Infrared-Transparent Visible-Opaque Fabrics for Wearable Personal Thermal Management

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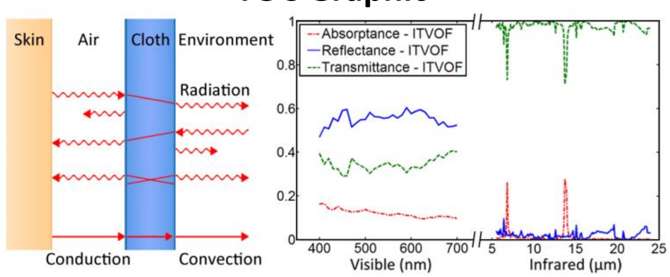
Abstract

Personal cooling technologies locally control the temperature of an individual rather than a large space, thus providing personal thermal comfort while supplementing cooling loads in thermally regulated environments. This can lead to significant energy and cost savings. In this study, a new approach to personal cooling was developed using an infrared-transparent visible-opaque fabric (ITVOF), which provides passive cooling via the transmission of thermal radiation emitted by the human body directly to the environment. Here, we present a conceptual framework to thermally and optically design an ITVOF. Using a heat transfer model, the fabric was found to require a minimum infrared (IR) transmittance of 0.644 and a maximum IR reflectance of 0.2 to ensure thermal comfort at ambient temperatures as high as 26.1°C (79°F). To meet these requirements, an ITVOF design was developed using synthetic polymer fibers with an intrinsically low IR absorptance. These fibers were then structured to minimize IR reflection via weak Rayleigh scattering while maintaining visible opaqueness via strong Mie scattering. For a fabric composed of parallel-aligned polyethylene fibers, numerical finite element simulations predict 1 μm diameter fibers bundled into 30 μm yarns can achieve a total hemispherical IR transmittance of 0.972, which is nearly perfectly transparent to mid- and far-IR radiation. The visible wavelength properties of the ITVOF are comparable to conventional textiles ensuring opaqueness to the human eye. By providing personal cooling in a form amenable to everyday use, ITVOF-based clothing offers a simple, low-cost solution to reduce energy consumption in HVAC systems.

TOC Graphic



Keywords: Thermal radiation, personal thermal management, cooling, Mie scattering, Rayleigh scattering, textile, synthetic polymers

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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.

Heat Transfer Analysis

In order to quantify the potential cooling power using thermal radiation, the maximum radiative heat transfer achievable between the human body and the surrounding environment can be computed using the Stefan-Boltzmann law. Past studies have shown that human skin behaves like a blackbody with an emittance near unity in the IR wavelength range.[19,20] Even if the skin is wet due to perspiration, the emittance is still 0.96 corresponding to water, which suggests human skin is an effective IR emitter for all levels of physical activity.[21] If it is assumed the surface area of an average adult human body is A = 1.8 m^2, the temperature of human skin is T_0 = 33.9°C (93°F), and the ambient temperature is T_3 = 23.9°C (75°F), which corresponds to the upper limit of a typical neutral temperature band for human thermal comfort in buildings, the radiative heat transfer coefficient between the skin and the environment is h_r = 6.25 W/m^2K.[22,23] Under these conditions, the cooling power predicted by the Stefan-Boltzmann law is 112 W.[24] Radiative heat loss from the human body is thus comparable to natural convection and the cooling power actually exceeds the total heat generation rate of q_{gen} = 105 W assuming a base metabolic rate at rest of 58.2 W/m^2.[25] From this estimation, it can be observed that thermal radiation clearly has the potential to provide significant cooling power.

To fully harness thermal radiation for cooling, clothing fabrics should be transparent to mid- and far-infrared radiation which is the spectral range where the human body primarily emits.[19,24] Although a total hemispherical transmittance of unity would be ideal, it would be useful to determine the transmittance required for the ITVOF to provide the necessary cooling power for an individual to feel comfortable at different indoor temperatures. This criterion is determined by assuming the cooling power should equal the total heat generation rate of q_{gen} = 105 W at a skin temperature of T_0 = 33.9°C (93°F) and a typical room temperature of T_3 = 23.9°C (75°F). Under these conditions, the effective heat transfer coefficient is equal to h_{ref} = 5.8 W/m^2K which is less than the maximum achievable using thermal radiation. If the ambient temperature increases, the additional cooling power, q_{cool}, needed is equal to the difference between the total heat generation rate, q_{gen}, and the heat loss due to h_{ref},

$$q_{cool} = q_{gen} - h_{ref}\left(T_0 - T_3\right) \quad (1)$$

For this study, the goal is to provide cooling at an elevated ambient temperature of T_3 = 26.1°C (79°F), which past studies have shown can lead to nearly 40% energy savings in indoor environments for certain regions of the United States.[22] Using equation (1) at this temperature, the fabric must provide 23 W of additional cooling.

Based on this criterion, a more detailed one-dimensional steady-state heat transfer model is used to determine the total mid- to far-IR transmittance and reflectance required for the ITVOF. This model, as illustrated in Fig. 1, includes a continuous cloth placed at a distance, t_a, from the human body to model the effect of a thermally insulating air gap when loose fitting clothing is worn. The cloth is assumed to cover 100% of the human body. The model combines a control volume analysis and an analytical formulation of the temperature profile within the cloth in order to evaluate heat transfer between the human body, the cloth, and the ambient environment. Radiative heat transfer, heat conduction, and convection are all included in the analysis (see Supplementary Information for further details). The thermal conductivity of air is k_a = 0.027 W/mK and the thermal conductivity of the cloth fabric is assumed to be k_y = 0.05 W/mK.[24] Assuming a cloth porosity of 0.15, which is typical for common clothing, the effective thermal conductivity of the cloth layer is k_c = 0.047 W/mK.[26] The thickness of the cloth is conservatively chosen to be t_c = 0.5 mm and the effect of air circulation through the fabric is neglected. The IR optical properties of the cloth are assumed to be gray and diffuse with the sum of the absorptance, α_c, reflectance, ρ_c, and transmittance, τ_c, equal to 1.

From this model, the effect of the cloth's optical properties on the total cooling power was evaluated by calculating the maximum ambient temperature that can be sustained without compromising personal thermal comfort. Figures 2a and 2b show contour maps of the maximum 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_3 = 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 ($\alpha_c = 1$), 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, respectively. The fabrics consist of fibers with a diameter of ~10 μm sewn into yarns that are 200 to 300 μm in size. Depending on the weave, the yarn can intertwine and overlap differently; however, the thickness of the cloth generally varies from one yarn to two overlapping yarns.

The visible wavelength optical properties of both cloth samples were measured using a UV/visible spectrometer. To account for the diffuse scattering of light from the samples, an integrating sphere was used to measure the hemispherical reflectance and transmittance of the cloth in the wavelength range of 400 nm to 800 nm. The results are shown in Fig. 3c. As expected, the undyed cloth samples exhibit no distinct optical features in the reflectance and transmittance spectra. Both samples show similar optical properties with a reflectance ranging from 0.4 to 0.5 and a transmittance ranging from 0.3 to 0.4. The high transmittance is primarily due to the intrinsic properties of cotton and polyester which are weakly absorbing in the visible wavelength range.[29,30]

Although these cloth samples exhibit a high transmittance, their apparent opaqueness is due to a combination of the contrast sensitivity of the human eye and the diffuse scattering of light. The human eye is a remarkably sensitive optical sensor that can respond to a large range of light intensities.[31,32] However, past studies have shown that the human eye can only perceive variations in light intensity when the change in intensity relative to the background is sufficiently large.[33–36] This implies that for clothing to appear opaque, the fraction of light reflected by the skin and observed by the human eye must be sufficiently smaller than the fraction of light reflected by the fabric into the same direction. For these cloth samples, light will reflect and transmit diffusively. In addition, skin is also a diffuse surface with a reflectance that is as high as 0.6 at longer wavelengths.[37] Since the observation of skin requires light to be reflected from the skin and transmitted through the cloth twice, more light will be scattered into directions beyond what is observable by the human eye compared to light that is only reflected by the cloth thus ensuring the opaque appearance of the cloth. It is for these reasons that common clothing appears opaque to the human eye despite an inherently high transmittance. From these results, the criteria for opaqueness of the ITVOF design will be assessed by comparing the hemispherical reflectance and transmittance to measured data shown in Fig 3c.

The IR transmittance spectra of the cloth samples, shown in Fig. 3d, were measured using a Fourier transform infrared (FTIR) spectrometer with a microscope objective accessory. Both the cotton and polyester samples exhibit a low transmittance of 1% across the entire IR wavelength range in agreement with previous studies.[27,38–40] Therefore, both samples are opaque in the IR and thus cannot provide the necessary cooling to the wearer at higher ambient temperatures according to the heat transfer model.

