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Window Performance for Human Thermal Comfort

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Abstract

A method based on the ASHRAE two-node comfort model has been developed for predicting the effect of windows on thermal comfort. The method embodies separate analyses for long-wave (thermal infrared) radiation, induced drafts, and solar load effects. Of these three impacts, modeling results demonstrate that long-wave exchange between the body and the window is the most significant except for the case where the body is in direct sun, in which case the impact solar load can be more significant. For most residential-size windows, draft effects exist but are typically small.

Generally, windows are not the primary element affecting the comfort of a building's occupants. However when a window is very hot or cold, the occupant is very close to the window, or other factors result in thermal conditions near the edge of the comfort zone, windows can become quite influential. Furthermore it is believed that current methods may under-predict discomfort caused by windows.

We discuss potential refinements to the method that might address this inaccuracy by accounting for asymmetries in radiant temperature. In the near term, the model could be used to create a simplified "window comfort index." To accompany the index, we envision educational material that would educate designers and consumers on the comfort implications of glazing selection.

Introduction

The comfort of a room's occupants can be adversely affected by the presence of large hot or cold surfaces—notably windows and skylights. Window surface temperatures often fluctuate much more than those of other surfaces in a room. Even when room air is maintained at a comfortable temperature, occupants may experience significant discomfort as a result of radiant heat exchange with window surfaces.

In *winter*, radiant heat loss toward a cold window surface, drafts induced by cold air drainage off the window surface, and temperature asymmetry between the room and the window can make an occupant feel uncomfortable, particularly if he or she is sedentary. In *summer*, solar gains from direct transmission and by re-radiated heat from absorbed energy may subject occupants in the perimeter zone to radiant temperatures above 60^{o}C (140^{o}F), which may make perimeter zones uncomfortable. In commercial buildings these problems make the space less attractive to tenants.

New high-performance windows alleviate thermal discomfort by reducing heat loss and/or heat gain and can lower heating, cooling, and electric lighting costs. They also exhibit inside surface temperatures that are closer to room air temperature, resulting in less thermal discomfort for the occupants. Glass and frame temperatures are readily calculated for specific environmental conditions using established computer design tools. However, human thermal sensations and comfort criteria are not as easily quantified. Numerous studies address thermal comfort in general but do not focus specifically on quantifying the impact of windows.

Like most new technologies, high-performance windows cost more, thus it is difficult for them to compete with "mainstream" products and gain a large share of the market. If the improved comfort associated with high-performance windows were to be quantified, it could be valued along with energy savings offered by these windows, and would help to justify their higher initial cost. Particularly while energy remains cheap, non-energy benefits of better windows may prove more valuable to consumers and specifiers.

A joint study has been commenced by the Windows and Daylighting Group at Lawrence Berkeley National Laboratory (LBNL) and the Center for Environmental Design Research (CEDR) at University of California at Berkeley. The project applies a parametric approach to study windows and their effect on indoor comfort. Ten generic glazing systems, ranging from a clear single-pane window to a high-performance window, are being examined for their comfort impacts.

Key areas being addressed by the study include:

- the relative importance of long and short-wave (solar) radiation and draft effects under both winter and summer conditions;
- the effect on occupant comfort of proximity to a window (view factors; radiant temperature asymmetry);
- the sensitivity of comfort predictions to subject posture, clothing and metabolic activity;
- the feasibility of defining simplified measures of thermal comfort for windows.

Existing standards for thermal comfort and recent specialized tools are being evaluated for possible adaptation and enhancement to help address the window comfort issue. This paper summarizes results to date and immediate future directions that will lead to the first fenestration-oriented computer tool for indoor comfort prediction.

Windows and Thermal Comfort

Human comfort in buildings is strongly influenced by a number of mechanisms, three of which are of interest here:

1. exchange of long-wave, electromagnetic radiation between building occupants and their surroundings;
2. convective effects from cooling or warming air currents;
3. absorption of solar radiation by the body.

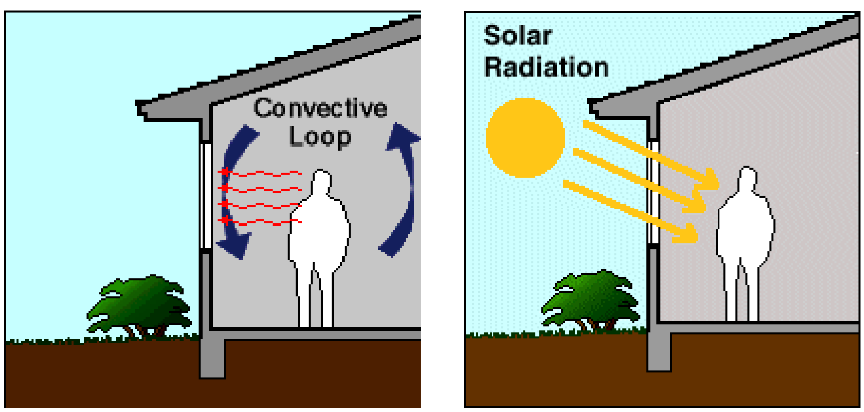

Figure 1. Convective, long-wave radiative and short-wave solar effects on thermal comfort.

Currently there are no specific procedures for predicting the comfort impact of windows. However, two general, internationally recognized standards address human thermal comfort in buildings (ASHRAE 1992, 1994 and ISO 1994).

