

UC Berkeley

Indoor Environmental Quality (IEQ)

Title

Modeling the comfort effects of short-wave solar radiation indoors

Permalink

<https://escholarship.org/uc/item/89m1h2dg>

Authors

Arens, Edward

Hoyt, Tyler

Zhou, Xin

et al.

Publication Date

2015-06-01

DOI

10.1016/j.buildenv.2014.09.004

Peer reviewed

MODELING THE COMFORT EFFECTS OF SHORT-WAVE SOLAR RADIATION INDOORS

Edward ARENS^{1*}, Tyler HOYT¹, Xin ZHOU^{1,3}, Li HUANG^{1,2}, Hui ZHANG¹, Stefano SCHIAVON¹

¹Center for the Built Environment, University of California, Berkeley, USA

²School of Architecture, Tsinghua University, Beijing, China

³School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai, China

*Corresponding email: earens@berkeley.edu.

Address: 390 Wurster Hall Berkeley, CA 94720.

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.

HIGHLIGHTS:

- SolarCal, a simplified whole-body model for the thermal comfort effects of shortwave solar radiation.
- Publicly available web interface for carrying out calculations using SolarCal <http://smap.cbe.berkeley.edu/comforttool>.
- SolarCal's ability to predict the impact of solar radiation on occupant thermal comfort verified against lab study.
- Several practical design scenarios where SolarCal can be effectively applied.
- Practitioner guidance for using the model and gathering the necessary data.

KEYWORDS: Solar load, Thermal comfort, Thermal sensation, Shading, MRT, ERF

INTRODUCTON

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 (Figure 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.



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

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, 12, 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 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.

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:

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

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 ($^{\circ}C$).

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, ERF_{solar} :

$$\alpha_{LW} ERF_{solar} = \alpha_{SW} E_{solar} \quad (2)$$

where E_{solar} is the short wave 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.

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

where f_{svv} is the fraction of sky vault in occupant's view (Figure 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 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 incident shortwave radiation to the total shortwave radiation passing through the glass and shades of a window system.

The total outdoor solar radiation on the horizontal (I_{TH}) is filtered by both T_{sol} and f_{svv} , and multiplied by the reflectance (albedo) of the floor and lower furnishings (R_{floor}). In addition, the short-wave reflected to the lower half of the body will be accompanied by

increased long-wave radiation from floor surfaces warmed by the non-reflected portion of the solar. This long-wave flux may be approximated by increasing the value of R_{floor} .

$$E_{refl} = 0.5 f_{eff} f_{svv} T_{sol} I_{TH} R_{floor} \quad (4)$$

where I_{TH} is the total horizontal direct and diffuse irradiance outdoors (W/m^2); and R_{floor} is the floor reflectance (a value might be (0.2+0.3) for short-wave plus long-wave combined).

Direct radiation affects only the projected area A_p of the body, and is reduced by any shading of the body provided by the indoor surroundings:

$$E_{dir} = (A_p/A_D) f_{bes} T_{sol} I_{dir} \quad (5)$$

where A_p is the projected area of a standard person exposed to direct beam sunlight; A_D is the DuBois surface area of the assumed person (around $1.8 m^2$); f_{bes} is the fraction of body exposed to sunlight (Figure 3. Note that this measure does not include the body's self-shading, only the shading from surroundings); and I_{dir} is direct beam (normal) solar radiation (W/m^2). The meteorological radiation parameters are related as: $I_{TH} = I_{dir} \sin \beta + I_{diff}$, where β is the solar altitude.

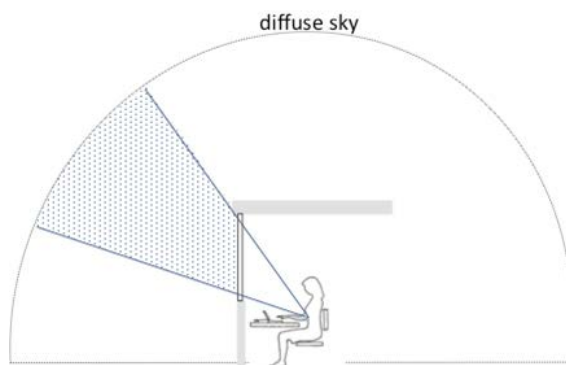


Figure 2. Fraction of sky vault in occupant's view (f_{svv})