The reasons for the low transmittances are two-fold. First, cotton and polyester are highly absorbing in the IR wavelength range. Figure 4a shows the FTIR transmittance spectra of a single strand of cotton yarn and a polyester thin film. Several absorption peaks can be observed which originate from the many vibrational modes supported in the complex molecular structure of these materials. Since fabrics are typically several hundreds of microns thick, which is much larger than the penetration depth, incident IR radiation is completely absorbed at these wavelengths. Second, the fibers in clothing are comparable in size to IR wavelengths, as shown in Figs. 3a and 3b, which enable the fibers to support optical resonances that can strongly scatter incident light. In this Mie regime, it is well known that particles can exhibit large scattering cross sections due to these resonances.[41–46] For an array of many fibers, the collective scattering by the fibers can result in a high reflectance. Therefore, the creation of an ITVOF must minimize these two contributions in order to maximize transparency to mid- and far-IR radiation.

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 become more diffuse. In conjunction with the contrast sensitivity of the human eye, this design approach can ensure the ITVOF is opaque to the human eye. Thus, the beauty of this structuring approach is that with an optimally chosen fiber diameter, two different regimes of light scattering are utilized in different spectral ranges in order to create a fabric which is simultaneously opaque in the visible wavelength range and transparent in the IR wavelength range.

In regards to the coloration of the ITVOF, polyethylene and nylon exhibit dispersionless optical properties in the visible wavelength range and with sufficient backscattering appear white in color. Despite the chemical inertness of polyethylene, it is possible to provide coloration through the introduction of pigments during fiber formation when polyethylene is in a molten state.[50] On the other hand, nylon fibers can be colored easily using conventional dyes.[51] Depending on the pigment or dye, additional vibrational modes may be introduced in the IR wavelength range reducing the overall transparency. However, for the sake of demonstrating the general concept of an ITVOF, this design aspect will be left for future studies.

To theoretically demonstrate the proposed strategy to create an ITVOF, numerical finite-element electromagnetic simulations were performed on a polyethylene fabric structure illustrated in Fig. 5. In these simulations, circular arrays of parallel fibers are arranged into collective bundles in order to represent the formation of yarn. The yarn is then positioned in a periodic staggered configuration oriented 30^o relative to the horizontal plane to mimic the cross section of a woven fabric. For all simulations, it is assumed the fiber separation distance, D_s, is 1 µm and the yarn separation distance, D_p, is 5 µm, which is consistent with the cloth structures observed in Figs. 3a and 3b. Simulations in the IR wavelength range were conducted from 5.5 to 24 µm. Wavelengths shorter than 5.5 µm contribute only 2.7% to total blackbody thermal radiation and are thus considered negligible. Wavelengths longer than 24 µm contribute 17.2% to total blackbody thermal radiation; however, longer wavelengths are expected to yield an even higher transparency since polyethylene does not support vibrational modes beyond 24 µm. As a conservative estimate, the optical properties of the ITVOF design are spectrally integrated and normalized within only the 5.5 to 24 µm wavelength range, which will underestimate the transmittance and overestimate the reflectance and absorptance. Furthermore, the spectral integration is weighted by the Planck's distribution assuming a skin temperature of 33.9^oC (93^oF).

Floquet periodic boundary conditions are used on the right and left boundaries to simulate an infinitely wide structure. Perfectly matched layers are used on the top and bottom boundaries to simulate an infinite free space. Simulations were conducted for incident light polarized parallel and perpendicular to the fiber axis at normal incidence. The optical properties for unpolarized light were determined by taking an average of the results for both polarizations. The optical constants of bulk polyethylene were taken from the literature.[30] Although the manufacture of polymer fibers and the subsequent stress imposed when woven into fabrics can introduce anisotropy in the dielectric permittivity, past studies have experimentally shown that the optical properties of drawn UHMWPE exhibit minimal change when subjected to a high draw ratio and high stresses.[52,53] Therefore, anisotropic effects were neglected in this study.

To assess the impact of reducing the size of the fiber (D_f) and the yarn (D_y), the IR optical properties were computed by varying the yarn diameter (D_y = 30 µm, 50 µm, and 100 µm) assuming a fixed fiber diameter of D_f = 10 µm and by varying the fiber diameter (D_f = 1 µm, 5 µm, and 10 µm) assuming a fixed yarn diameter of D_y = 30 µm. The results are shown in Fig. 6 along with the total spectrally integrated IR transmittance (τ_c) and reflectance (ρ_c) weighted by the Planck's distribution assuming a skin temperature of 33.9^oC (93^oF). Based on these results, a reduction in the yarn diameter does yield a higher spectral transmittance in the IR wavelength range as evidenced by the increase in the total hemispherical IR transmittance from 0.48 for D_y = 100 µm to 0.76 for D_y = 30 µm. Simultaneously, the total hemispherical IR reflectance also decreases from 0.35 to 0.19. This can be explained by a reduction in the total material volume, which is defined in this study for a single yarn on a 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_s = 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.

It can also be observed in Fig. 7 that the reflectance and transmittance do not follow the same trend as the absorptance. This can be attributed to the optical coupling of neighboring fibers in the fabric which collectively introduce additional optical resonances in the system due to the periodic nature of the assumed fabric structure. For a more realistic fabric structure where fiber and yarn spacing are nonuniform, long range optical coupling will be minimized resulting in a fabric which more diffusively scatters light. Due to the similarity to the experimentally characterized cloth samples, these results suggest the ITVOF design is optically opaque to the human eye. Furthermore, Fig. 7 clearly shows the contrast between the visible and IR properties of the ITVOF design which indicates that by optimally sizing the fiber, two vastly different regimes of light scattering can be simultaneously used.

Based on these results, it may appear that the creation of an ITVOF requires substantial reduction in material volume since the highest IR transmittance of 0.972 was predicted for the smallest yarn diameter (D_y = 30 µm) and fiber diameter (D_f = 1 µm). Although decreasing both of these parameters will certainly improve the overall transmittance in the IR wavelength range, additional simulations (see Supplementary Information) for various fiber diameters (D_f = 1 µm, 5 µm, and 10 µm) assuming a larger yarn diameter of D_y = 50 µm show a similar trend in the enhancement of transmittance. For a fiber diameter of D_f = 1 µm, the total hemispherical IR transmittance and reflectance was 0.969 and 0.019, respectively, which is similar to the case where D_y = 30 µm despite a material volume that is three times larger at 445 μm^2. This result shows that reducing the fiber diameter is far more crucial to improving transmittance compared to reducing the yarn diameter. Therefore, it may be suitable to create an ITVOF that is comparable in size to conventional fabrics so long as the fiber diameter is sufficiently small.

In addition, a polyethylene-based ITVOF may not exhibit sufficient fabric handedness due to the nature of the material used. To ensure the fabric is comfortable to the wearer, it may be necessary for the fabric to be composed of a mixture of different material fibers which will affect the transmittance of the fabric. To assess the potential extent in which the transmittance will be reduced, simulations were also performed (see Supplementary Information) for different volumetric concentrations of polyethylene and polyester (PET) again assuming D_f = 1 µm and D_y = 30 µm. The optical constants for PET were also taken from the literature.[29] For the most absorbing case of 25%PE/75%PET, the total hemispherical mid- to far-IR transmittance and reflectance was 0.728 and 0.038, respectively, which indicates that a fabric blend can still achieve a high transmittance and a low reflectance to provide sufficient cooling using thermal radiation.

In summary, we demonstrated a design for an infrared-transparent visible-opaque fabric (ITVOF) in order to provide personal cooling via thermal radiation from the human body to the ambient environment. We developed an ITVOF design made of polyethylene, which is an intrinsically low absorbing material, and structured the fibers to be sufficiently small in order to maximize the IR transparency and the visible opaqueness. For a 1 µm diameter fiber and a 30 µm diameter yarn, the total mid- and far-IR transmittance and reflectance are predicted to be 0.972 and 0.021, respectively, which exceed the minimum transmittance of 0.644 and maximum reflectance of 0.2 required to provide sufficient cooling at an elevated ambient temperature of 26.1^{o}C (79^{o}F). Simultaneously, the total hemispherical reflectance and transmittance in the visible wavelength range are comparable to existing textiles which indicates that the design is optically opaque to the human eye.