An excellent review of comfort models and thermal adaptation appears in Brager and de Dear (1998). An earlier study by Tham and Ullah (1993) modeled the comfort impact of fenestration on occupants of commercial buildings in Singapore, a hot humid climate. Standard ASHRAE 55-1992 is based on the "New Effective Temperature," ET*, which uses a two-node model for the human body (skin and body core) and was developed by Gagge et al (1986). In comparison, ISO 7730 uses the PMV-PPD model of

Fanger (1972) which is based on a human body energy balance and combined with an empirical fit to thermal sensation. PMV is the "Predicted Mean Vote" (on a seven-point, cold-to-hot sensation scale) for a large population of people exposed to a certain environment. PPD is the "Percentage of People Dissatisfied" at each PMV value. PPD can be thought of as the probability that an average person will be dissatisfied with his or her state of thermal comfort.

Radiant asymmetry is a long-standing concern when trying to predict window effects on comfort. This is the difference in radiant temperatures that would be "seen" by a small flat element looking in opposite directions, i.e., towards and away from the window. Although it is believed that people are less sensitive to a cold vertical surface than to an overhead warm surface, glazing surfaces can fluctuate markedly and have more potential than others to cause radiant asymmetry. As a guideline, ASHRAE 55 states that for vertical surfaces radiant asymmetry should be kept to less than 10°C (18°F).

Temperature differences between the window surface and room air can induce air movement, particularly in cold weather. Drafts caused by such air movement can also cause discomfort. At 20°C (68°F), more than 0.1 m/s (0.3 ft/s) mean air velocity leads to greater than 10% PPD. This relates to discomfort around the head, neck and shoulders.

To quantify the impact of windows on the comfort of building occupants, the project described in this paper is developing algorithms that address the following:

1. long-wave exchange between the window and building occupants;
2. room drafts caused by air drainage off a cold window surface;
3. the skin-heating effect of direct-beam solar radiation striking an occupant;
4. the relative importance of, and tradeoffs among the window's long-wave, short-wave (solar) and draft effects under both winter and summer conditions;
5. the effect of an occupant's proximity to a window (view factors and window size; radiant temperature asymmetry);
6. the sensitivity of comfort prediction to subject posture, clothing and metabolic activity.

A Specific Example of Window-Induced Discomfort

Consider a person seated 1 m (3.3 ft) from a large window in a typical office environment. The window occupies the entire exterior façade, 3 m (10 ft) wide and 2.7 m (9 ft) high. For simplicity we ignore the effects of window frames. (In this paper the terms "glazing" and "window" are used interchangeably unless the frame component is specifically relevant.) Standard ASHRAE winter conditions are assumed; the outdoor dry-bulb temperature is -17.8°C (0°F) while the room air temperature is 21.1°C (70°F). From Table 1, we see that a window with clear double glazing has an inside surface temperature of 7.4°C (45.3°F). All other surfaces surrounding the occupant are assumed to be at the same temperature as the room air. The room dimensions are not in themselves significant, only the surface temperatures. The relative humidity is 50%.

Using the simple model outlined by ASHRAE (1992), these conditions lead to a "radiant temperature asymmetry" of 9.4 K (16.9°F). This is the difference in plane radiant temperatures between the window-facing and non-window-facing directions. The temperature difference is calculated after accounting for dimensions, temperatures and all view factors between the person and the surrounding surfaces, especially the window. The asymmetry comes close to ASHRAE Standard's recommended maximum horizontal direction limit of 10K (18°F). Furthermore, although all surfaces except the windowpane are at 21.1°C (70°F), the mean radiant temperature sensed by the person is only 11.9°C (53.4°F) – too cool for sedentary office workers who frequently sit close to window walls.

Long-Wave Radiation Exchange Between Window and Building Occupants

To obtain an averaged estimate of the effect of inside glazing surface temperature on comfort, the mean radiant temperature (MRT) experienced by a room occupant must be evaluated. Table 1 shows the ten benchmark glazing systems used by LBNL and CEDR. The WINDOW 4.1 program (LBNL, 1994) was used to predict glazing temperatures under various sets of environmental conditions.

Mean radiant temperatures were predicted in accordance with the ASHRAE 55-1992 standard for thermal comfort. The magnitude of the radiant temperature *asymmetry* was also evaluated but has not yet been incorporated in our comfort model. In a wintertime example, it is important that the model ultimately be able to distinguish between, say, the colder window-facing side of the body compared with the warmer room-facing side. In summer, sunlit absorbing glazings reach temperatures above ambient, which may reverse the asymmetry.

The PPD was evaluated according to Fanger (1972) as embodied in the ISO Standard 7730. The actual calculation process was expedited by using the ASHRAE Thermal Comfort Tool software (Fountain & Huizenga, 1995) run parametrically in a batch mode. The Thermal Comfort Tool employs a two-node model for the human body, using skin and core temperature.

Drafts

There is a dearth of empirical or modeling studies of air currents resulting from glazing surfaces whose temperatures differ significantly from room air temperature. However a window comfort model must estimate the discomfort risk resulting from cold air draining off the window surface. Heiselberg et al (1995) presented an empirical study of downdrafts created by cold glazing surfaces. The authors noted that downdrafts from glazed facades might cause thermal discomfort. Conventionally, convectors are placed close to the façade to reduce downdraft but this can cause an increase in energy consumption because of conduction of heat through the nearby window. Heiselberg investigated whether the framing members of a glazed facade could be sized and positioned to reduce downdraft and avoid thermal comfort problems in the occupied zone.

