case where the air gap between the skin and cloth is less insulating (t_a = 1.05 mm) despite the reduction in the convective heat transfer coefficient (h = 3 W/m^{2}K). This suggests heat conduction and thermal radiation are comparable in this limit, thus for conventional clothing it is crucial to minimize the thermal resistance to heat conduction. However, as the mid- to far-IR transparency of the cloth increases, radiative heat transfer becomes more dominant compared to heat conduction. As a result, the impact of the insulating air gap on cooling is mitigated, thus a higher maximum ambient temperature can be sustained, when the convective heat transfer coefficient is larger (h = 5 W/m^{2}K) even though the air gap is more insulating (t_a = 2.36 mm) as shown in Fig. 2b. These results show that by designing clothing to be transparent to mid- and far-IR radiation, it is possible to provide persistent cooling using thermal radiation even for loose fitting clothing where the trapped air normally acts as a thermally insulating barrier, which impedes heat transfer in conventional personal cooling technologies.

To determine quantitatively the optical properties required for the ITVOF to provide 23 W of additional cooling at an ambient temperature of T_a = 26.1°C (79°F), additional cooling power curves were computed as a function of the cloth's total reflectance and transmittance in Figs. 2c and 2d. In the limit of an ideal opaque fabric (α_c = 1), it can be seen for both cases that it is not possible to reach 23 W of additional cooling. This indicates that unless convective cooling is improved, which is challenging to achieve for everyday use as described earlier, it is impossible to maintain personal thermal comfort using opaque clothing; hence, the clothing must exhibit transparency to mid- and far-IR radiation.

For the case where t_a = 1.05 mm and h = 3 W/m^{2}K in Fig. 2c, if the cloth reflectance is larger than 0.2, it is also not possible to reach 23 W of additional cooling. This again shows that a higher cloth reflectance is more detrimental to the cooling performance of the cloth than absorption. Thus, when increasing the transmittance of the cloth, it is crucial that the reflectance is simultaneously reduced in order to maximize radiative cooling. Based on these results, the ITVOF must exhibit a maximum reflectance of 0.2 and a minimum transmittance of 0.644 in order to meet the personal thermal comfort criterion. For the case where t_a = 2.36 mm and h = 5 W/m^{2}K in Fig. 2d, the optical properties of the ITVOF become less stringent with a maximum reflectance of 0.3 and a minimum transmittance of 0.582. It should be emphasized that the reflectance and transmittance of the ITVOF are intrinsically coupled, thus a decrease in reflectance will lead to a corresponding decrease in the transmittance required to maintain thermal comfort as shown in Figs. 2c and 2d.

Experimental Characterization of Common Clothing

In order to design the ITVOF, a baseline reference was first established by characterizing the optical properties of common clothing. Specifically, the optical properties of undyed cotton and polyester cloths, which comprise nearly 78% of all textile fiber production, were measured in both the visible and IR wavelength ranges.[28] Figures 3a and 3b show SEM images of the cotton and polyester cloths,

Design and Simulation of an ITVOF

Based on the heat transfer modeling and the experimental results, the design strategy for an ITVOF is to use alternative synthetic polymers which are intrinsically less absorptive in the IR wavelength range and to structure the fibers to minimize the overall reflectance of the fabric in order to maximize radiative cooling. In general, synthetic polymers with simple chemical structures are ideal since fewer vibrational modes are supported thus resulting in less absorption. Additionally, these polymers must also be compatible with extrusion and drawing processes to ensure manufacturability for large scale production. Based on these criteria, polyethylene and polyacprolactam, more commonly known as nylon, were identified as potential candidate materials. It should be emphasized however that given the full gamut of synthetic polymers available, other synthetic polymers may also be suitable for an ITVOF.

