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The measurement of the solar absorptance of the clothed human body – The case of Japanese, college-aged male subjects

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ABSTRACT

In an outdoor environment, thermal comfort is affected by various factors, in particular solar radiation. Quantifying the solar absorptance of a human body is necessary for accurately assessing outdoor thermal comfort. Numerous studies have measured the solar absorptance of skin and fabrics. However, these measurements do not represent the solar absorptance of clothed humans. This study intends to determine the average solar absorptance of the human body wearing a combination of specific black and white garments and measure the average solar absorptance of Japanese, college-aged male subjects wearing casual summer, autumn, and winter clothing. The solar absorptance of the entire clothed human body was derived from these measurements. The solar absorptance of a black-shirt and black-trousers combination was found to be 0.76. For the combination of a white-shirt and white-trousers, the minimum solar absorptance was 0.38. Furthermore, the average solar absorptances of 30 Japanese, college-aged male subjects wearing casual clothing in summer, autumn, and winter were 0.66, 0.69, and 0.77, respectively. In summer, the average solar absorptance of the subjects in casual clothing depended on the color of tops. The average solar absorptances were suggested to be 0.76, 0.56, and 0.68 for subjects wearing black tops, white tops, and tops with Munsell values between 2 and 8, respectively.

1. Introduction

In an outdoor environment, thermal comfort is affected by various factors, in particular solar radiation. The solar radiation received by a human body is one of the most important components for human-energy balance. Several thermal indices for evaluating outdoor thermal comfort such as the physiological equivalent temperature (PET) [1], the outdoor standard effective temperature (OUT_SET*) [2], the enhanced conduction-corrected modified effective temperature (ETFe) [3], the universal effective temperature (ETU) [4], and the universal thermal climate index (UTCI) [5], were proposed. These models require mean radiant temperature (MRT), including short wave fluxes, as an input. One of the procedures to calculate MRT of a person exposed to a strong directional irradiation from a high-intensity radiant source, was proposed by Fanger [6] and described in VDI 3787 Part 2 [7]. The solar absorptance of the human body is required to calculate an outdoor MRT. Therefore, the solar absorptance of the clothed human body must be quantified for accurately assessing outdoor thermal comfort. Thorsson et al. [8] calculated the outdoor MRT on the basis of six individual measurements of short-wave and long-wave radiation fluxes as well as solar absorptance.

The solar absorptance of human skin was measured in several studies. Hardy [9] reported that the solar absorptance for darkly pigmented skin is 0.8 and that for lightly pigmented skin is 0.6–0.7. ASHRAE Handbook Fundamentals [10] presents a graph depicting the relationship between color temperature and human-skin absorptance. The graph shows that the solar absorptances for darkly and lightly pigmented skins are approximately 0.8 and 0.6, respectively. Moreover, the solar absorptances of fabrics or garments were measured in several studies. According to the previous literature, the solar absorptance of fabrics ranges from 0.14 for white silk [11] to 0.97 for black velvet [12], as shown in Table 1. Absorptances clearly vary considerably with respect to color and fabric. However, the reported values represent the solar absorptance of the human skin or fabrics and not of the entire clothed human body.

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Table 1
Solar absorptance values of garments or clothing materials reported in the literature. When only albedo measurement of an object was presented in the papers, solar absorptance was derived by subtracting the value from unity. When transmittance and absorptance values of an object were presented, solar absorptance was derived by adding these values.

Researchers	Fabric properties	Solar absorption factor dimensionless
Martin [12]	White cotton shirt, two thicknesses, unstarched	0.29
	Khaki cotton shirt	0.57
	Dark grey flannel suiting	0.88
	Dress suit	0.95
	Black velvet	0.97
Aldrich (quoted in Blum [25],)	Shirt, Mock Leno, slightly permeable	0.56
	Cotton, khaki-8.2 oz.	0.44
	Cotton, percale, white	0.33
	Cotton, percale, O.D.	0.52
	Cotton, tubular balbriggan	0.38
	Cotton, twill, khaki	0.48
	Cotton, shirting worsted, O.D.	0.61
	Cotton, denim, blue	0.67
	Cotton, herringbone twill	0.74
	Cotton, duck No. 746	0.93
Clark and Cena [26]	Pure cotton shirt, black	0.95
	Pure cotton shirt, red	0.72
	Pure cotton shirt, yellow	0.53
	Pure cotton shirt, white	0.30
Nielsen [27]	Polyester, white	0.60
	Polyester, black	0.74
	Cotton, white	0.55
	Cotton, black	0.75
Shinohara and Tokumoto [11]	Silk, white	0.14
	Wool, black	0.49
	Cotton or Polyester, excluding black and white	Approx. 0.3
Watanabe et al. [28]	Cotton shirt, black	0.61
	Cotton shirt, white	0.17
	Cotton shirt, gray	0.36
	Cotton shirt, red	0.47
	Cotton shirt, blue	0.57
Kuwabara et al. [29]	Cotton shirt, white	0.33
	Cotton shirt, gray	0.54
	Cotton shirt, black	0.69
	Cotton shirt, red	0.61
	Cotton shirt, blue	0.66
	Cotton shirt, yellow	0.41
	Cotton shirt, olive	0.68
	95% polyester, 5% cotton, shorts, dark blue	0.65