Empirical algorithms developed by Heiselberg (1994) were employed in our study to estimate an upper bound for the velocities of air currents. The velocities were evaluated as a function of glazing temperature, window size and distance between the window and an occupant. The resulting estimates were input to the Thermal Comfort Tool to help determine PPD estimates. Following the model of Heiselberg (1994), maximum downdraft velocity may be predicted. For the one-meter (3.3 ft) distance to the window in the previous example, the air velocity will be about 0.25 m/s (0.8 ft/s), which is sufficient to cause cooling discomfort on bare skin. At milder outdoor temperatures or for smaller glazed areas, the peak air velocity is predicted to be in the range 0.1-0.2 m/s (0.3-0.6 ft/s). In practical terms, the actual drafts experienced by a subject may be less, as a result of shielding and deflection by other objects in the room, as well as the fact that most of the body is above floor level.

Computational fluid dynamics (CFD) is a powerful and flexible tool for evaluating draft effects, especially if very large glazed areas are considered. CFD will be considered for future refinements to the window comfort model.

Solar Radiation

Solar radiation falling directly on a person significantly affects their perception of thermal comfort. Solar radiation is classified as a high-intensity source, as is radiation from infrared heaters. An analytic treatment of the energy balance, for a room occupant, is given by Fanger (1972), an empirical study was conducted by Sullivan (1986a, 1986b).

Direct solar radiation is potent determinant of comfort. In winter it may, on balance, result in a pleasant sensation if the ambient air temperature or MRT is low. For example, classical, direct-gain passive solar design in housing relies on homeowners' acceptance of direct solar gain in return for nighttime comfort and savings on heating energy. But in summer or in commercial spaces, direct-beam solar radiation is generally unwelcome. Methods developed by Arens et al (1986) and Sullivan (1986a, 1986b) were adapted in this project for the estimation of PPD when direct solar radiation is present. Glazing systems vary considerably in their direct solar transmittance. Direct solar transmittances at a 45^{o} angle of incidence (a typical solar altitude for middle latitudes) were obtained from WINDOW 4.1. Our method employs a linearized algorithm that predicts the change in a subject's predicted mean comfort vote as a result of a given magnitude of solar irradiance. The PPD is calculated from the net predicted mean vote. The net vote is the sum of the "no solar" vote calculated by the Thermal Comfort Tool, plus the solar correction. Once the "no solar" and the "with solar" PPDs are known, the "solar only" PPD is obtained by subtraction, as represented in Figure 2.

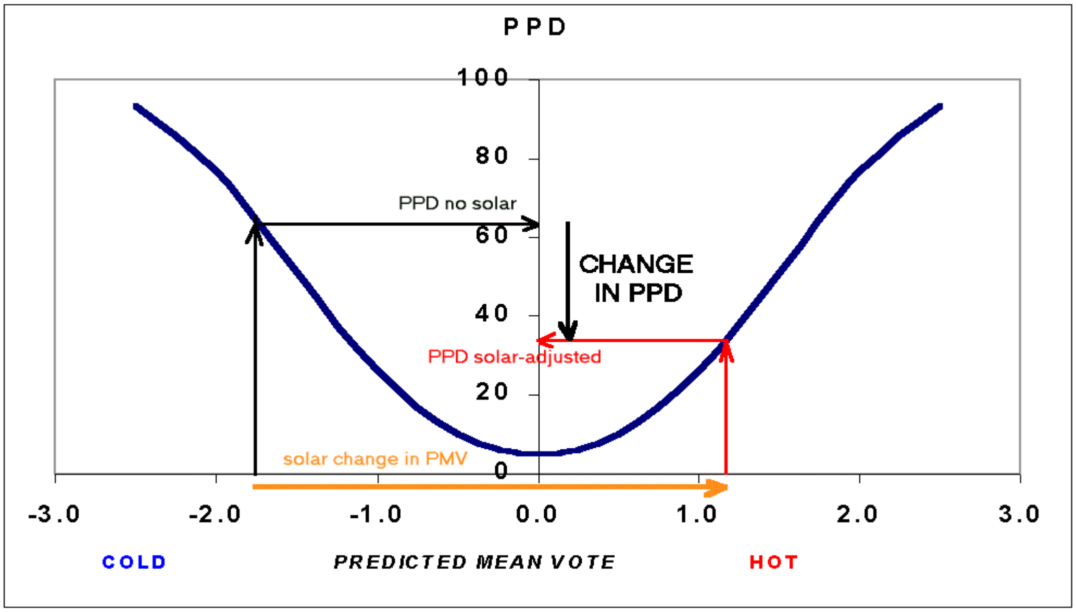

Figure 2. Fanger PPD-PMV relationship, showing adjustment for solar load.

To study the relative importance of and tradeoffs among the window's long-wave, short-wave (solar radiation) and draft effects under both winter and summer conditions, we used the method outlined above to partition the total PPD into no-solar and solar components. This enabled the tradeoffs to be examined for a wide range of glazing types and environmental conditions.

Direct solar radiation may greatly increase radiant temperature asymmetry well beyond that considered by Fanger in his recommendations. Sullivan (1986b) presents a simple linearized expression for the sensitivity of PMV to the incident solar flux:

$$\frac{dPMV}{dq} = \frac{dPMV}{dMRT} ? \frac{dMRT}{d(afq)} ? \frac{d(afq)}{dq}$$

where: a = average solar absorptance of person

f = projected area factor for person

= (area projected to beam)/(effective radiation area of person), Ap/Aeff

q = solar insolation on surface normal to beam, W/m2

= solar irradiance times direct solar transmittance of window, IsTs

Following Fanger (1972), $a \approx 0.6$, $f = 0.3$ and q is obtained from WINDOW 4.1 calculations as shown in Table 1.