Polyethylene is one of the simplest synthetic polymers available and the most widely used in industry today. The chemical structure of polyethylene consists of a repeating ethylene monomer with a total length that varies depending on the molecular weight. Because the chemical structure consists entirely of carbon-carbon and carbon-hydrogen bonds, few vibrational modes are supported. This is evidenced in Fig. 4b which shows measured FTIR transmittance spectra for an ultra-high molecular weight polyethylene (UHMWPE) thin-film (McMaster 85655K11). Absorption peaks can be observed at 6.8 μm corresponding to CH_2 bending modes, 7.3 μm and 7.6 μm to CH_2 wagging modes, and 13.7 μm and 13.9 μm to CH_2 rocking modes.[47] At longer wavelengths, additional rocking modes do exist, but are typically very weak. For textile applications, woven polyethylene fabrics are often used as geotextiles, tarpaulins, and tapes.[48] To assess the suitability of polyethylene for clothing applications, further studies are needed to evaluate mechanical comfort and durability.

Nylon (McMaster 8539K191) exhibits a similar structure to polyethylene with the key difference being the inclusion of an amide chemical group. As shown in Fig. 4b, this results in additional vibrational modes from 6 μm to 8 μm and 13 μm to 14 μm corresponding to the various vibrational modes from the amide group.[49] Although nylon is absorptive over a larger wavelength range compared to polyethylene, the advantage of nylon is that it is currently used in many textiles.

Compared to cotton and polyester, Fig. 4b shows that polyethylene and nylon exhibit fewer vibrational modes particularly in the mid-IR wavelength range near 10 μm where the human body thermally radiates the most energy. This indicates that polyethylene and nylon are intrinsically less absorptive and are therefore suitable for the creation of an ITVOF.

In order to further improve the IR transparency of an ITVOF constructed from these materials, structural photonic engineering can be introduced for both the fiber and yarn. Specifically, absorption by weaker vibrational modes can be minimized by reducing the material volume. This can be accomplished by simply decreasing the yarn diameter. To minimize backscattering of IR radiation, the fibers can also be reduced in size such that the diameter is small compared to IR wavelengths. In this manner, incident IR radiation will experience Rayleigh scattering where the scattering cross section of infinitely long cylinders in this regime decreases rapidly as a function of the diameter raised to the 4^{th} power.[41] By reducing the scattering cross section, back scattering of IR radiation will significantly decrease resulting in an overall lower IR reflectance.

Conversely, for the visible wavelength range the ITVOF must instead have a low transmittance to ensure ITVOF-based clothing is opaque to the human eye. Since polyethylene and nylon are not strongly absorptive in the visible wavelength range, reflection must be maximized. This can be achieved by using fibers that are comparable in size to visible wavelengths so that incident light experiences Mie scattering. In exactly the same manner that conventional clothing is opaque to IR radiation, fibers in this regime can support optical resonances that significantly increase the scattering cross section of each fiber thus increasing the overall backscattering of incident light.[41] Since the fabric is composed of an array of these fibers, not only will the total reflectance increase, but light scattering with the cloth will

per unit depth basis with units of μm^2 corresponding to the cross section of the yarn. As the yarn diameter decreases from D_y = 100 μm to D_y = 30 μm, the material volume decreases from 4870 μm^2 to 550 μm^2, which results in less absorption. Additionally, a reduction in the yarn diameter will also decrease the number of fibers that can scatter incident IR radiation, which leads to less reflection. These results suggest that by decreasing only the yarn diameter to D_y = 30 μm, it is possible to create an ITVOF that already exceeds the minimum transmittance of 0.644 and maximum reflectance of 0.2 required to maintain thermal comfort at an ambient temperature of 26.1°C (79°F) in Fig. 2c.