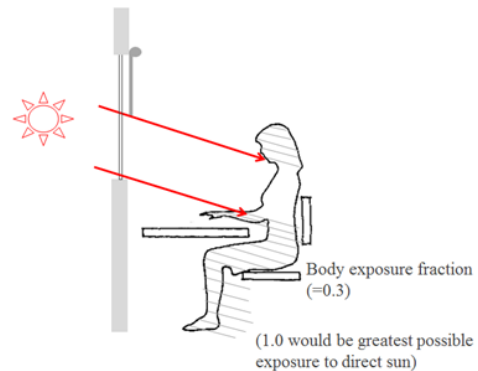


Figure 3. Fraction of body exposed to sun (f_{bes})

ERF_{solar} can therefore be calculated from the following equation:

$$ERF_{solar} = (0.5 f_{eff} f_{svv} (I_{diff} + I_{TH} R_{floor}) + A_p f_{bes} I_{dir} / A_D) T_{sol} (\alpha_{SW} / \alpha_{LW}) \quad (6)$$

In direct beam sunlight, the projected area of a human body varies with solar altitude and azimuth. Fanger [7] quantified this using the empirically determined projected area factor (f_p):

$$A_p = f_{eff} f_p A_D \quad (7)$$

In the CBE Comfort tool, f_p for seated and standing postures were taken from the graphs in ASHRAE Standard 55-2013 [2] and fit using a 2-D interpolating spline (Figure 4).

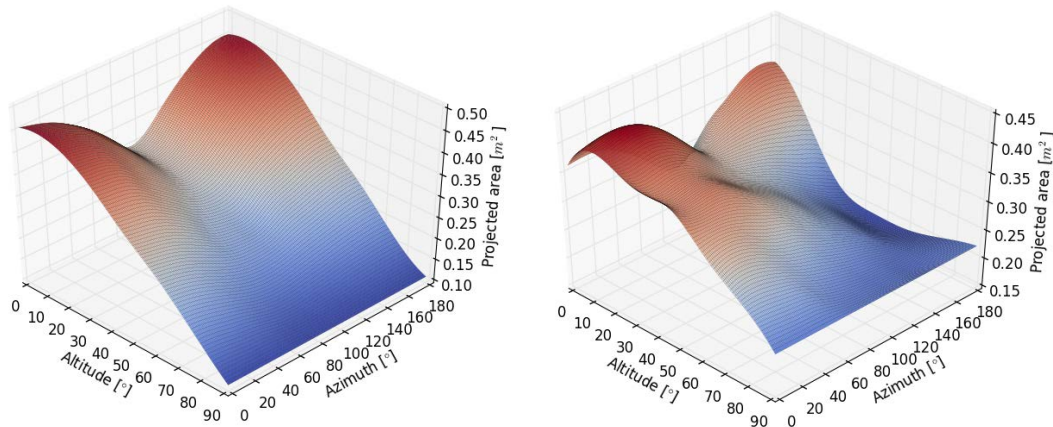


Figure 4. Projected area of body exposed to sun (A_p) as a function of altitude and azimuth, in standing posture (left) and seated posture (right). Azimuth zero represents the sun in front of the occupant.

To obtain ERF_{solar} with equation (6), the inputs are f_{svv} , f_p , T_{sol} , f_{bes} , I_{diff} , I_{TH} , R_{floor} , I_{dir} , α_{SW} , and α_{LW} along with solar altitude (β) and azimuth. To reduce the climate data input in SolarCal, I_{diff} may be estimated as $I_{diff} = 0.17 I_{dir} \sin\beta$. Finally, ERF_{solar} is added to the longwave ERF input to determine a new solar-adjusted MRT (ΔMRT) using equation (1). This allows a new PMV to be calculated for an occupant exposed to shortwave radiation.

INPUT DATA

The following paragraphs suggest methods for obtaining good estimates for the SolarCal input parameters.

Direct beam solar radiation (I_{dir}) values can be found in Typical Meteorological Year (TMY) weather files [22]. The column labeled DNI (Direct Normal Intensity) contains a year's worth of representative hourly solar intensity data, which can be used to derive a design condition. For example, the 95th percentile of the daily maximum DNI may be a reasonable design condition. Should hourly weather data not be available, Table 1 contains direct solar beam radiation data for a standard cloudless atmosphere [4] that can be used in this situation. The best value can be chosen by considering the latitude of the site and the season of the design condition. For example, the maximum solar altitude occurring on the summer solstice in Berkeley, CA is about 75°, corresponding to a design condition of 915 W/m².