Table 1. Indicative thermal, solar, and surface-temperature data for ten generic glazing systems under standard ASHRAE environmental conditions Data are derived from the WINDOW 4.1 computer program (LBNL, 1994)

Glazing No.	Glazing Type	Glazing Abbreviation	U-factor ($W/m^2.K$)	U-factor ($Btu/ft^2.h.F$)	SHGC	Winter Inside Glass Surface Temp (C)	Winter Inside Glass Surface Temp (F)	Summer Inside Glass Surface Temp (C)	Summer Inside Glass Surface Temp (F)	Summer Direct Insolation @45° incidence In W/m^2 ($Btu/h.ft^2$)
1	Single 3mm clear	S Cl	6.30	1.11	0.87	-8.4	16.9	23.9	75.0	641 (203)
2	Single 3mm bronze	S Br	6.29	1.11	0.72	-8.4	16.9	37.0	98.6	471 (149)
3	Double 3mm, clear/12mm air/clear	D Cl	2.78	0.49	0.77	7.4	45.3	31.8	89.2	533 (169)
4	Double 3mm, bronze/12mm air/clear	D Br	2.78	0.49	0.62	7.4	45.3	34.0	93.2	390 (124)
5	Double 3mm, clear/13mm argon/pyrolytic low-E (0.20)	D LE1Ar	1.73	0.30	0.72	12.4	54.3	37.3	99.1	437 (139)
6	Double 3mm, pyrolytic low-E (0.20)/13mm argon/clear (reversed)	D LE1FlipAr	1.73	0.30	0.64	12.4	54.3	31.1	88.0	437 (139)
7	Double 3mm, sputtered low-E (0.08)/13mm argon/3mm clear (high SHGC)	D LE2Ar	1.47	0.26	0.58	13.6	56.5	29.7	85.5	385 (122)
8	Double 3mm, selective low-E (0.04)/13mm argon/3mm clear (low SHGC)	D SSLEAr	1.37	0.24	0.41	14.0	57.2	28.3	82.9	272 (86)
9	Triple 3mm, low-E (0.08)/ 9.5 Kr / clear / 9.5 Kr / low-E 0.08	T LEKr	0.65	0.11	0.49	17.6	63.7	33.5	92.3	272 (86)
10	Hypothetical high-performance window (low U, low SHGC)	Super	0.49	0.09	0.39	18.4	65.1	35.0	95.0	168 (53)

If we insert the above values in the equation given, the result is $d(PMV)/dq$ = 0.0024 per W/m^2. In other words, the predicted mean vote increases with incident solar radiation at this rate. For the standard window range in Table 1, the increase in PMV ranges from about 2.2 (for single clear glazing) to 0.6 (for a high-performance window).

Proximity to the Window

We used established methods to approximate view factors between the occupant and surrounding surfaces. The person is modeled as a simple plane element parallel to the plane of the window. A real person is much larger and has a complex three-dimensional geometry with surfaces facing in all directions (as depicted in Figure 3), not just toward and away from the window. It is likely that a person will be acutely aware of radiant temperature asymmetry and seek to move away from the window.

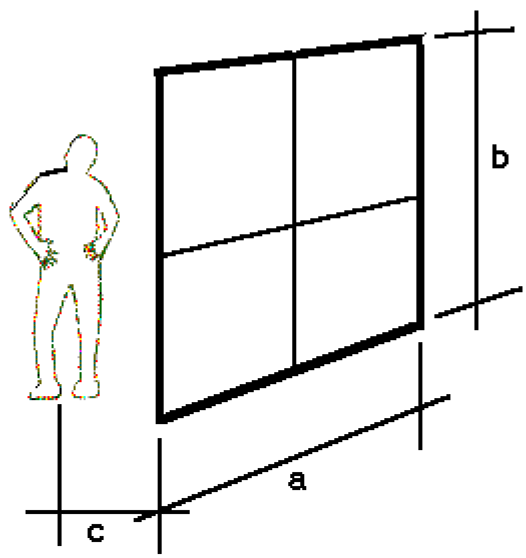

Figure 3. Occupant/window geometry used for view factor calculations.

Future modeling efforts will concentrate on improved depiction of the human body using a three-dimensional representation, instead of a simple planar shape. Such a model is expected to better account for radiant asymmetries. Work is continuing to extend the comfort model so that any arbitrary room/window/body geometry can be accommodated.

Influence of Other Factors

The two-node comfort model on which our current results are based is flexible and sensitive mean radiant temperature, clothing (summer, winter) and occupant activity (sitting, typing, standing, moving around). Pilot parametric calculations have been carried out for typical standing posture, clothing and metabolic rate. Two reference window sizes and one reference window-occupant distance have been examined. The reference relative humidity was kept constant at 50%.

Procedure

The ASHRAE Thermal Comfort Tool was used in a batch, parametric mode to calculate the PMV for each combination of occupant/window geometry, window surface temperature and clothing insulation. Results were post-processed in a spreadsheet. If a solar load was present, the resulting change in PMV was calculated according to the method described in the equation above. The net PPD was derived in each case and the results were plotted in 3-D form to help visualize trends for the dependence of thermal discomfort on clothing and window type.

