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Modeling the comfort effects of short-wave solar radiation indoors

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ABSTRACT

Exposure to sunlight indoors produces a substantial effect on an occupant's comfort and on the air conditioning energy needed to correct for it, yet has in the past not been considered in design or in thermal comfort standards. A public online model of the effects of solar radiation on human heat gain and comfort has been developed to make this possible. SolarCal is a whole-body model for ease of use in early design. Its predictions compare closely (<0.1 PMV mean absolute error) to results of a human subject test. It can be used to determine the allowable transmittance of fenestration in a perimeter office.

1. Introduction

Windows unshaded from direct solar radiation are common in commercial buildings. They often introduce significant problems by admitting large amounts of solar (aka shortwave) radiation indoors. Some of the problems are visual, such as glare, but three thermal ones are also very important.

First, in most buildings the heat gain from solar radiation absorbed indoors must be removed by energy-intensive air-conditioning. *Second*, solar gain in the occupied zone is intensely variable and difficult to control: in attempting to keep the temperature of a sunlit section under control, adjacent spaces are likely to be overcooled. A *third* issue is the topic of this paper: solar radiation landing on occupants directly affects their thermal comfort. The solar heat absorbed and liberated in clothing and skin must be offset by cooler air and surface temperatures around the body for the occupant to remain comfortably in thermal balance (Fig. 1). The temperature offset may be substantial and beyond the corrective capacity of conventional cooling systems.

This third issue has received surprisingly little notice in the design or evaluation of buildings. For example, the relevant indoor environmental standards ASHRAE Standard 55 *Thermal environmental conditions for human occupancy* [2], EN-ISO Standard 7730 [5], and CEN-15251 [6] do not even mention shortwave radiation. Although Fanger published projected area factors for the human body in 1970 [7], the subject of shortwave gain and comfort has been almost absent from the research literature until recently. A few studies [8,9,16,19] have addressed the effect of solar heating on comfort.

There are no readily available design tools for predicting the effect of solar radiation falling directly on occupants in buildings. Potential developers of such tools may have been discouraged by the complexity of the task: identifying an occupant's position, determining the position of solar beam radiation on interior room surfaces, determining the shading and reflection from interior furnishings, and determining the effect of solar altitude and azimuth on the occupant's non-cylindrical body shape.

There are complex multi-segment thermal physiology and comfort models that predict detailed radiative heat exchanges between the human body and its environment via view factors [11–13]. These models also predict solar loads on local body parts. For example, the commercial software RadTherm [20] distributes solar loads to local body segments in the Fiala thermophysiological model, from which local skin temperatures are predicted [11]. The Berkeley Advanced Comfort Model [15] performs the same functions. In both of these, the predicted local skin temperatures are then converted to local thermal sensation and comfort using the Zhang et al. [14] comfort model. Multi-segment physiology and

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Fig. 1. Occupant exposed to direct solar irradiation (image courtesy of Seattle Times).

comfort models are most commonly used in automotive design. The process is more time-intensive and constrained than typical building design, in which speed of use is more of an issue. Multi-segment models may be linked with CFD simulation, and with advanced fenestration models. WINDOW 6.2 [17] predicts bidirectional scattering for solar radiation impinging on complex window systems (glass, louvers, and shades). The scattered solar might be linked to a human manikin in order to distribute solar loads on different body parts [10]. Solar scattering models have not yet been linked to thermophysiological and comfort models.

For the foreseeable future, building designers will need a way to quickly calculate the consequences of different levels of indoor solar radiation indoors on comfort, peak cooling load, and energy use. The comfort consequences should be quantified on well-accepted thermal comfort scales. The peak cooling load and energy consequences should be quantified by how much the space's temperature would have to be reduced to offset the solar heat liberated on the occupant. The solar variables under the designer's control would be: the presence or absence of sunlight on the person, the extent of the person's body area exposed to direct sun, and the intensity of solar radiation after filtering through glass and window furnishings. Evaluating these variables may not require great geometric precision since occupants' positions in buildings cannot be very precisely predicted or fixed.