To practically realize an ITVOF, further studies are needed to experimentally evaluate the impact of radiative heat transfer on personal cooling. Although challenging, the fabrication of an ITVOF could be achieved using conventional manufacturing processes including drawing, extrusion, or electrospinning. Thermal and mechanical evaluation can be conducted using standardized testing methods as shown in previous studies including the use of thermal manikins, wash and dry cycling, and subject testing.[11,15,54–56] Additionally, vapor transport through the cloth, which is another key component for thermal comfort, must also be considered in future ITVOF designs. Although the porosity of the proposed ITVOF design is 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^{o} 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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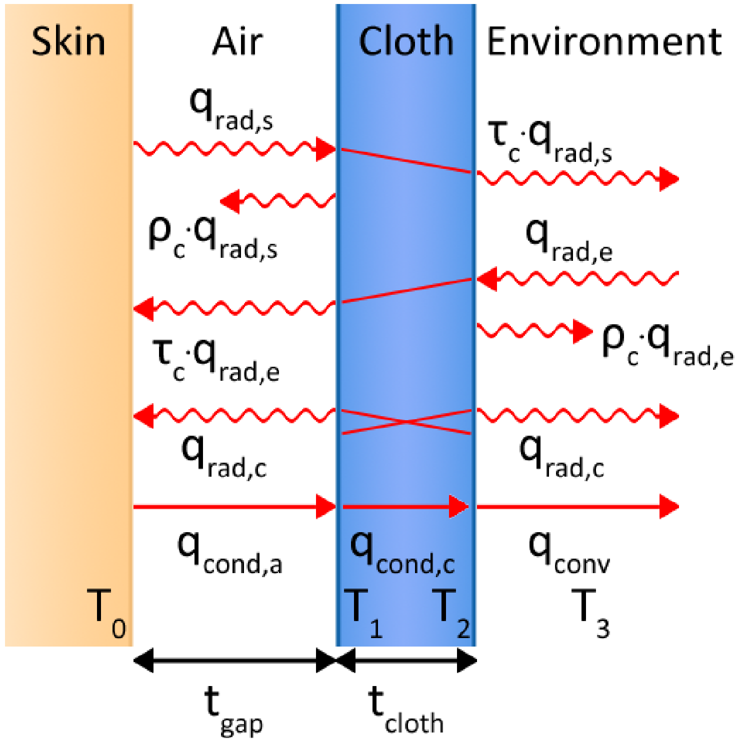

Figure 1: A heat transfer model was developed to analyze heat dissipation from a clothed human body to the ambient environment. Various heat transfer contributions that lead to dissipation of heat from the human body, such as radiation, heat conduction, and heat convection are included. To model loose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

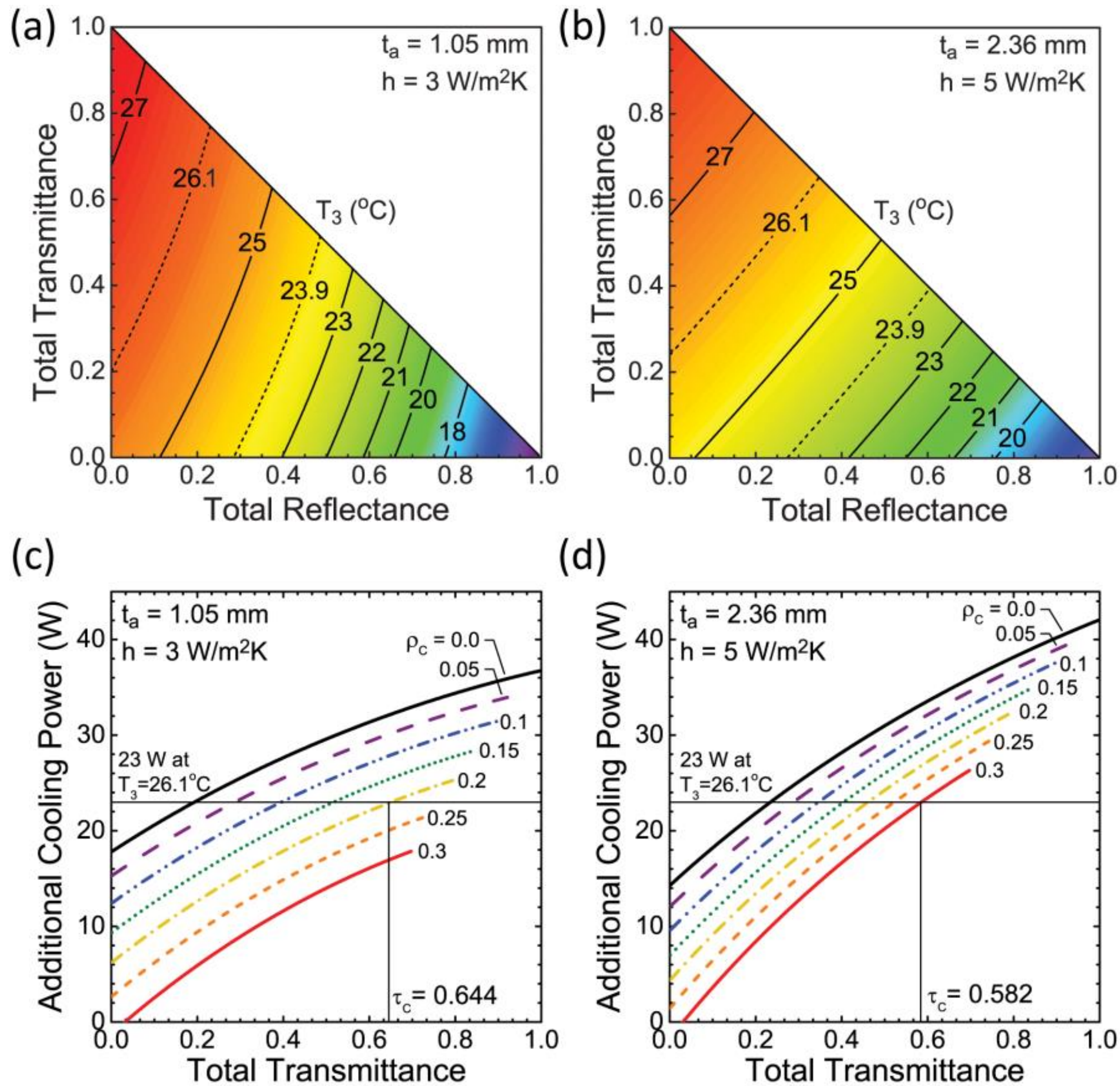

Figure 2: Evaluation of ITVOF mid- to far-IR optical requirements to maintain personal thermal comfort at elevated ambient temperatures. (a) A temperature map was computed showing the maximum ambient temperature attainable without compromising thermal comfort as a function of the total reflectance and transmittance of the cloth. It is assumed the air gap is t_a = 1.05 mm and the convective heat transfer coefficient is h = 3 W/m^{2}K. (b) A corresponding temperature map assuming t_a = 2.36 mm and h = 5 W/m^{2}K. The range of h is typical for cooling via natural convection. (c) An additional cooling power curve showing quantitatively the effect of radiative cooling as a function of the total cloth transmittance and reflectance assuming t_a = 1.05 mm and h = 3 W/m^{2}K. (d) An additional cooling power curve assuming t_a = 2.36 mm and h = 5 W/m^{2}K. As shown, by decreasing the reflectance and increasing the transmittance, it is possible to achieve the necessary 23 W of cooling at an ambient temperature of 26.1 ^{o}C using only thermal radiation.

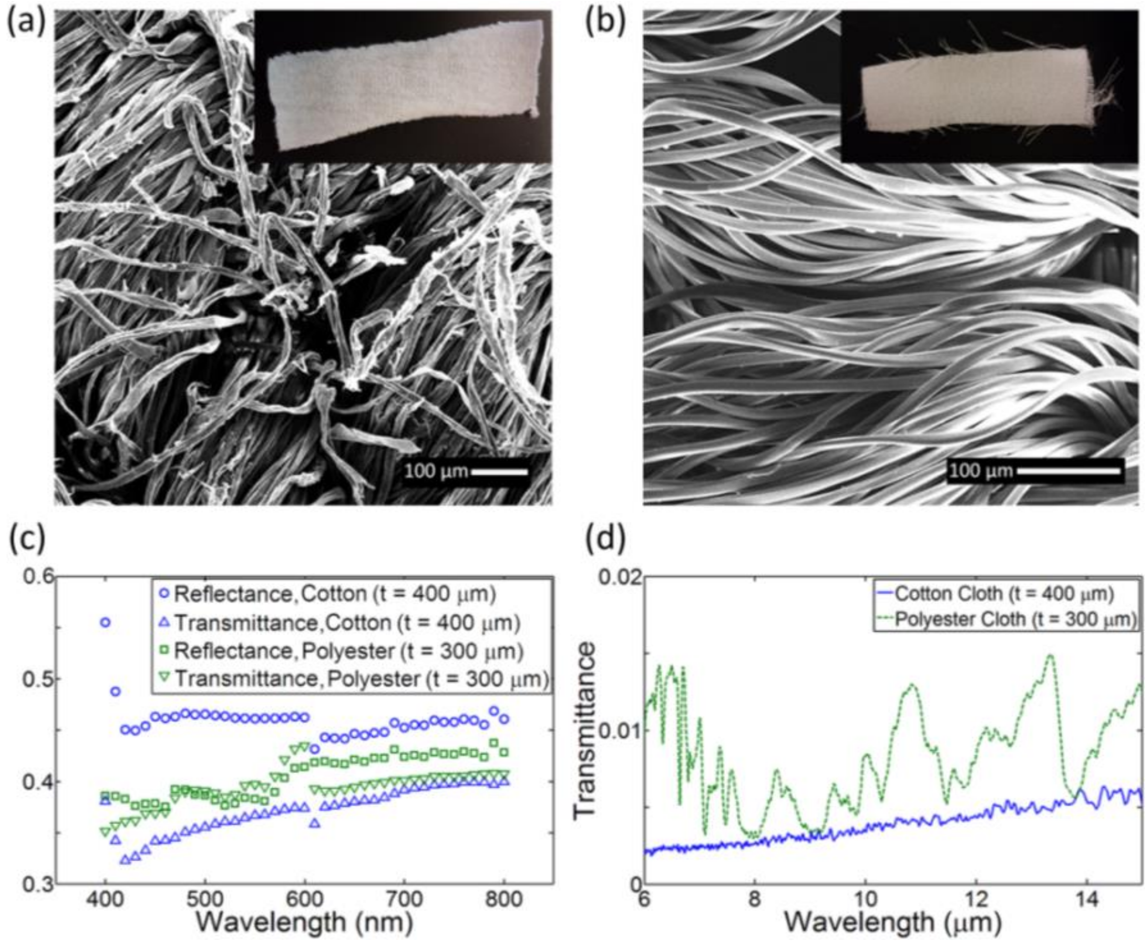

Figure 3: Optical properties of conventional clothing. SEM images of (a) undyed cotton cloth and (b) undyed polyester cloth which show the intrinsic fabric structure. The insets are optical images of the samples characterized. For both samples, the fiber diameter is on average 10 µm and the yarn diameter 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.