Parametric calculations were undertaken to examine the variation of PPD for eight sets of environmental conditions, ten glazing systems, up to seven clothing ensembles, and two window sizes. The occupant to window distance was fixed at one meter (3.3 ft). The center of the occupant was fixed at 0.9 meter (3 ft) above the floor and mid-way between the jambs of the window. A subset of results, for the three most interesting cases, is summarized in Figures 5-7. The weather sets comprise ASHRAE summer conditions, ASHRAE winter conditions and a "mixed" condition (No. 4 in Table 2) with cold, sunny weather that tests the impact of long-wave radiation effects, drafts and solar loads simultaneously. The windows are ranked in order of decreasing solar heat gain coefficient (summer) or decreasing U-factor (winter). This facilitates the visualization of trends as the two parameters vary.

Table 2. Eight Environmental Conditions Used for Parametric Study of Window Comfort Impacts

No.	Description	Outdoor Dry Bulb		Indoor Dry Bulb		Wind		Vertical Solar	
		(^{o}C)	(^{o}F)	(^{o}C)	(^{o}F)	(m/s)	(mi/h)	(W/m^2)	(Btu/h.ft^2)
1	Hot, sunny	31.7	89.1	23.9	75.0	3.4	7.6	783	248
2	Very hot, sunny	40.0	104.0	23.9	75.0	3.4	7.6	783	248
3	Hot, cloudy	31.7	89.1	23.9	75.0	3.4	7.6	300	95
4	Cold, sunny	-10.0	14.0	21.1	70.0	3.4	7.6	783	248
5	Very cold, cloudy	-18.0	-0.4	21.1	70.0	3.4	7.6	250	79
6	Cool, sunny	0.0	32.0	21.1	70.0	3.4	7.6	783	248
7	Cold night	-10.0	14.0	21.1	70.0	3.4	7.6	0	0
8	Very cold night	-18.0	-0.4	21.1	70.0	6.7	15.0	0	0

Table 3. Building, Subject and Environmental Parameters Studied.

Parameter	Range of Values
Glazing types	As per Table 1
Glazing sizes	2.1 m (7 ft) (H) X 1.8 m (6 ft) (W) glazed door 1.2 m (4 ft) X 1.2 m (4 ft) window
Distance from subject to glazing	1 m (3.3 ft)
Clothing insulation	0.2 to 1.4 Clo (0.031 to 0.217 m^2.K/W, 0.005 to 1.23 ft^2.^{o}F.h/Btu)
Metabolic activity	1 met (58.2 W/m^2, 18.4 Btu/h.ft^2)
Environmental conditions	Nos. 1, 4, 8 as per Table 2

Results

Summer Conditions

The trend results in Figure 5 demonstrate that, in summer, solar load dominates the perception of comfort. Discomfort increases with both clothing insulation and glazing solar heat gain coefficient (SHGC). However there is a secondary effect resulting from the absorption of incident solar energy by the glazing system and the accompanying rise in the glazings' inside surface temperatures. For example, single bronze glazing is 13 K (23°F) hotter than single clear. When an occupant is wearing light summer clothing (0.4 Clo), the resulting additional longwave radiation sensed by the occupant causes the PPD to increase from 36% to 45%. PPD is mostly uncorrelated with U-factor but is closely related to SHGC; some low-E double-pane windows result in as much discomfort as uncoated single-pane windows.

Cold, Sunny Winter Conditions

Figure 6 shows that window comfort impact is very sensitive to the particular combination of U-factor, SHGC, and clothing. For multiple-pane windows, different minima in PPD are seen for different clothing levels. This is because a tradeoff occurs between glazing U-factor (which affects long-wave heat loss from the body) and solar body heating (from absorbed solar radiation). Clearly, some windows create "shirt-sleeve" conditions much better than others. These results have strong implications for comfort in day-use buildings that rely on passive solar gain to offset winter heating costs.

Draft Contribution to Discomfort. Under cold, sunny winter conditions (condition no. 4 in Table 2), Figure 4 shows the breakdown of PPD into long-wave, short-wave solar and draft components. The PPD resulting from draft does not exceed 10%; for higher performance windows it is insignificant. Although this may seem at odds with popular impressions of "drafty" windows in winter, we suggest that people often mistake long-wave heat loss to a cold window for a draft, or the air movement is caused by direct infiltration related to poor weather stripping.

When long-wave, solar radiation and draft effects are present simultaneously, the *net* PPD is very sensitive to the magnitudes of the individual mechanisms. For many glazings under winter conditions, the body-warming effect may be welcome and is seen as a reduction in PPD (negative contribution to PPD shown in Figure 4).