To assess outdoor thermal comfort accurately, solar absorptance for a combination of garments and uncovered skin should be used to calculate the human-energy balance. Several researchers quantified the solar absorptance of the completely clothed human body. Terjung and Louie [13] applied a value of 0.6 as a generalized skin-clothing solar absorptance in an outdoor model of the human-energy balance. Brown and Gillespie [14] applied an average solar absorptance of 0.63 for the skin-clothing combination in an outdoor thermal-comfort assessment. Blazejczyk et al. [15] applied an average solar absorptance of 0.67 for skin and clothing to calculate of heat flux absorbed by a human in the outdoors. However, these values were not derived from measurements, but they were estimated on the basis of the solar absorptance of the skin or garments reported in previous literature. A value of 0.7, as prescribed in VDI 3787 Part 2 [7], is frequently used as a standard for solar absorptance of humans in the outdoors. Many researchers have adopted this value while assessing outdoor thermal comfort [16–21]. However, this value is applicable only to the average human and not to variations in clothing color and/or fabrics although absorptance depends on the radiation properties of objects. When the solar absorptances of 0.6 and 0.7 are assumed for the human body on a beach in summer (air temperature, 30.8 °C; global solar radiation, 939.8 W/m^2; and air velocity, 2.57 m/s) [22], MRTs are calculated as 68.6 °C and 72.4 °C, respectively. While applying these values to calculate operative temperature (OT) as a final thermal-comfort index, the respective OTs of 40.2 °C and 41.6 °C were obtained. A MRT difference of 3.8 °C cannot be neglected in a thermal-comfort assessment.

This study intends to determine the solar absorptance of the human body wearing an ensemble of specific black and white garments. The measurements for a black-shirt and black-trousers (B–B) ensemble should provide the upper boundary for the solar absorptance of clothed humans. Similarly, a white-shirt and white-trousers (W–W) ensemble should provide the lower boundary. Next, the solar absorptances of 30 Japanese, college-aged male subjects wearing their own casual summer, autumn, and winter clothing are measured. Naturally, factors such as culture, age, and gender may influence the selection of garments and colors. However, while quantifying the average solar absorptance of humans, even specific subjects, these factors may be part of comprehensive solar-absorptance data. Note that the silhouettes of the subjects are similar when they wear the same ensemble and have the same posture even if their physical characteristics are different.

2. Materials and methods

2.1. Experiment-1 (black and white clothing)

Measurements were performed from autumn to early winter (October, 29; November, 9; December, 2 and 4, 2009) at Daido University (35°04′ N, 136°54′ E) in Nagoya, Japan. Measurements were performed between 12:00 and 14:00 to avoid low solar-altitude conditions. In generally, albedo measurements should be performed when the solar zenith angle is maximum because the signals from a pyranometer are maximized, thereby reducing the overall uncertainty in albedo measurements [23]. Sampling information and the corresponding meteorological data are listed in Table 2.

Four Japanese, college-aged male subjects participated in the experiment. The average height and weight of the subjects were 174.0 cm with a standard deviation (SD) of 6.1 cm and 60.4 kg with a SD of 2.0 kg, respectively. All subjects were 20 years old. Black shirts, black trousers, white shirts, and white trousers made of specific 100% cotton were used, as described in Table 3. Shirts with long sleeves and trousers without tuck were designed fitted to each subject. Four ensembles in combinations of black and white garments were tested, i.e., a black shirt and black trousers (B–B), a black shirt and white trousers (B–W), a white shirt and black trousers (W–B), and a white shirt and white trousers (W–W) (Fig. 1.)

2.2. Experiment-2 (casual clothing)

Measurements were performed at the same site as that of Experiment-1 during three-days in summer (July 22, 23, and 26, 2010), autumn (November 4, 5, and 9, 2010), and winter (January 11, 12, and 13, 2011). Measurements were performed between 10:00 and 14:00 to avoid low solar altitude. On all sampling days except for January 12, 2011 (partly cloudy), the skies were clear. The measuring periods and the corresponding meteorological data are listed in Table 2.

Experiment-2 comprised 30 Japanese, college-aged male subjects. Table 4 shows information about subjects' physical characteristics. The subjects were asked to wear their own casual