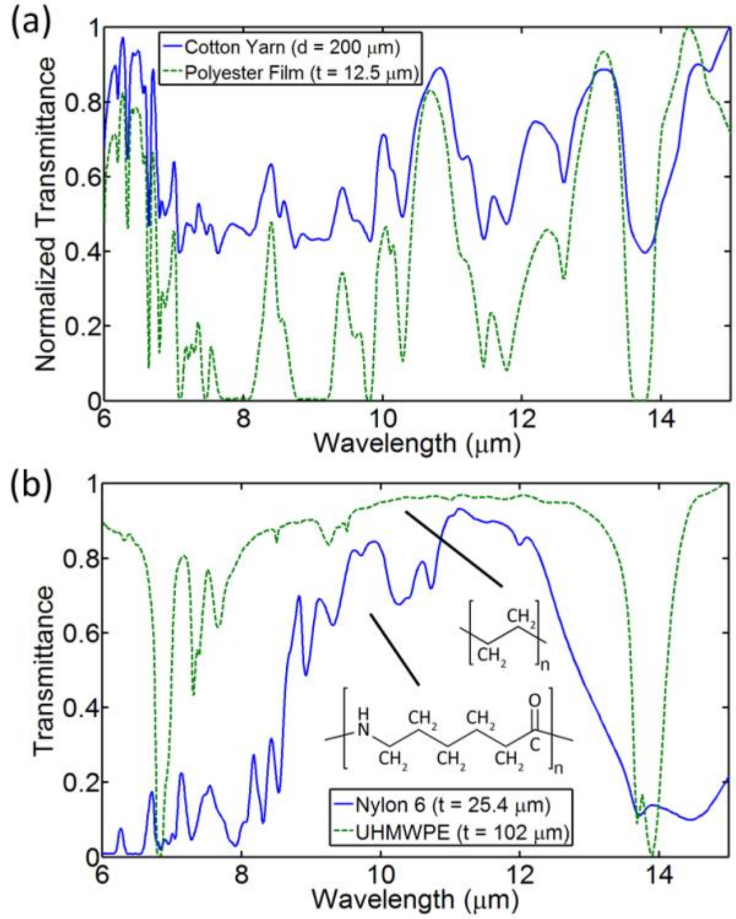

Figure 4: Intrinsic absorptive properties of various synthetic polymers. (a) The FTIR transmittance spectra for a single cotton yarn (diameter, d = 200 μm) and a polyester thin-film (thickness, t = 12.5 μm). The transmittance spectra is normalized to provide similar scaling due to the order of magnitude difference in sample size. (b) The FTIR transmittance spectra for two candidate materials for the ITVOF. These materials include thin-films of nylon 6 (t = 25.4 μm) and UHMWPE (t = 102 μm).

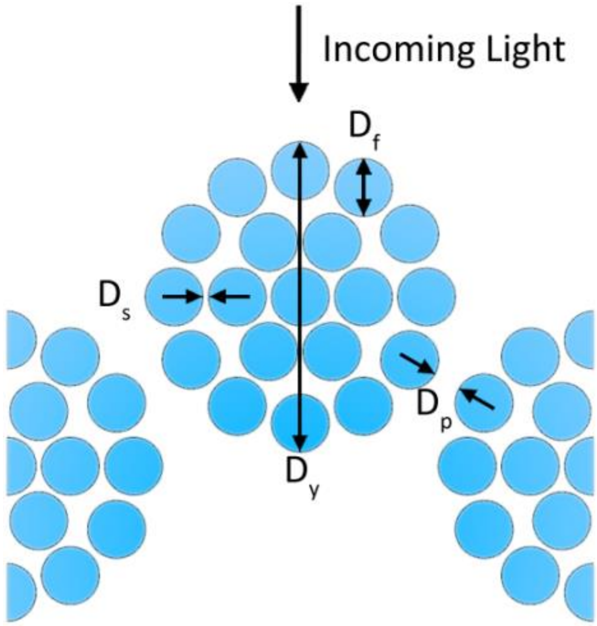

Figure 5: A schematic of the numerical simulation model used to predict the optical properties of the ITVOF design. The parameters include: D_f – the fiber diameter, D_y – the yarn diameter, D_s – the fiber separation distance, and D_p – the yarn separation distance. For all simulations, the yarns were staggered 30^o relative to the horizontal plane. In addition, incident light was assumed to be at normal incidence and the optical properties for unpolarized light were calculated by average light polarized parallel and perpendicular to the fiber axis.

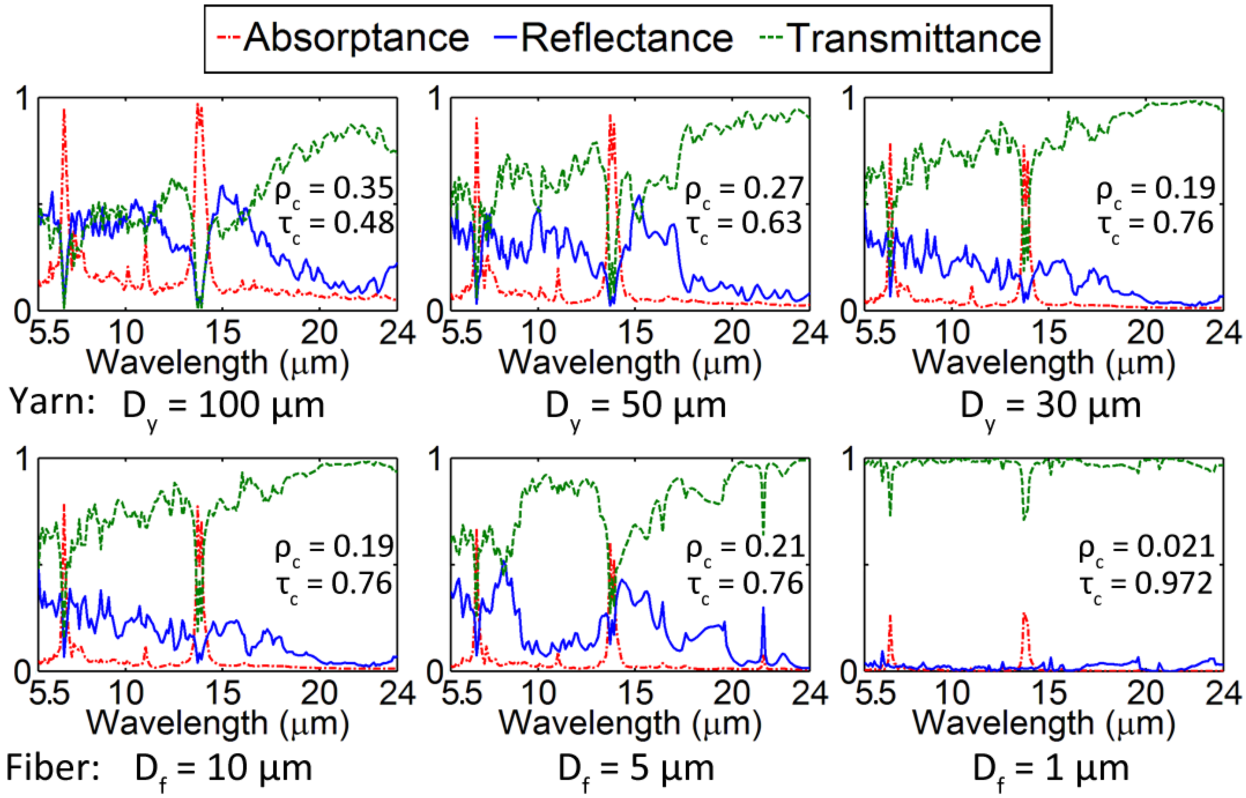

Figure 6: Numerical simulation results for the IR optical properties of a polyethylene-based ITVOF illustrating the effect of reducing the fiber and yarn size. Upper row: The yarn diameter is varied (D_y = 30 µm, 50 µm, and 100 µm) assuming a fixed fiber diameter of D_f = 10 µm. Lower row: The fiber diameter is varied (D_f = 1 µm, 5 µm, and 10 µm) assuming a fixed yarn diameter of D_y = 30 µm. For all simulations, the fiber separation distance is D_s = 1 µm and the yarn separation distance is D_p = 5 µm. The spectrally integrated transmittance (τ_c) and reflectance (ρ_c) is shown in each plot weighted by the Planck's distribution assuming a body temperature of 33.9°C (93°F). For D_f = 10 µm, the material volume per unit depth for a single yarn is 4870 µm^2 for D_y = 100 µm, 1492 µm^2 for D_y = 50 µm, and 550 µm^2 for D_y = 30 µm. For D_y = 30 µm, the material volume is 373 µm^2 for D_f = 5 µm and 136 µm^2 for D_f = 1 µm. The optical properties of the ITVOF are calculated for the wavelength range from 5.5 to 24 µm, which will provide a conservative estimate of the total transmittance and the reflectance.