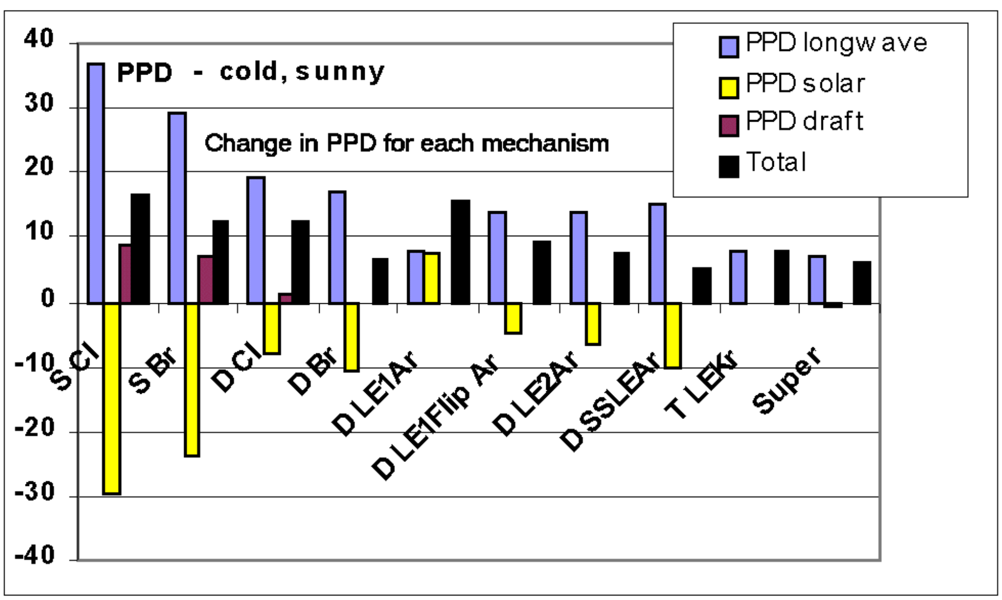

Figure 4. Long-wave, solar radiation and draft contributions to the Percentage People Dissatisfied for a large glazed door.

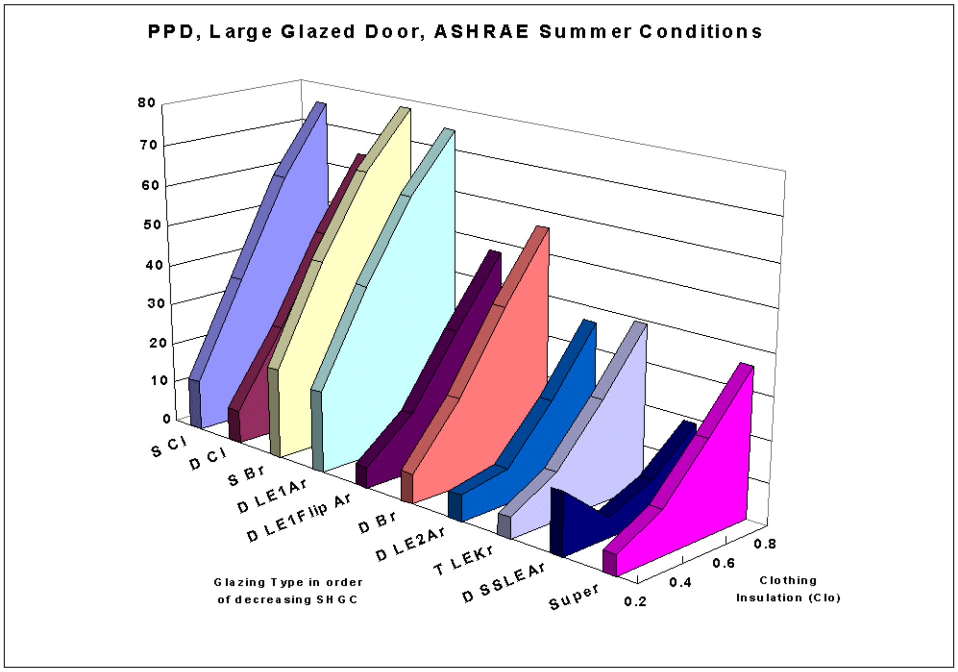

Figure 5. Percentage People Dissatisfied under ASHRAE Summer Conditions
(No. 1 in Table 2) as a function of clothing level and glazing solar heat gain coefficient.

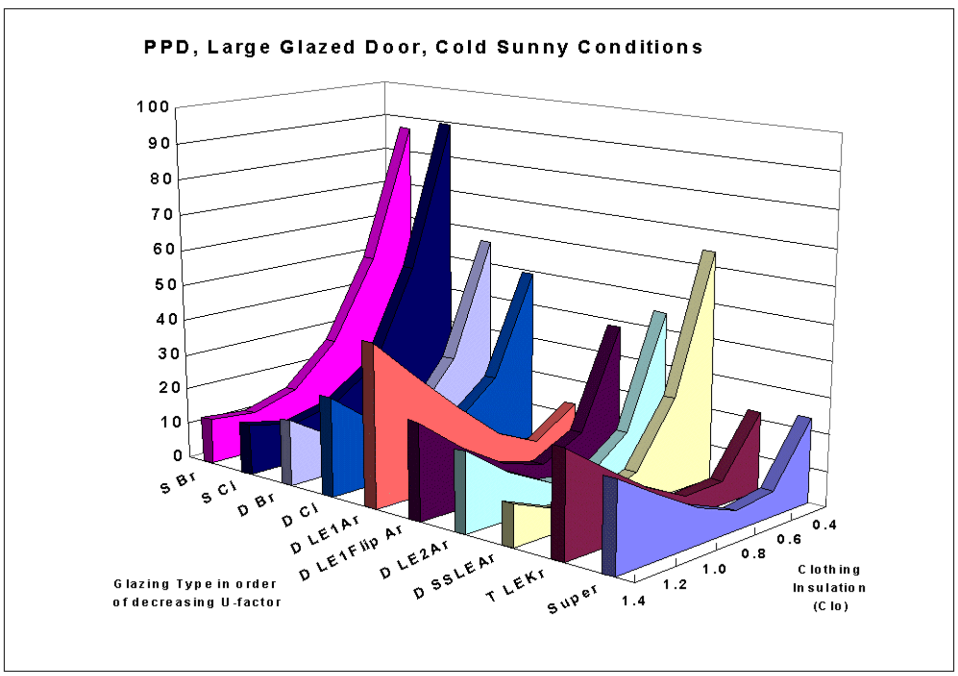

Figure 6. Percentage People Dissatisfied under cold sunny conditions (No. 4 in Table 2)as a function of clothing level and glazing U-factor.