However, the spectral optical properties in Fig. 6 indicate there is still room to further improve the transparency of the ITVOF as absorption and reflection are still substantial particularly at shorter wavelengths. In this wavelength range, the size of the fiber (D_f = 10 μm) is comparable to the wavelength and is thus in the Mie regime where the fiber can support cavity resonances that can couple to and scatter incident IR radiation. Since the mode density of these resonances is higher at shorter wavelengths, the overall reflectance of the fabric structure will be higher as well. By reducing the size of the fiber, the number of supported cavity resonances will decrease resulting in a lower reflectance. The total material volume will also be reduced further from 550 μm^2 for D_f = 10 μm to 136 μm^2 for D_f = 1 μm thus decreasing the absorptance even further.

When the fiber diameter is reduced to 5 μm, the absorptance exhibits a marginal decrease. On the other hand, the reflectance actually increases compared to the case where D_f = 10 μm. This indicates that the fiber is still sufficiently large enough to support cavity resonant modes. Although there are fewer modes supported, as shown by the variation in reflectance, these modes become leakier for smaller size fibers thus resulting in a larger scattering cross section and a higher reflectance. As a result, there is little enhancement to the overall IR transmittance. Once the fiber diameter decreases to 1 μm, the reflectance dramatically decreases, which suggests the fiber is sufficiently small such that incident mid- to far-IR radiation will primarily experience Rayleigh scattering. In this Rayleigh regime, the fibers are too small to support cavity mode resonances thus reducing the reflection of IR radiation. Furthermore, the reduction in fiber size further reduces the total material volume again decreasing the absorptance. As a result, the total mid- to far-IR transmittance further increases from 0.76 for D_f = 10 μm to 0.972 for D_f = 1 μm, making the structure even more transparent to thermal radiation emitted by the human body. Simultaneously, the total mid- to far-IR reflectance decreases substantially from 0.19 to 0.021. By reducing the fiber diameter, the resulting improvements to the optical properties enable this ITVOF design to clearly surpass the requirements needed to provide 23 W of additional cooling at an ambient temperature of 26.1°C (79°F) based on Figs. 2c and 2d. It should again be noted that the calculated optical properties of the ITVOF only considered wavelengths from 5.5 to 24 μm. Since polyethylene is transparent at longer wavelengths, these results likely underestimate the total hemispherical transmittance and overestimate the total hemispherical reflectance and absorptance for mid- and far-IR radiation.

To assess the visible opaqueness, additional simulations were performed for the polyethylene-based ITVOF design assuming a constant refractive index of n = 1.5 and an extinction coefficient of $k = 5 \cdot 10^{-4}$ based on literature values for the visible wavelength range from 400 nm to 700 nm.[30] These simulations were performed for the optimal design where D_f = 1 μm, D_y = 30 μm, D_z = 1 μm, and D_p = 5 μm. The results are shown in Fig. 7 along with the experimentally measured optical properties of undyed cotton and polyester cloth for comparison. The polyethylene-based ITVOF design exhibits a total hemispherical reflectance higher than 0.5 and a hemispherical transmittance less than 0.4 across the entire visible wavelength range, which is comparable to the optical properties of the experimentally characterized cotton and polyester cloth samples. The oscillatory behavior of the total hemispherical absorptance is indicative of whispering gallery and Fabry-Perot resonances supported in each fiber (see Supplementary Information) which confirms that light interaction is indeed in the Mie regime. As a result, these optical resonances provide strong backscattering to help ensure the fabric is opaque.

based on typical clothing, it would nonetheless be useful to quantitatively assess vapor transport to optimally design ITVOF-based clothing.[57] The inclusion of coloration for aesthetic quality is another important aspect that must be considered without compromising the effectiveness of radiative cooling. Alternative synthetic polymers, such as polypropylene or polymeric blends of UHMWPE and PET, should also be investigated for their suitability in an ITVOF design. Ultimately, ITVOF-based clothing offers a simple, low-cost approach to provide cooling locally to the human body in a variety of indoor and outdoor environments without requiring additional energy consumption, compromising breathability, or requiring any lifestyle change. Therefore, ITVOF provides a simple solution to reduce the energy consumption of HVAC systems by enabling higher temperature set points during the summer.