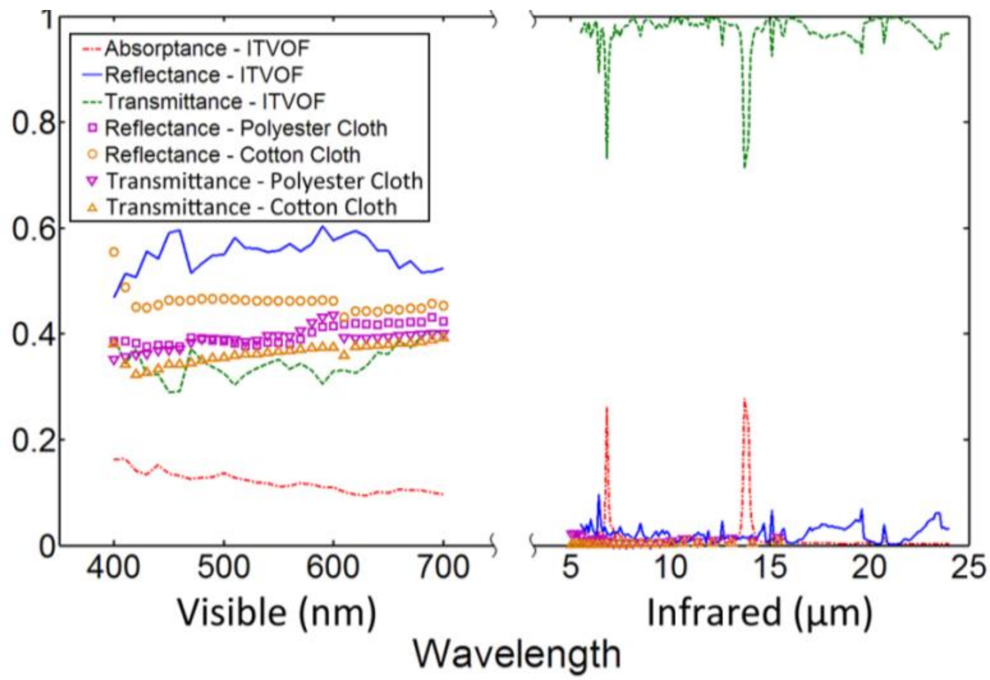

Figure 7: Theoretical results for the visible and IR wavelength range highlighting the contrast in optical properties needed for an ITVOF. These results correspond to the case of D_f = 1 µm, D_y = 30 µm, D_s = 1 µm, and D_p = 5 µm. For comparison, the experimentally measured reflectances and transmittances of cotton and polyester cloths are also shown.

For Table of Contents Use Only

Infrared-Transparent Visible-Opaque Fabrics for Wearable Personal Thermal Management

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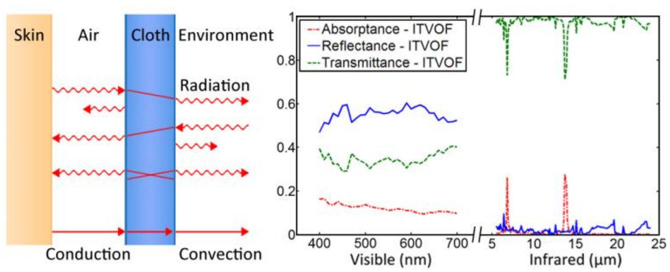

Synopsis

Personal cooling technologies locally control the temperature of an individual rather than a large space, thus providing personal thermal comfort while supplementing cooling loads in thermally regulated environments. This can lead to significant energy and cost savings. In this study, a new approach to personal cooling was developed using an infrared-transparent visible-opaque fabric (ITVOF), which provides passive cooling via the transmission of thermal radiation emitted by the human body directly to the environment. Here, we present a conceptual framework to thermally and optically design an ITVOF. Using a heat transfer model, the fabric was found to require a minimum infrared (IR) transmittance of 0.644 and a maximum IR reflectance of 0.2 to ensure thermal comfort at ambient temperatures as high as 26.1^{o}C (79^{o}F). To meet these requirements, an ITVOF design was developed using synthetic polymer fibers with an intrinsically low IR absorptance. These fibers were then structured to minimize IR reflection via weak Rayleigh scattering while maintaining visible opaqueness via strong Mie scattering. For a fabric composed of parallel-aligned polyethylene fibers, numerical finite element simulations predict 1 µm diameter fibers bundled into 30 µm yarns can achieve a total hemispherical IR transmittance of 0.972, which is nearly perfectly transparent to mid- and far-IR radiation. The visible wavelength properties of the ITVOF are comparable to conventional textiles ensuring opaqueness to the human eye. By providing personal cooling in a form amenable to everyday use, ITVOF-based clothing offers a simple, low-cost solution to reduce energy consumption in HVAC systems.

Supplementary Information

Infrared-Transparent Visible-Opaque Fabrics (ITVOF) for Personal Cooling

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1. Heat transfer model. To evaluate the impact of a cloth's IR optical properties on personal cooling, a 1D steady-state heat transfer model was adopted, as illustrated in Fig. 1a of the main text. This model combines a control volume analysis and an analytical formulation of the temperature profile within the cloth to analyze heat dissipation from a clothed human body to the ambient environment. Radiative, conductive, and convective heat transfer are all included in this analysis. For convenience, the following denotations are used in this model: 0 – surface of human skin, 1 – inner surface of the cloth, 2 – outer surface of the cloth, and 3 – the ambient environment. The following sections provide a summary of the assumptions, input parameters, and a derivation of the analytical formulas used in this analysis.

Assumptions. For convenience, all assumptions in the model are summarized as follows,

(1) In general, the human body can be modelled as a cylinder with a 1 m diameter. In this analysis, the air gap thickness, t_a, and cloth thickness, t_c, are assumed to be much smaller compared to the diameter. Therefore, curvature effects are assumed to be negligible, thus heat transfer is modelled as 1D transport through parallel slabs. In this analysis, heat transfer is expressed as area-normalized heat fluxes.

(2) The human body is assumed to be in a sedentary state with a uniform skin temperature and heat generation.

(3) The cloth is assumed to cover 100% of the human body.

(4) The air between the skin and cloth is assumed to be stationary thus convective heat transfer is negligible in this region.

(5) Air circulation through the cloth is neglected.

(6) All optical properties are assumed to be gray and diffuse.

(7) The skin and environment are assumed to be an ideal blackbody emitter and absorber.

(8) An average cloth temperature (e.g. mean of T_1 and T_2) is assumed for thermal emission by the cloth.

(9) All radiative view factors are equal to 1.

(10) Internal scattering and self-absorption effects are neglected within the cloth.

(11) It is assumed the absorption and emission profile is linear within the cloth. This is an approximation of the more rigorous exponential profile that governs absorption and emission when internal scattering is negligible. In the limit of either high cloth transmittance or reflectance, this is a reasonable assumption due to the linearity of the exponential decay. In the limit of high absorptance, this assumption will no longer be accurate. Despite this, the cooling power and the

maximum ambient temperature can still be reasonable predicted since the difference between the inner and outer cloth temperatures is expected to be small.

Input parameters. Table 1 shows a list of the input parameters used in this study. In order to determine the total cooling power through the cloth, the net heat flux in this analysis can be multiplied by the surface area of the human body, A.

Additionally, the cloth is assumed to be partially reflective, transmissive, and absorptive with gray and diffuse optical properties. In conjunction with Kirchoff's law, the cloth's optical properties will adhere to the following relation,

$$\varepsilon_c = \alpha_c = 1 - \rho_c - \tau_c \tag{S1}$$

where ε_c, α_c, ρ_c, and τ_c are the cloth's total hemispherical emittance, absorptance, reflectance, and transmittance, respectively.

