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

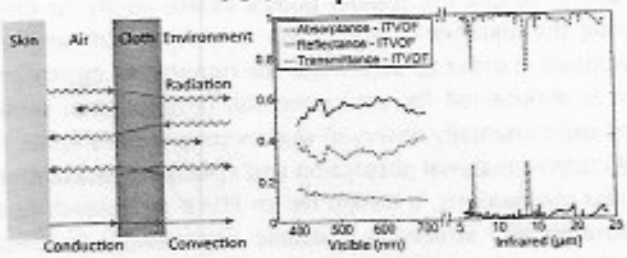
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Abstract

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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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

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.

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° 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°C (93°F).

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°C (93°F). 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

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°C (79°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

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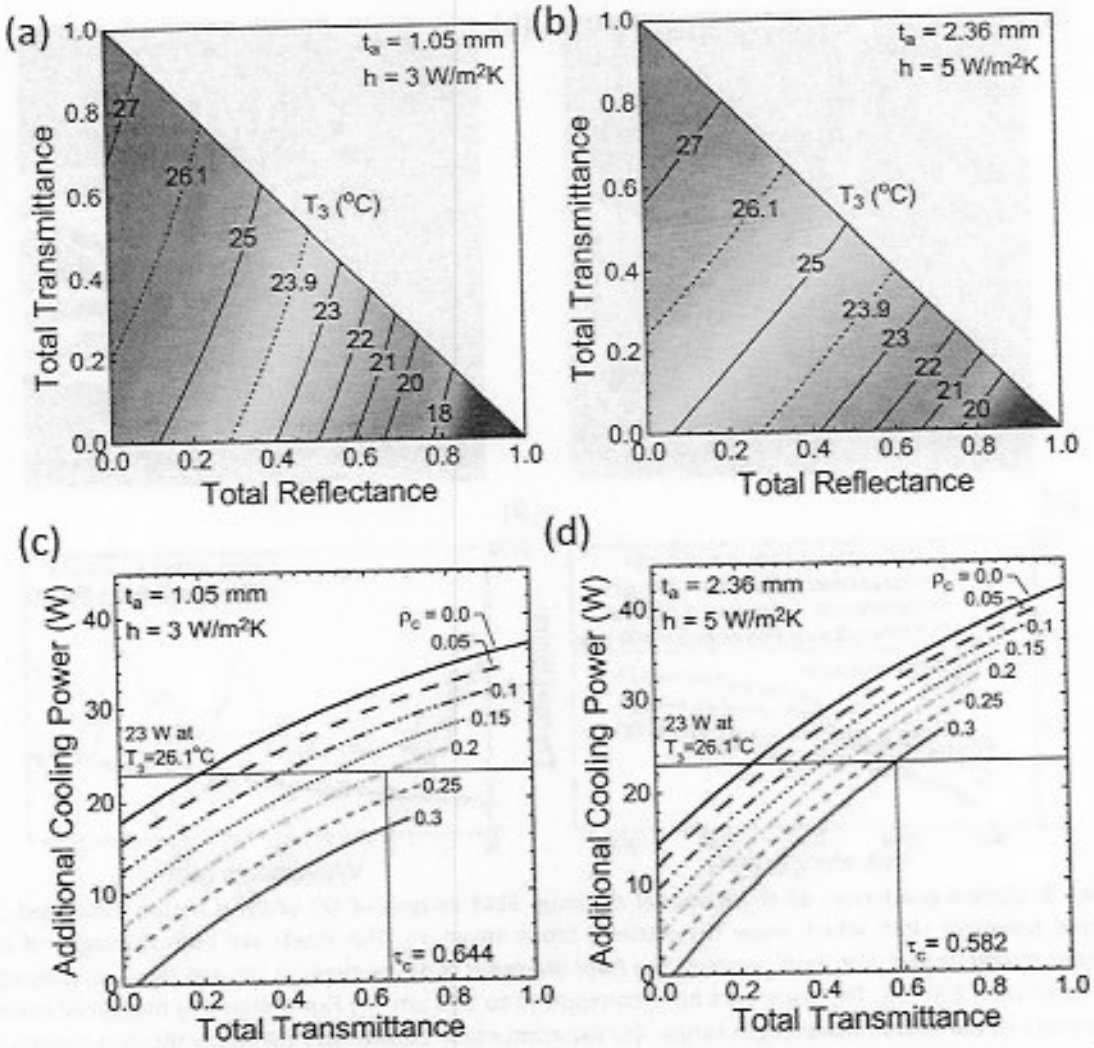


Figure 2: Evaluation of ITVOF mid- to far-IR optical requirements to maintain personal thermal comfort at elevated ambient temperatures. (a) A temperature map was computed showing the maximum ambient temperature attainable without compromising thermal comfort as a function of the total reflectance and 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 °C using only thermal radiation.

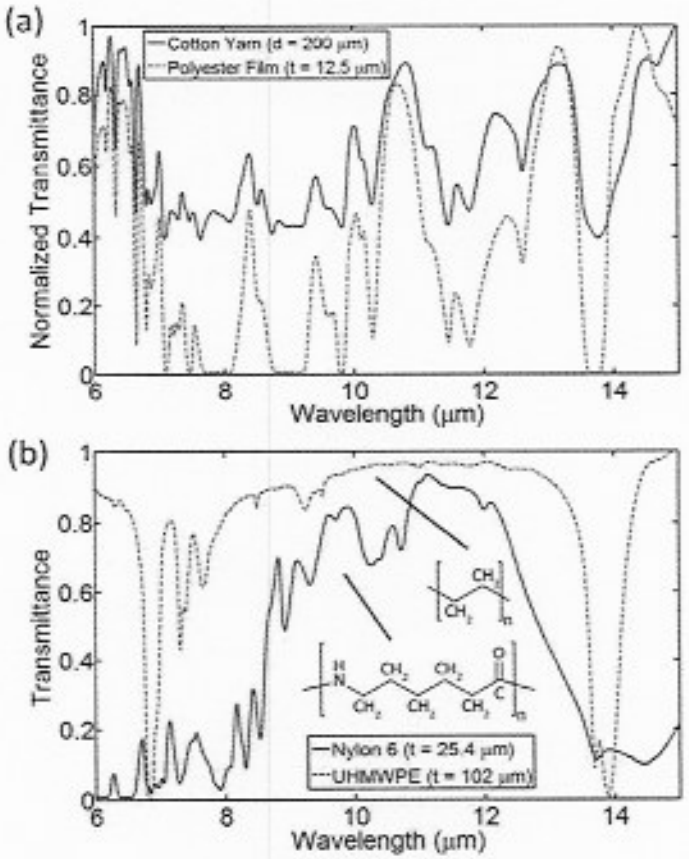


Figure 4: Intrinsic absorptive properties of various synthetic polymers. (a) The FTIR transmittance spectra for a single cotton yarn (diameter, d = 200 μm) and a polyester thin-film (thickness, t = 12.5 μm). The transmittance spectra is normalized to provide similar scaling due to the order of magnitude 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).