Methods

UV/Visible Characterization. A custom UV/visible wavelength spectrometer was used to measure the optical properties of the cloth samples in the visible wavelength range. This system consisted of a 500 W mercury xenon lamp source (Newport Oriel Instruments, 66902), a monochromator (Newport Oriel instruments, 74125), an integrating sphere (Newport Oriel Product Line, 70672) and a silicon photodiode (Newport Oriel instruments, 71675). Total hemispherical reflectance measurements were performed by placing the cloth samples onto a diffuse black reference (Avian Technologies LLC, FGS-02-02c) to avoid reflection from the underlying substrate. Total hemispherical transmittance measurements were performed by placing the cloth samples onto the input aperture of the integrating sphere. All measurements were calibrated using a diffuse white reference (Avian Technologies LLC, FWS-99-02c).

Infrared Characterization. A commercially available FTIR spectrometer (Thermo Fisher Scientific, Nicolet 6700) and an IR objective accessory (Thermo Fisher Scientific, Reflachromat 0045-402) was used to measure the optical properties of the cloth samples and the polymer films in the infrared wavelength range. The objective was placed 15 mm behind the samples, corresponding to the working distance of the objective, in order to capture infrared radiation transmitted through the samples. For the cloth samples, the total hemispherical transmittance will be underestimated since not all of the IR radiation that is diffusively transmitted through the cloth sample is captured. However, the objective used in this study was designed to capture IR radiation at a 35.5° acceptance angle. Since it is expected that IR radiation will transmit diffusively, the measured results are likely underestimated by a few percent, which is still in agreement with previous studies.

Associated Content

Supporting Information provides further details on the heat transfer modeling, the optical constants of polyethylene (PE) and polyethylene terephthalate (PET), Mie theory calculations for a single isolated polyethylene fiber, numerical finite element simulations of a polyethylene-based ITVOF for a larger yarn diameter, and numerical finite element simulations for an ITVOF blend of polyethylene and polyester.

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Notes

The authors declare no competing financial interest.

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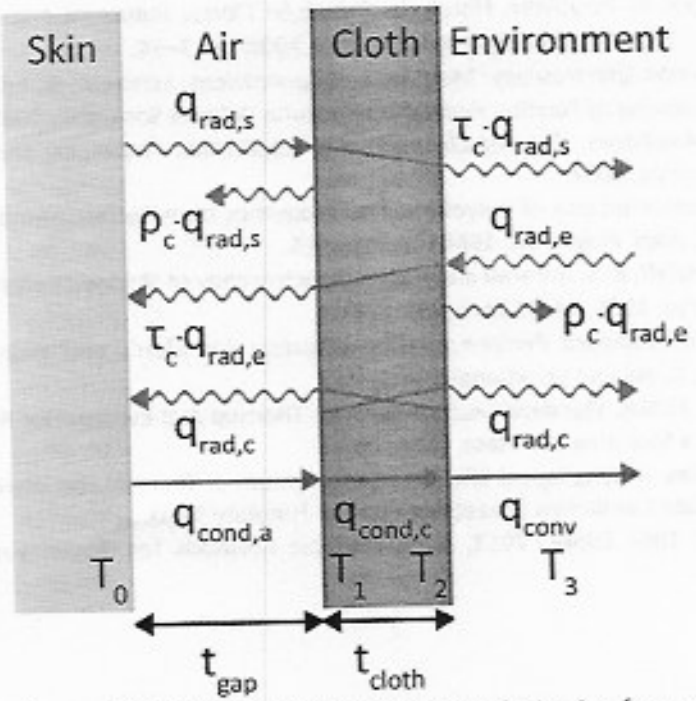


Figure 1: A heat transfer model was developed to analyze heat dissipation from a clothed human body to the ambient environment. Various heat transfer contributions that lead to dissipation of heat from the human body, such as radiation, heat conduction, and heat convection are included. To model loose fitting clothing, a finite air gap is assumed between the cloth and the skin.