Table 1: Input Parameters

Parameter Name	Value	Parameter Name	Value
Human body surface area, A	1.8 m^2	Cloth thickness, t_c	0.5 mm
Heat generation rate, q_{gen}	58.2 W/m^2	Total emittance of skin	1
Skin temperature, T_0	33.9°C (93°F)	Total emittance of environment	1
Thermal conductivity of air, k_a	0.027 $Wm^{-1}K^{-1}$	Conv. heat transfer coeff., h	3-5 $Wm^{-2}K^{-1}$
Thermal conductivity of yarn, k_y	0.05 $Wm^{-1}K^{-1}$	Air gap thickness, t_a	1.05-2.36 mm
Cloth porosity	0.15	Cloth reflectance, ρ_c	0-1
Thermal conductivity of cloth, k_c	0.047 $Wm^{-1}K^{-1}$	Cloth transmittance, τ_c	0-1

Model formalism. In this model, the overall goal is to determine the maximum ambient temperature that can be sustained without compromising a person's thermal comfort as a function of the cloth's optical properties. Although a minimum ambient temperature also exists, this is related to personal heating and is thus beyond the scope of this work. The criterion used to evaluate personal thermal comfort is based on the equivalence of the total cooling power with the total heat generation rate of 105 W from the human body. For a given set of material and environmental conditions, the ambient temperature is increased iteratively until the net cooling power can no longer dissipate the amount of heat generated by the human body. By fixing the skin temperature to be 33.9°C (93°F), the primary unknown variables in this model are the inner surface cloth temperature, T_1, the outer surface cloth temperature, T_2, and the ambient temperature, T_3.

Additionally, the air gap thickness, t_a, and the convective heat transfer coefficient, h, can also be varied to simulate different environmental conditions (i.e. tight-fitting vs. loose fitting cloth on different areas of the human body, varying levels of air circulation within the ambient environment, etc.)

independent of the environment temperature. In order to compare the impact of the cloth's optical properties on personal cooling for various environmental conditions, we constrain the air gap thickness and convective heat transfer coefficient to ensure a consistent baseline neutral temperature band is used regardless of the environmental conditions. To accomplish this, we adopt a reference case that assumes an ambient temperature of 23.9^{o}C (75^{o}F), corresponding to the upper limit of a typical neutral temperature band. The reflectance and transmittance of the cloth are also assumed to be ρ_c = 0.3 and τ_c = 0.03, respectively, corresponding to measurements of conventional polyester and cotton fabrics as shown in Fig. 2 of the main text. Under these conditions, we first choose the convective heat transfer coefficient and iterate the air gap thickness until the total cooling power exactly balances the total heat generation rate using the model equations as shown below. In this manner, the maximum ambient temperature for various environmental conditions and conventional clothing is always 23.9^{o}C (75^{o}F). Thus, any subsequent improvements can only be attributed to radiative cooling through the cloth. In this work, we assume an individual is cooled via natural convection, thus the convective heat transfer coefficient has a typical range of 3-5 W/m^{2}K with a corresponding air gap thickness of 1.05-2.36 mm.

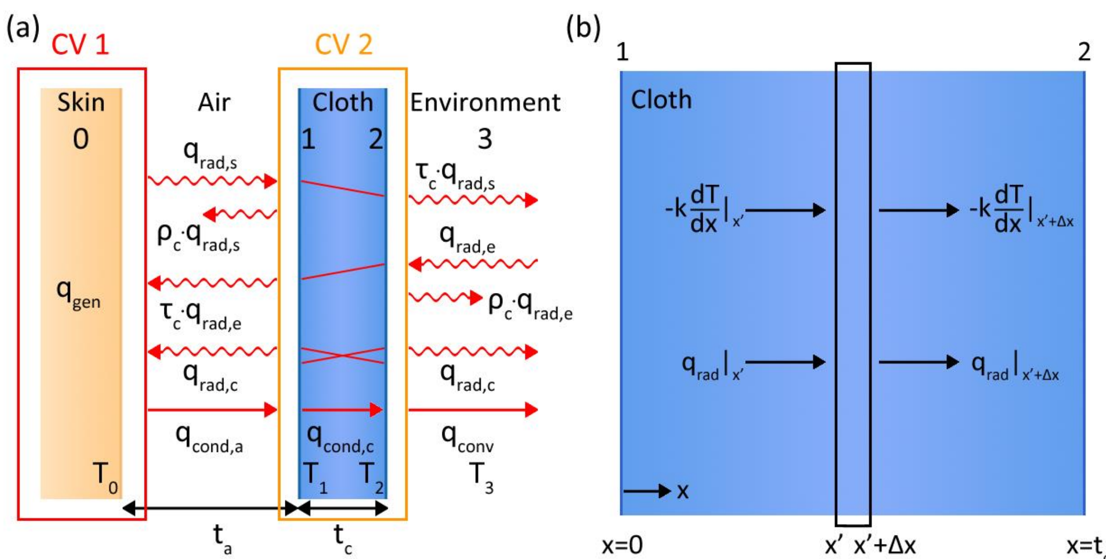

Figure S1: Illustrations depicting the control volume analysis and temperature profile formulation for the heat transfer model. (a) The control volumes chosen in this analysis consist of CV1 around the human body and CV2 around only the cloth. (b) A schematic illustrating the differential element and energy balance used to derive the temperature profile within the cloth. In addition to heat conduction, this analysis includes radiative absorption and emission.

Control volume analysis. The first component of the heat transfer model is to identify relevant control volumes (CV) and to apply an energy balance in order to obtain equations that connect the various heat transfer mechanisms included in this model. As shown in Fig. S1a, there are two control volumes that will be used in this study: CV1 is defined around only the human body and CV2 is defined around the entirety of the surrounding cloth. The expressions obtained when applying an energy balance around CV1 and CV2 are as follows,

$$\text{CV 1: } q_{gen} + q_{rad,c} + \tau_c \cdot q_{rad,e} - \left(1 - \rho_c\right) \cdot q_{rad,s} - q_{cond,a} = 0 \tag{S2}$$

$$\text{CV 2: } \left(1 - \rho_c - \tau_c\right) \cdot q_{rad,s} + \left(1 - \rho_c - \tau_c\right) \cdot q_{rad,e} + q_{cond,a} - 2 \cdot q_{rad,c} - q_{conv} = 0 \tag{S3}$$

where q_{gen} is the heat generation rate per unit area, $q_{cond,a}$ is the conductive heat flux between the skin and the cloth, q_{conv} is the convective heat flux from the cloth to the ambient environment, $q_{rad,s}$ is the radiative heat flux from the skin, $q_{rad,e}$ is the radiative heat flux from the ambient environment, and $q_{rad,c}$ is the radiative heat flux from the cloth. The conductive, convective, and radiative heat flux terms are expressed using Fourier's law, Newton's law of cooling, and the Stefan-Boltzmann law as follows,

$$q_{cond,a} = k_a \cdot \frac{T_0 - T_1}{t_a} \tag{S4}$$

$$q_{conv} = h \cdot \left(T_2 - T_3\right) \tag{S5}$$

$$q_{rad,s} = \sigma T_0^4 \tag{S6}$$

$$q_{rad,e} = \sigma T_3^4 \tag{S7}$$

$$q_{rad,c} = \varepsilon_c \sigma \left(\frac{T_1 + T_2}{2}\right)^4 \tag{S8}$$

where T_0 is the skin temperature, T_1 is the inner surface cloth temperature, T_2 is the outer surface cloth temperature, T_3 is the ambient temperature, k_a is the thermal conductivity of air, t_a is the air gap thickness, h is the convective heat transfer coefficient, σ is the Stefan-Boltzmann constant equal to $5.67 \cdot 10^{-8}$ $Wm^{-2}K^{-4}$. In equation (S8), we assume a mean temperature of T_1 and T_2 to approximate radiative emission by the cloth. Additionally, in equations (S2), (S3), (S6), and (S7), it was assumed the skin and environment behave like an ideal blackbody with an absorptance and emittance equal to 1.

Based on the control volume analysis, we obtain two fundamental equations (S2) and (S3) that describe the various contributions to heat transfer in this system. Since there are three unknowns that must be solved for, an additional equation is required in order to complete this model. Equations (S2) and (S3) describe heat transfer around the human body and the cloth, respectively. By deduction, the remaining equation must describe the nature of heat transfer within the cloth itself. Specifically, by considering heat conduction, radiative absorption, and radiative emission, a temperature profile can be derived in order to link the unknown temperatures T_1 and T_2.