Very Cold, Nighttime Winter Conditions

At night there is no solar load, so SHGC is not relevant. In Figure 7, the two predictors of comfort are glazing U-factor and clothing insulation. The results fall into four distinct groups which are, from worst to best: single-pane, uncoated double-pane, low-E double-pane and the triple-pane / high-performance window pair.

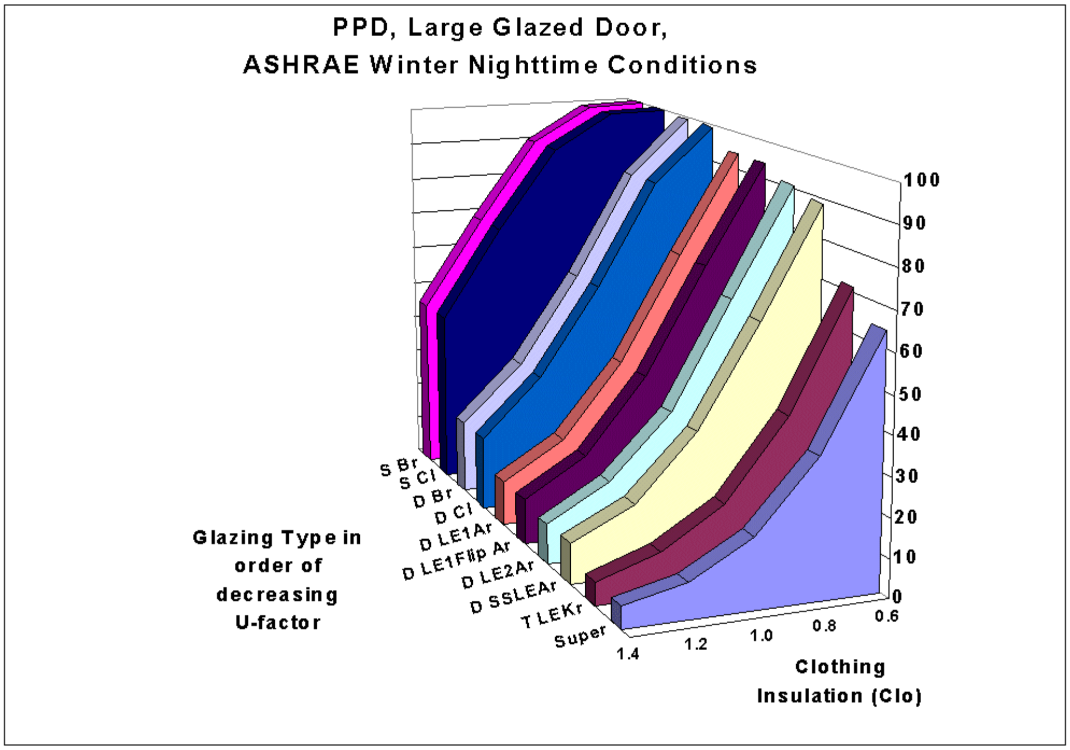

Figure 7. Percentage People Dissatisfied under ASHRAE Winter Conditions (No. 8 in Table 2) as a function of clothing level and glazing U-factor.

Future Work

A Multinode Model for the Human Body in Radiant-Exchange Calculations

As discussed above, the human body has a complex three-dimensional geometry with surfaces facing many directions, not just toward or away from a window. A simple two-node model cannot distinguish direction but instead averages radiant temperature effects over the whole body, even when severe asymmetry exists. Thus, radiant asymmetry is not necessarily included in the comfort calculation and the model may misleadingly predict that a person is comfortable "on average."

To address these shortcomings, a new multinode thermal comfort model (Huizenga 1999) is being developed that defines 16 separate segments for head, chest, arms, legs and other key body parts. In each segment, five temperature nodes are defined: core, muscle, fat, skin, and clothing. This model can account for subtleties such as the blocking effect of an arm on a torso's view of a window. The model can predict, for example, that the right arm near the window in Figure 8 is cold compared with the rest of the body. The model is able to account for transient and time-varying effects, heat transport via blood flow around the body, heat loss by evaporation, convection, radiation, and conduction. The clothing model includes including heat and moisture transfer.

The model uses rendering software to create a realistic three-dimensional model of the human body in any desired pose. A matrix of view factors is computed for each body segment and surrounding surfaces. Using these view factors and the temperatures of surrounding temperatures, radiation each transfer is calculated explicitly rather than using the MRT method.

It is hoped that these advances will form the basis of improved software for evaluating window comfort impacts.

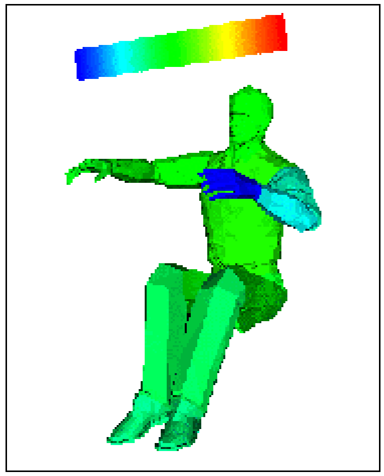

Figure 8. UC Berkeley Comfort Model, depicting asymmetric temperature distribution on subject.