Table 1. Typical direct beam solar radiation values for a standard cloudless atmosphere depending on the solar altitude angle.

Solar altitude angle [°]	5	10	20	30	40	50	60	70	80	90
Direct beam solar radiation [W/m ²]	210	390	620	740	810	860	890	910	920	925

The sky vault view fraction, f_{svv} , may be estimated directly or with a simple equation. It is equal to the ratio of the sky vault covered by the window aperture after it is projected onto the sky vault from the position of the occupant. This value depends mostly on the dimensions of the window (width w , height h) and the distance between the occupant and the window (d). With these values we can derive the approximation

$$f_{svv} \approx \frac{\tan^{-1}\left(\frac{h}{2d}\right) \tan^{-1}\left(\frac{w}{2d}\right)}{90.180} \quad (8)$$

where the inverse tangent function returns values in degrees. When calculating f_{svv} for multiple windows, the f_{svv} for each may be calculated and summed to get an approximate total f_{svv} . Note that exterior objects obstructing the sky vault should not be considered, since they have a similar diffuse reflectivity as the sky vault.



Figure 5. From the moving walkway, the altitude angle to the top of the window is approximately 60°. Since the width of the window is very large, we have a f_{svv} value of about 1/3.

Image courtesy of YuFeng Zhang

The solar transmittance T_{sol} is most easily obtained from the International Glazing Database, containing data from many glazing manufacturers [23]. The database is included in the WINDOW software developed by LBNL [24].

Transmittance is sometimes specified in terms of shading coefficient (SC). SC is by definition referenced to the radiation passing through clear glass with a T_{sol} of 0.87. Similarly, center-of-glass Solar Heat Gain Coefficient (SHGC) provides an approximation of T_{sol} . These metrics differ from T_{sol} in that they include the inward longwave flux resulting from shortwave radiation absorbed in the glass. This additional flux does not arrive at the occupant in the collimated beam of direct shortwave radiation. Using SC and SHGC, the model will tend to overpredict solar gain on the occupant when glass absorptance is high, or the occupant is further from the window.

In SolarCal, the solar altitude/azimuth parameters only determine the radiation incident on the occupant. Transmission through the building's fenestration also depends on the angle of the sun relative to the glazing, but the SolarCal model does not extend to including the glazing orientation. It is the designer's responsibility to adjust T_{sol} for transmission reductions caused by non-normal solar incidence angles on the window.

The shortwave absorptivity α_{sw} of the occupant may range widely depending on the color of the occupant's skin, as well as the color and amount of clothing covering the body. In the SolarCal web tool, we choose 0.67 as a reasonable estimate for this value. If the user has specific assumptions about the clothing or skin color of the occupants, a more accurate estimate can be calculated using Table 2 [3].

Table 2. Shortwave absorptivity (α_{sw}) values for common clothing and skin types.

	<u>White clothing</u>	<u>Khaki clothing</u>	<u>Black clothing</u>	<u>White skin</u>	<u>Brown skin</u>	<u>Black skin</u>
<u>α_{sw}</u>	<u>0.2</u>	<u>0.57</u>	<u>0.88</u>	<u>0.57</u>	<u>0.65</u>	<u>0.84</u>

Note: because SolarCal is a whole-body model, it cannot differentiate between local body parts (such as check, back, hand etc.), or between body parts with or without clothing. Comfort effects stemming from such differences must be modeled with multiple-segment comfort models as described in the *Introduction* above [15, 20].

COMPARING MODEL PREDICTIONS TO A HUMAN SUBJECT TEST

Hodder and Parsons ('H/P') used an automobile mockup (Figure 6) with moveable heat lamps to emulate four levels of solar radiation impinging on human subjects [8]. Air temperature was between 22.8 and 24.0°C, metabolic rate 1.2 met, and clothing resistance 0.7 clo. Figure 7 shows the input variables for modeling the test, as represented in the SolarCal interface.