Temperature profile of cloth. To determine the temperature profile within the cloth, heat conduction and radiative heat transfer must be included in the heat transfer analysis. If a differential volume element is taken within the cloth, as shown in Fig. S1b, the heat equation will take the following form,[1]

$$k_c \frac{\partial^2 T}{\partial x^2} - \frac{\partial}{\partial x}\left(q_{rad}\right) = 0 \tag{S9}$$

where k_c is the cloth thermal conductivity and q_{rad} is the net radiative transfer within the cloth. In general, q_{rad} must be determined rigorously using the radiative heat transfer equation in order to account for all absorption, emission, and internal scattering processes. For simplicity, we assume internal scattering effects are negligible and only consider IR reflection at the boundaries of the cloth, as will be later shown when determining the expressions for each radiative heat flux. Additionally, self-absorption effects are also neglected. Therefore, the net radiative heat transfer will consist only of incident radiative absorption and outgoing radiative emission as follows,

$$k_c \frac{\partial^2 T}{\partial x^2} = \frac{\partial}{\partial x}\left(q_{rad,cL'}\right) + \frac{\partial}{\partial x}\left(q_{rad,cR'}\right) + \frac{\partial}{\partial x}\left(q_{rad,s'}\right) + \frac{\partial}{\partial x}\left(q_{rad,e'}\right) \tag{S10}$$

where $q_{rad,cL'}$ is the radiative emission from the cloth to the skin, $q_{rad,cR'}$ is the radiative emission from the cloth to the ambient environment, $q_{rad,s'}$ is the absorption of radiation emitted from the skin, and $q_{rad,e'}$ is the absorption of radiation emitted from the ambient environment.

In general, the analytical form for radiative absorption and emission in the limit of negligible internal scattering will consist of an exponential decay in accordance to the Beer-Lambert law.[1] However, we again simplify the analysis by instead assuming the absorption and emission profile to be linear as follows,

$$q_{rad,i}\left(x\right) = A \cdot x + B \tag{S11}$$

where A and B are unknown coefficients that will depend on the boundary conditions assumed for each radiative heat flux. In the limit of high absorption, the approximation of a linear absorption and emission profile will be inaccurate. Despite this limitation, it is nonetheless expected that this approximation will provide a reasonable estimation of heat transfer through the cloth since the difference in the inner and outer cloth temperature is not expected to be large, thus inherently making this analysis less sensitive to the absorption and emission profile used. Using equation (S11) and appropriate boundary conditions for each radiative flux, we obtain the following,

1. Emission from cloth to skin:

$$\begin{aligned} q_{rad,cL'}(x=0) &= -q_{rad,c} \\ q_{rad,cL'}(x=t_c) &= 0 \end{aligned} \quad \rightarrow q_{rad,cL'}(x) = \frac{q_{rad,c}}{t_c} x - q_{rad,c} \tag{S12}$$

2. Emission from cloth to ambient environment:

$$\begin{aligned} q_{rad,cR'}(x=0) &= 0 \\ q_{rad,cR'}(x=t_c) &= q_{rad,c} \end{aligned} \quad \rightarrow q_{rad,cR'}(x) = \frac{q_{rad,c}}{t_c} x \tag{S13}$$

3. Absorption by cloth from skin:

$$\begin{aligned} q_{rad,s'}(x=0) &= (1-\rho_c)\cdot q_{rad,s} \\ q_{rad,s'}(x=t_c) &= \tau_c \cdot q_{rad,s} \end{aligned} \quad \rightarrow q_{rad,s'}(x) = -\frac{\alpha_c \cdot q_{rad,s}}{t_c} x + (1-\rho_c)\cdot q_{rad,s} \tag{S14}$$

4. Absorption by cloth from ambient environment:

$$\begin{aligned} q_{rad,e'}(x=0) &= -\tau_c \cdot q_{rad,e} \\ q_{rad,e'}(x=t_c) &= -(1-\rho_c)\cdot q_{rad,e} \end{aligned} \quad \rightarrow q_{rad,e'}(x) = -\frac{\alpha_c \cdot q_{rad,e}}{t_c}(x-t_c) - (1-\rho_c)\cdot q_{rad,e} \tag{S15}$$

Upon substituting equations (S12)-(S15) into (S10) and using the definition of heat fluxes defined by (S6)-(S8), the heat equation will become,

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{k_c t_c}\left(2\varepsilon_c \sigma \left(\frac{T_1+T_2}{2}\right)^4 - \alpha_c \sigma T_0^4 - \alpha_c \sigma T_3^4\right) \tag{S16}$$

where a mean temperature of T_1 and T_2 is again used to approximate radiative emission from the cloth. Although radiative emission from the cloth technically depends on the local temperature T as a function of position x, the use of a mean temperature is a reasonable approximation since T_1 and T_2 are not expected to be significantly different.

To determine the temperature profile, all that remains is to integrate equation (S16) and apply appropriate boundary conditions,

$$\frac{\partial T}{\partial x} = \frac{1}{k_c t_c}\left(2\varepsilon_c \sigma \left(\frac{T_1+T_2}{2}\right)^4 - \alpha_c \sigma T_0^4 - \alpha_c \sigma T_3^4\right)x + C_1 \tag{S17}$$

$$T = \frac{1}{2k_c t_c}\left(2\varepsilon_c \sigma \left(\frac{T_1+T_2}{2}\right)^4 - \alpha_c \sigma T_0^4 - \alpha_c \sigma T_3^4\right)x^2 + C_1 x + C_2 \tag{S18}$$

The boundary conditions applied in this analysis includes temperature and heat flux continuity at surface 1 (x = 0) as follows,

$$T\left(x=0\right)=T_1 \tag{S19}$$

$$-k\frac{\partial T}{\partial x}\left(x=0\right)=q_{cond,a} \tag{S20}$$

Upon applying (S19) and (S20) in equations (S17) and (S18), we obtain the final expression for the temperature profile within the cloth,

$$T=\frac{1}{2k_c t_c}\left(2\varepsilon_c\sigma\left(\frac{T_1+T_2}{2}\right)^4-\alpha_c\sigma T_0^4-\alpha_c\sigma T_3^4\right)x^2-\frac{k_a}{k_c}\frac{\left(T_0-T_1\right)}{t_a}x+T_1 \tag{S21}$$

By taking x = t_c in equation (S21), the following temperature relation is obtained,

$$T_2=\frac{t_c}{2k_c}\left(2\varepsilon_c\sigma\left(\frac{T_1+T_2}{2}\right)^4-\alpha_c\sigma T_0^4-\alpha_c\sigma T_3^4\right)-\frac{k_a t_c}{k_c t_a}\left(T_0-T_1\right)+T_1 \tag{S22}$$

Therefore, with equations (S2), (S3), and (S22), we now have a complete set of equations to describe heat transfer from a human body covered by cloth to the ambient environment. These equations are used to first obtain the air gap thickness, t_a, for the previously described reference case with an assumed convective heat transfer coefficient. Following this calculation, we then use the same equations to solve for T_1, T_2, and T_3 as a function of the cloth's optical properties and the assumed environmental conditions. From this analysis, we can find the maximum ambient temperature, T_3, which can be sustained without compromising personal thermal comfort.

2. Supplementary Figures:

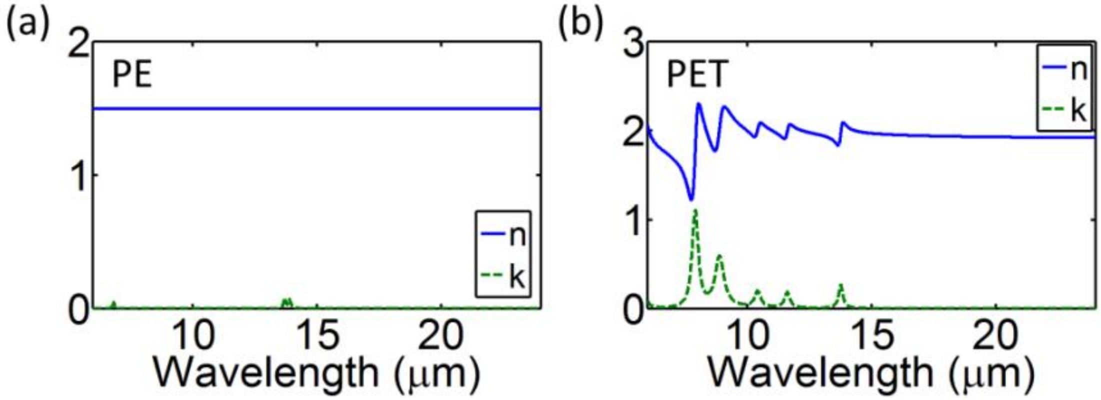

Figure S1: The optical constants of: (a) polyethylene (PE) and (b) polyethylene terephthalate (PET), more commonly known as polyester, taken from the literature. For polyethylene, the refractive index, n, is extrapolated from shorter wavelength data. Based on the dispersion of the extinction coefficient, k, it is expected the refractive index will also exhibit some dispersion. However, this is assumed to be small and is thus neglected in this study. For polyester, a Lorentzian model was used to fit experimental data from previous studies.[2]