This paper describes a solar calculator (SolarCal) that is incorporated in the Center for the Built Environment (CBE) web-based Comfort Tool [18]. The Comfort Tool contains the provisions of ASHRAE Standard 55 [2] as its core, but it also has optional features beyond the current requirements of the Standard [21]. SolarCal is based on a method developed by Arens et al. [1] to evaluate the effect of solar radiation on comfort outdoors. The SolarCal model is intentionally simplified so it can be used to quickly estimate the solar radiation in undetermined environments or in environments with simple geometries. In this paper, we compare SolarCal simulations against a recent human subject test of solar effects and comfort, to evaluate the effectiveness of SolarCal's simplified radiation calculations, and its ability to predict comfort in terms of predicted mean thermal sensation votes (PMV) [7]. We also estimate the level of window shading needed to prevent unacceptable PMV increases for occupants near windows.

2. Method of calculating solar gain to the body indoors

The SolarCal model is based on the *effective radiant field* (ERF), a measure of the net radiant energy flux to or from the human body. ERF is used to describe the additional (positive or negative) long-wave radiation energy at the body surface when surrounding surface temperatures are different from the air temperature. It is in W/m^2, where area refers to body surface area. The surrounding surface temperature of a space is commonly expressed as *mean radiant temperature* (MRT). The ERF on the human body from long-wave exchange with surfaces is related to MRT by:

$$\mathrm{ERF} = f_{\mathrm{eff}} h_r (\mathrm{MRT} - T_a) \quad (1)$$

where f_{eff} is the fraction of the body surface exposed to radiation from the environment (=0.696 for a seated person and 0.725 for a standing person [7]); h_r is the radiation heat transfer coefficient (W/m^2 K); and T_a is the air temperature (°C).

The energy flux actually absorbed by the body is ERF times the long-wave emissivity/absorptivity α_{LW}, typically equal to 0.95. Solar radiation absorbed on the body's surface can be equated to an additional amount of longwave flux, $\mathrm{ERF}_{\mathrm{solar}}$:

$$\alpha_{\mathrm{LW}} \mathrm{ERF}_{\mathrm{solar}} = \alpha_{\mathrm{SW}} E_{\mathrm{solar}} \quad (2)$$

where E_{solar} is the shortwave solar radiant flux on the body surface (W/m^2); α_{SW} is short-wave absorptivity, ≈0.67 for (white) skin and average clothing.

E_{solar} is the sum of three fluxes that have been filtered by fenestration properties and geometry, and are distributed on the occupant body surface: direct beam solar energy coming directly from the sun (E_{dir}), diffuse solar energy coming from the sky vault (E_{diff}), and solar energy reflected upward from the floor (E_{refl}). These are defined below.

Diffuse radiation from the sky is assumed to be distributed on the upper half of the radiatively-exposed portion of the body.

$$E_{\mathrm{diff}} = 0.5 f_{\mathrm{eff}} f_{\mathrm{svv}} T_{\mathrm{sol}} I_{\mathrm{diff}} \quad (3)$$

where f_{svv} is the fraction of sky vault in occupant's view (Fig. 2); I_{diff} is diffuse sky irradiance received on an upward-facing horizontal surface (W/m^2); I_{diff} is a standard meteorological parameter measured in open terrain (Note: in less open terrain, natural and built surfaces protruding above the horizon block the diffuse sky radiation behind them. SolarCal assumes that the reduction in I_{diff} is compensated for by the radiation reflected from the surfaces. In clear weather the angular fluxes from reflected and diffuse sky are roughly equal); T_{sol} is the total solar transmittance, the ratio of

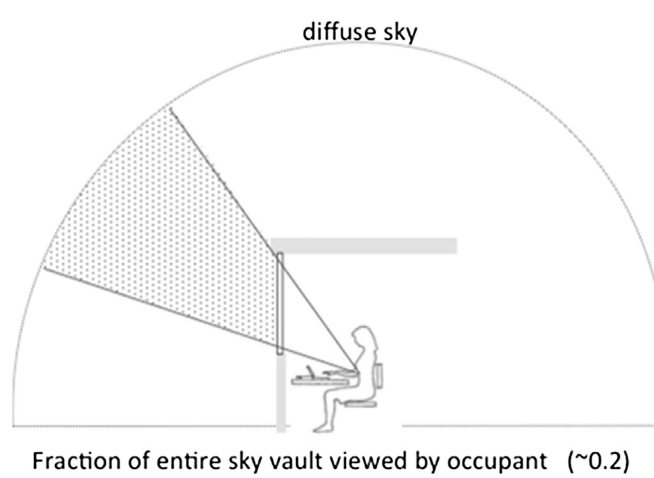

Fig. 2. Fraction of sky vault in occupant's view (f_{svv}).