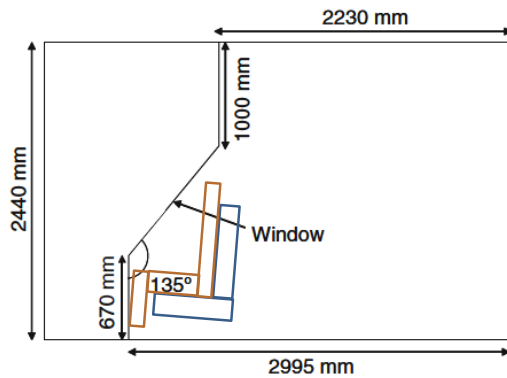


Figure 6. Automotive test chamber

SolarCal: shortwave radiation calculator ✕

Posture Seated ▾

Solar altitude (0 - 90°) [β] °

Solar azimuth (0 - 180°. Facing front = 0°) °

Direct beam (normal) solar radiation [I_{dir}] W/m²

Total solar transmittance [T_{sol}]

Sky vault view fraction [f_{svv}]

Fraction of body exposed to sun [f_{bes}]

Average shortwave absorptivity [α]

Floor reflectance [R_{floor}]

ERF : W/m²

Mean radiant temperature delta : °C

Figure 7. Input for modeling the test

Table 3 first shows solar loads on the subject (W/m^2) predicted by SolarCal's A_p method and by BCM's detailed 5000 polygon manikin; SolarCal is 7% low. The ΔMRT from SolarCal is then compared to ΔMRT calculated from H/P's globe thermometer readings. The two ΔMRT values were then used to calculate PMV. The experiment found that $200 W/m^2$ solar gain produced an increase of roughly one PMV scale unit. The SolarCal PMV prediction agrees well with the experiment's actual thermal sensation votes (<0.1 PMV mean absolute error), which use the identical scale as PMV. The discrepancies are less than 0.15 scale unit except with zero radiation.

Table 3. Comparison of modeled and experimental results

	Solar radiation level (W/m^2)	600	400	200	0
	Air temperature (°C)	24.0	23.4	23.4	22.8
Solar load (W/m^2)	BCM with 5000 polygon manikin	103.4	68.9	34.5	0
	SolarCal model	96.7	64.4	32.2	0

ΔMRT	H/P test using Globe T	20.0	18.4	14.3	1.4
	SolarCal model	23.1	15.4	7.7	0
PMV	H/P results using computed MRT	2.8	2.3	1.9	0.2
	SolarCal model	3.1	1.9	0.9	-0.1
Actual mean thermal sensation vote in H/P experiment		3.1	1.9	1.1	0.2

CALCULATION EXAMPLES

In this section we will develop two example SolarCal calculations.

1) Should skylights admit solar radiation onto the occupant from overhead, SolarCal can be used to assess the resulting comfort impact. The designer must determine a time in the year when direct solar radiation strikes the occupant, and obtain T_{sol} for that time, accounting for the incidence angle of the solar beam on the skylight glazing.

Assume the occupant is seated and a horizontal skylight with dimensions 2m x 2m is 4m directly above the occupant. The site is Miami, FL, where the solar altitude angle in summer is high enough to admit direct solar through this skylight onto the occupant. For a maximum solar altitude angle of 87° , use Table 1 to determine a direct solar beam intensity of 925 W/m^2 . The skylight glass has a rated T_{sol} of 0.2, which will remain about the same for this near-normal solar incidence angle.

Only the occupant's lower legs will be shaded by the desk under this overhead sun angle, so the f_{bes} is 0.9. We will assume shortwave absorptivity of 0.7. The floor is covered with a dark carpet with reflectivity of 0.2. We will assume the longwave from the absorbed solar gain in the carpet adds another 0.3 to the floor reflectance, for a total of 0.5. The f_{svv} is approximated from equation (8):

$$f_{svv} \approx \frac{\tan^{-1}\left(\frac{2}{8}\right) \tan^{-1}\left(\frac{2}{8}\right)}{90.180} = 0.01 \quad (9)$$

These conditions result in a MRT delta of 3.9°C , and an ERF of 16.5 W/m^2 . We will discuss the significance of this later.

Notice that if this modest skylight is enlarged to a size often seen in glazed atria ($f_{svv} \sim 0.5$) the MRT delta increases to a MRT delta of 8.2°C and an ERF of 34.2 W/m^2 .