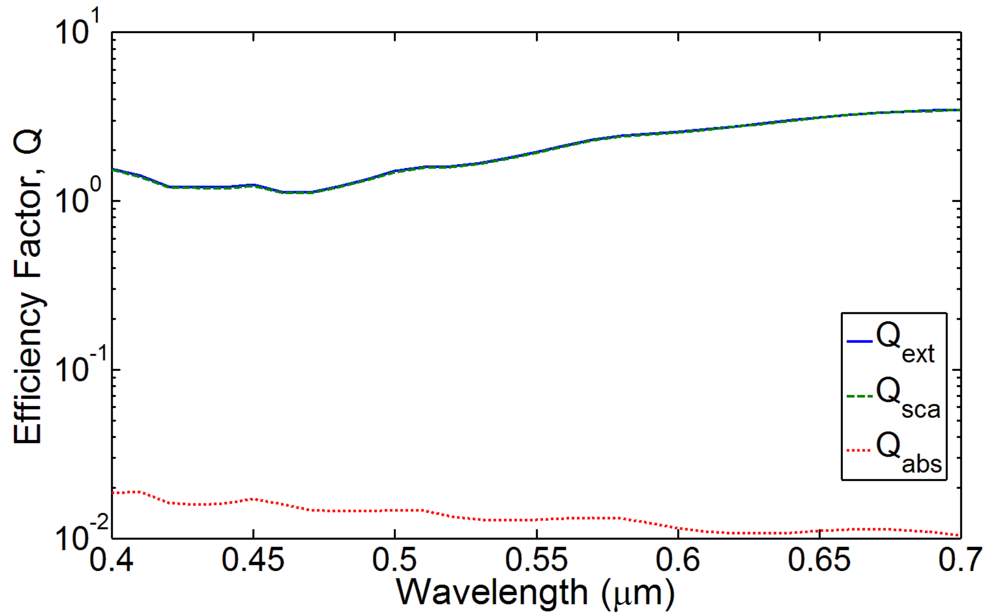

Figure S2: The visible wavelength extinction, scattering, and absorption efficiency of a single polyethylene fiber. The efficiency factor, Q, is defined as the ratio of the effective cross section normalized to the geometric cross section. The diameter of the fiber is D = 1 μm and the incident light is assumed to be unpolarized. For computation, the standard Mie theory solutions for an infinitely long cylinder were used.[3] As shown, the absorption efficiency exhibits a similar trend to the total hemispherical absorptance shown in Fig. 6 in the main text. The oscillatory behavior is indicative of whispering gallery modes supported by the fiber which are broadened due to material loss ($n = 1.5$, $k = 5\cdot10^{-4}$). In addition, a broad Fabry-Perot resonance is also supported by the fiber as indicated by the scattering efficiency, which increases from 460 nm to 700 nm.

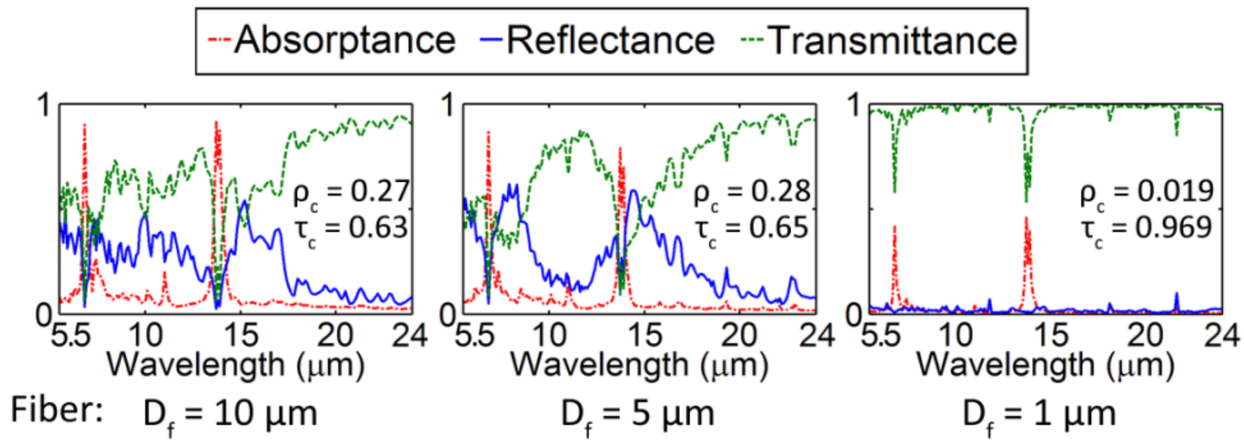

Figure S3: Numerical simulation results for the IR optical properties of a polyethylene-based ITVOF for the case of a varying fiber diameter (D_f = 1 μm, 5 μm, and 10 μm) assuming a fixed yarn diameter of D_y = 50 μm. As before, all simulations assume the fiber separation distance is D_s = 1 μm and the yarn separation distance is D_p = 5 μm. The spectrally integrated transmittance (τ_c) and reflectance (ρ_c) is shown in each plot weighted by the Planck's distribution assuming a body temperature of 33.9°C. Compared to the case where D_y = 30 μm, the overall transmittance is lower, as expected, due to the combination of a larger material volume that absorbs more incident IR radiation and a larger number of fibers available to scatter incident IR radiation thus increasing the reflectance. However, by reducing the size of the fiber to be D_f = 1 μm, which is far smaller than IR wavelengths, the total transmittance can again be significantly enhanced from 0.63 to 0.969 which is nearly equal to the case where D_y = 30 μm. Simultaneously, the reflectance of the ITVOF is reduced from 0.27 to 0.019 further improving radiative cooling. These results show that reducing the fiber size is far more important than reducing the yarn size. Therefore, this structuring methodology could potentially be applied to ITVOF that are comparable in size to conventional fabrics. The material volume per unit depth for a single yarn is 1492 μm^2 for D_f = 10 μm, 1217 μm^2 for D_f = 5 μm, and 445 μm^2 for D_f = 1 μm. The optical properties of the ITVOF are again calculated for the wavelength range from 5.5 to 24 μm, which will provide a conservative estimate of the total transmittance and the reflectance.

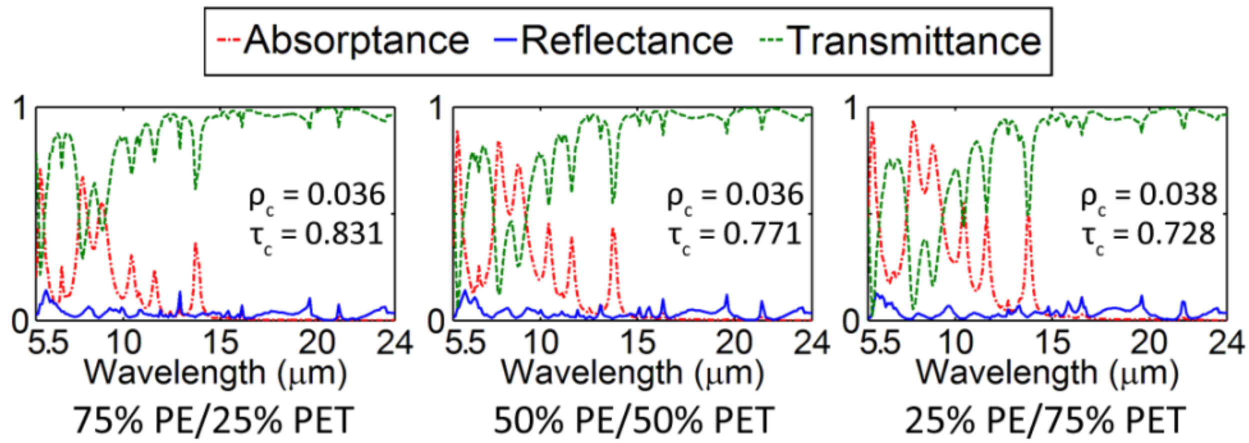

Figure S4: Numerical simulation results for the IR optical properties of an ITVOF blend of polyethylene and polyester with varying volumetric concentrations. The PE and PET fibers were randomly distributed in the simulation. For all simulations it is assumed D_f = 1 μm, D_y = 30 μm, D_s = 1 μm, and D_p = 5 μm. Again, the spectrally integrated transmittance (τ_c) and reflectance (ρ_c) is shown in each plot weighted by the Planck's distribution assuming a body temperature of 33.9^{o}C. As shown, a progressive increase in the volumetric concentration of PET results in an increase in the spectral absorptance thus decreasing the total transmittance. However, it can also be observed that the spectral reflectance is ~0.04 for all cases and exhibits no significant variation spectrally further reinforcing the point that so long as the fiber is sufficiently small compared to IR wavelengths, scattering will be minimal. Based on these results, even the highest volumetric concentration of PET fibers (25%PE/75% PET) can provide sufficient cooling to raise the ambient temperature to 26.1^{o}C due to a combination of a high total transmittance of 0.728 and a low total reflectance of 0.038. The material volume per unit depth for a single yarn in all cases is equal to 135.9 μm^2. The optical properties of the ITVOF are again calculated for the wavelength range from 5.5 to 24 μm, which will provide a conservative estimate of the total transmittance and the reflectance.

References:

1. Modest, M. F. *Radiative Heat Transfer*. (Academic Press, 2003).
2. Laskarakis, A. & Logothetidis, S. Study of the electronic and vibrational properties of poly(ethylene terephthalate) and poly(ethylene naphthalate) films. *J. Appl. Phys.* **101,** 053503 (2007).
3. Bohren, C. F. & Huffman, D. R. *Absorption and Scattering of Light by Small Particles*. (WILEY-VCH Verlag GmbH & Co. KGaA, 2007).