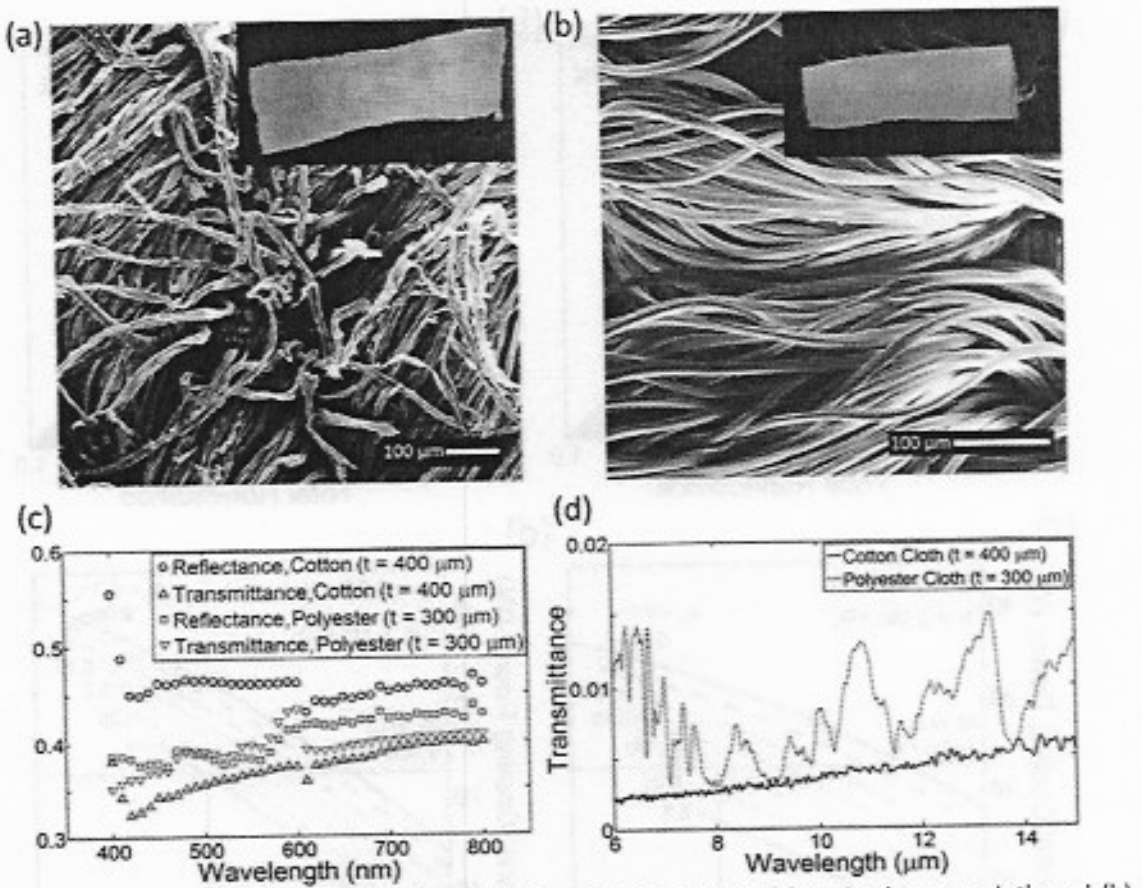


Figure 3: Optical properties of conventional clothing. SEM images of (a) undyed cotton cloth and (b) undyed polyester cloth which show the intrinsic fabric structure. The insets are optical images of the samples characterized. For both samples, the fiber diameter is on average 10 μm and the yarn diameter is greater than 200 μm. The scale bars both correspond to 100 μm. (c) Experimentally measured optical properties in the visible wavelength range. (d) Experimentally measured FTIR transmittance spectra of undyed cotton cloth (thickness, t = 400 μm) and undyed polyester cloth (t = 300 μm) showing the opaqueness of common fabrics in the IR.