2) Here we analyze a shading design for an occupant placed near a window, as in Figure 1. The solar altitude is 75° with a direct solar intensity of 910 W/m^2 . The vertical glass has a rated T_{sol} of 0.5, which the designer determines to be 0.3 for the sun angle under consideration. The occupant is seated facing the 3m x 3m window at a distance of 1m, yielding a f_{svv} of 0.32. In this case we will assume that half of the body is shaded by the furniture of the occupant, and that the absorptivity is 0.7. A light beige-colored floor

has a total SW+LW reflectivity of 0.6. Under these conditions, the ΔMRT is 8.0°C. The results of this are plotted in Figure 8. In both cases, the air temperature (25°C) and relative humidity (50%) are represented by the red dot, airspeed is 0.1 m/s, clothing is a typical summer ensemble (0.5 CLO), and the metabolic rate is 1.2 MET. On the left hand side, the MRT is 25°C. On the right, the MRT is 33°C, after the 8.0°C adjustment. The blue area represents the comfort zone on the chart for the respective conditions, where the PMV is between -0.5 and 0.5.

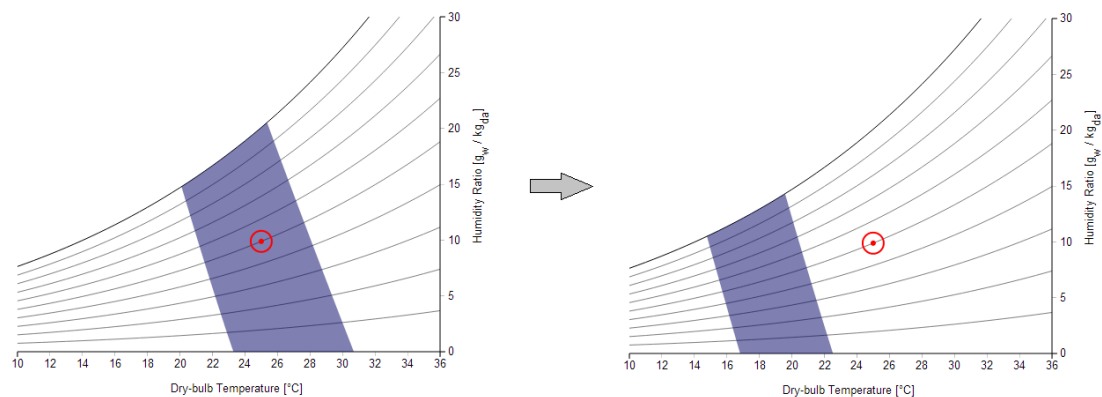


Figure 8. The psychrometric chart with comfort zone representing the range of -0.5 to 0.5 PMV before (L) and after (R) an 8.0°C ΔMRT has been applied to a typical comfort model input condition. The tool is available online:

<http://smap.cbe.berkeley.edu/comforttool>.

The solar increase to MRT clearly produces an unmanageable shift in the occupant's comfort zone, moving the occupant well outside its boundaries with a high PMV. The designer can use the model to evaluate solar control options that reduce this heat gain.

APPLICATION TO SHADING

The PMV increase caused by short-wave solar radiation can be used to determine a practical maximum for allowable T_{sol} in architectural interiors.

It seems reasonable to assume that solar gain in a typical conditioned office should not increase the occupant's PMV more than one-half a scale unit (e.g., from 0 to +0.5, starting at the neutral temperature and increasing to the upper boundary of the comfort zone).

The total T_{sol} required to limit occupant overheating is shown in Table 2 for the geometry of a simulated perimeter zone cubicle shown in Figure 9. $I_{dir} = 900 \text{ W/m}^2$, solar altitude = 65°, $f_{svv} = 0.3$, $f_{bes} = 0.5$, and $R_{floor} = 0.5$. The indoor environment is: air speed = 0.1 m/s, relative humidity = 50%; and occupant clothing = 0.57 clo. The sun is from the side at 90° azimuth, and activity is 1.1 met.

Table 2. Solar transmission (T_{sol}) that limits an occupant's PMV increase to one-half scale unit

Metabolic rate (met)	Azimuth		
	30°	90°	120°
1	12.2%	13.5%	14.1%
1.1	13.5%	14.9%	15.5%
1.2	15.2%	16.7%	17.5%
1.3	16.4%	18.1%	18.9%

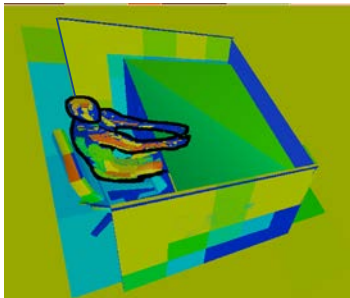


Figure 9. Office cubicle geometry

However, if a building were being maintained at the cool boundary of the comfort zone, solar gain might usefully increase the occupant's PMV by as much as one scale unit. (For energy reasons, this strategy should only be allowed in the heating season!). Figure 10 uses the above cubicle example to show the boundary of allowable T_{sol} for a range of indoor ambient temperature conditions. It is the red line representing the PMV = 0.5 contour. The blue and black lines in the figure are the PMV=0 and PMV= -0.5 contours, respectively. An ambient temperature deviation of 1.5°C from neutral corresponds to a 0.5 PMV scale change, as does a 0.15 change in T_{sol} .

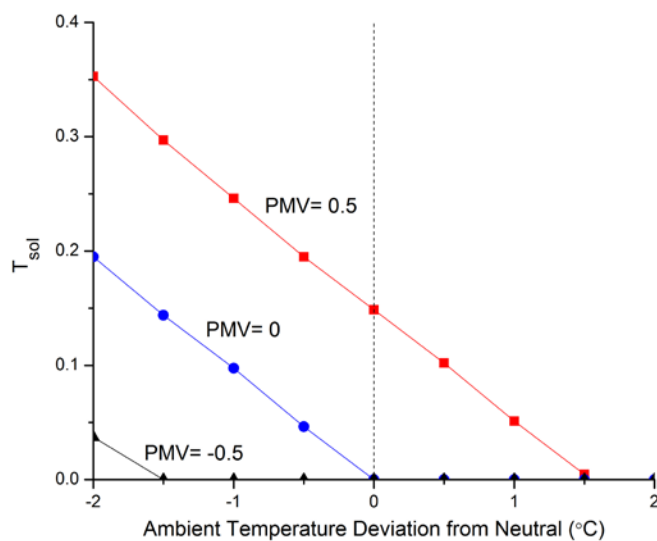


Figure 10. T_{sol} boundary predicted by the SolarCal model

In the absence of solar gain, lowering 1.5°C from neutral causes thermal sensation to drop from PMV=0 to -0.5. Adding solar radiation 15% T_{sol} brings thermal sensation up 0.5 PMV units, back to neutral. To reach the upper threshold (PMV=0.5) from this lower temperature, T_{sol} can be as high as 30% before PMV exceeds 0.5. However, above neutral ambient temperatures (the right side of the figure), the allowable T_{sol} must be below 0.15, reaching zero at 1.5°C above neutral.

LIST OF SYMBOLS

Symbol	Description	Unit
MRT	Mean radiant temperature	°C
ERF	Effective radiant field	W/m ²
f_{eff}	Fraction of body exposed to sun	-
h_r	Radiation heat transfer coefficient	W/m ² -K
T_a	Air temperature	°C
α_{LW}	Longwave radiation absorptivity	-
α_{SW}	Shortwave radiation absorptivity	-
ERF_{solar}	Effective radiant field solar component	W/m ²
E_{solar}	Total shortwave solar radiant flux	W/m ²
E_{dir}	Direct beam component of shortwave solar radiant flux	W/m ²
E_{diff}	Diffuse component of shortwave solar radiant flux	W/m ²
E_{refl}	Reflected component of shortwave solar radiant flux	W/m ²
f_{svv}	Fraction of sky vault exposed to body	-
T_{sol}	Glazing solar transmittance	-
I_{dir}	Direct solar beam intensity	W/m ²
I_{diff}	Diffuse solar intensity	W/m ²
I_{TH}	Total horizontal solar intensity	W/m ²
R_{floor}	Floor reflectivity	-
A_p	Projected area	m ²
f_{bes}	Fraction of body exposed to sun	-
β	Solar altitude angle	deg

CONCLUSIONS

- The direct warming effect of solar radiation on occupants may cause discomfort, and require a large amount of correction by the cooling system. It should be accounted for in architectural and engineering design, preferably early in the process. This paper describes SolarCal, a new public online web-based tool for

predicting solar effects on comfort.

- The SolarCal model computes an increase in MRT equivalent to shortwave gains from direct, diffuse, and indoor-reflected radiation on a person. This is then used to compute PMV using the method prescribed in ASHRAE Standard 55-2013.
- Comparison of results from SolarCal, the advanced multi-segment Berkeley Comfort Model, and a physical experiment shows SolarCal giving reasonable predictions of solar effects on MRT, and on comfort expressed as PMV.
- Low solar transmittance is needed to prevent excessive increase in occupants' thermal sensation indoors. The transmission of glass plus shades together probably should not exceed 15% if the sun will be shining on an occupant indoors.

REFERENCES

- [1] Arens E, Gonzalez R, Berglund L. Thermal comfort under an extended range of environmental conditions. *ASHRAE Transactions* 1986;92(1):18–26.
- [2] ASHRAE. Standard 55-2004: Thermal environmental conditions for human occupancy, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE); 2004.
- [3] Blum HF. Solar heat load, its relationship to the total heat load, and its relative importance in the design of clothing. *Journal of Clinical Investigation* 1945;24: 712–721.
- [4] Brooks FA. An introduction to physical microclimatology, University of California Davis 1959.
- [5] ISO 7730: Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. 3rd version. International Organization for Standardization, Geneva; 2005.
- [6] CEN15251: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. European Committee for Standardization, Brussels; 2007.
- [7] Fanger PO. *Thermal Comfort*. New York: McGraw-Hill Inc; 1970.
- [8] Hodder S, Parsons K. The effects of solar radiation on thermal comfort. *International Journal of Biometeorology* 2007;51:233–250.
- [9] Hodder S, Parsons K. The effects of solar radiation and black body re-radiation on thermal comfort. *Ergonomics* 2008;51(4):476–491.
- [10] Hoffmann S, Jedek C, Arens E. Assessing thermal comfort near glass facades with new tools. BEST 3 Building Enclosure Science and Technology Conference, Atlanta GA, 2012.
- [11] Fiala D, Lomas K, Stohrer M. A computer model of human thermoregulation for a wide range of environmental conditions: the passive system. *Journal of Applied Physiology* 1999;87:1957–1972.
- [12] Kobayashi Y, Tanabe S. Development of JOS-2 human thermoregulation model

- with detailed vascular system, *Building and Environment* 2013;66:1–10.
- [13] Tanabe S, Kobayashi K, Nakano J, Ozeki Y, Konishi M. Evaluation of thermal comfort using combined multi-node thermoregulation (65MN) and radiation models and computational fluid dynamics (CFD). *Building and Environment* 2002;34:637–646.
- [14] Zhang H, Arens E, Huizenga C, Han T. Thermal sensation and comfort models for non-uniform and transient environments: Part I: local sensation of individual body parts. *Building and Environment* 2010;45(2):380–388.
- [15] Huizenga C, Zhang H, Arens E. A model of human physiology and comfort for assessing complex thermal environments. *Building and Environment* 2001;36: 691–699.
- [16] La Gennusa M, Nucara A, Rizzo G, Gianluca S. The calculation of the mean radiant temperature of a subject exposed to the solar radiation - a generalised algorithm. *Building and Environment* 2005;40(3):367–375.
- [17] Mitchell R, Kohler C, Klems J, Rubin M, Arasteh D, Huizenga C, Yu T, Curcija D. WINDOW 6.2 /THERM 6.2 Research Version User Manual. Lawrence Berkeley National Laboratory; 2008.
- [18] Schiavon S, Hoyt T, Piccioli A. Web application for thermal comfort visualization and calculation according to ASHRAE Standard 55. *Building Simulation* 2014;7(4):321–334.
- [19] Tzempelikos A, Bessoudo M, Athienitis AK, Zmeureanu R. Indoor thermal environmental conditions near glazed facades with shading devices – Part II: Thermal comfort simulation and impact of glazing and shading properties. *Building and Environment* 2010;45(11):2517–2525.

WEB REFERENCES

- [20] RadTherm Heat Transfer Analysis Software,
<http://www.thermoanalytics.com/products/radtherm>, last accessed 8/10/2014.
- [21] Hoyt T, Schiavon S, Piccioli A, Moon D, Steinfeld K. CBE Thermal Comfort Tool. Center for the Built Environment, University of California Berkeley 2012-2014.
<http://smap.cbe.berkeley.edu/comforttool/>, last accessed 6/20/2014.
- [22] NREL , National Solar Radiation Data Base,
http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/, last accessed 6/20/2014.
- [23] Lawrence Berkeley National Labs, International Glazing Database,
<http://windows.lbl.gov/materials/IGDB/>, last accessed 6/20/2014.
- [24] Lawrence Berkeley National Labs, WINDOW 6.3,
<http://windows.lbl.gov/software/window/6/>, last accessed 6/20/2014.