Expanded Building Applications for the Window Comfort Model

A comprehensive and flexible model is essential for predicting the comfort impact of fenestration systems. Such a model would be capable of accommodating very large windows and overhead glazing such as atria and sunspaces. The modeling could be extended to an U.S.-wide or worldwide climatic database, such as that used by the DOE-2 energy simulation program (Birdsall et al 1990), by RESFEN (LBNL 1999), or other prominent simulation packages. More flexible choices for subject metabolic activity and clothing styles are also options for the future.

Meanwhile, development continues on the WINDOW+5 program (LBNL 1999) that will update capabilities for researching and rating the energy performance of fenestration products. The NFRC currently provides conventional thermal, solar and optical data for windows. However this information alone is not sufficient to quantify the comfort impact of windows. An integrated "comfort module" using surface temperatures as depicted in Figure 9 would assist rating and standards bodies such as the National Fenestration Rating Council (NFRC) in quantifying the comfort impact of windows, thereby offering immediate and more refined evaluation of window performance.

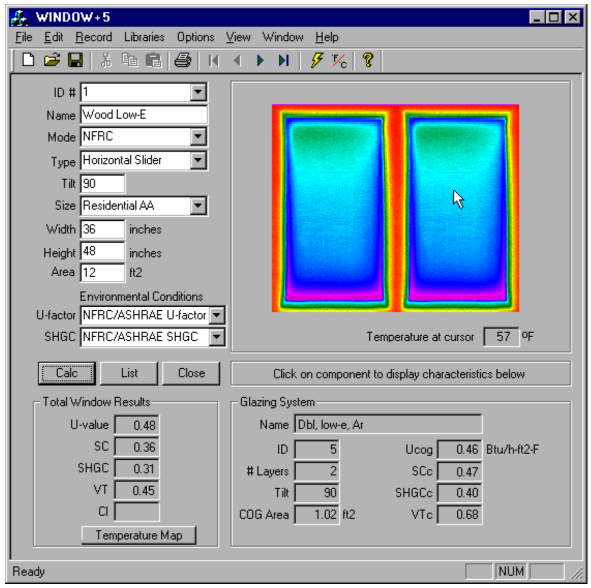

Figure 9. Concept for mapping of glazing inside surface temperature in WINDOW+5 computer program (LBNL, 1999).

Conclusions

The two-node model for window-related thermal comfort achieves the following:

- predicts the comfort impact of windows (within acknowledged current limitations in the way that geometry is modeled);
- performs separate analyses to establish trends for long-wave (thermal infrared), draft and solar effects;
- shows that long-wave effects dominate under no-solar conditions;
- shows that direct solar load has a major influence on perceptions of comfort;
- shows that for most residential-size windows, draft effects are generally small.

An improved, multinode model under would need to incorporate much more realistic geometry that defines the building occupants and their surroundings. These changes will refine the calculation procedure for radiative exchange. The outcome will be a general yet powerful tool to allow prediction of the comfort implications of glazing choices.

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References

ASHRAE 55-1992 with Addendum 55a-1994. Thermal comfort conditions for human occupancy.

ISO 7730:1994. Moderate thermal environments-determination of the PMV and PPD indices and specification of the conditions for thermal comfort.

Brager, G. S. and de Dear, R. J. 1998. Thermal adaptation in the built environment: a literature review. *Energy and Buildings*, 27: 83-96.

Tham, K.W and Ullah, M.B. 1993. Building energy performance and thermal comfort in Singapore. *ASHRAE* Transactions 99(1).

Gagge, A.P., Fobelets, A.P. and Berglund, L.G. 1986. A standard predictive index of human response to the thermal environment. *ASHRAE Transactions*. 92(2b) 709-731.

Fanger, P.O. 1972. Thermal comfort. McGraw-Hill (translation of original Danish edition published 1970).

Windows and Daylighting Group (http://windows.lbl.gov). WINDOW 4.1-A PC Program for Analyzing Window Thermal Performance In Accordance with NFRC Procedures. 1994. Lawrence Berkeley National Laboratory, Berkeley, California, USA.

Fountain, M. and Huizenga, C. 1995. A thermal sensation model for use by the engineering profession. *Environmental Analytics*, Piedmont, California, USA.

Heiselberg, P. 1994. Draught risk from cold vertical surfaces. *Building & Environment*, 29, 297-301.

Heiselberg, P., Overby, H. and Bjorn, E. 1995. Energy-efficient measures to avoid downdraft from large glazed facades. *ASHRAE Transactions* 101(2), 1127-1135.

Sullivan, Robert 1986a, 1986b. Thermal comfort issues in the LRI study. Internal Memorandum/Report, Windows and Daylighting Group, Lawrence Berkeley National Laboratory, Berkeley, California, USA.

Arens, E., Gonzalez, R. and Berglund, L. 1986. Thermal comfort under an extended range of environmental conditions. *ASHRAE Transactions* 92(1).

Huizenga, C., Zhang, H., Duan, T. and Arens, E. 1999. An improved multinode model of human physiology and thermal comfort. Submitted to *Building Simulation '99*, conference of the International Building Performance Simulation Association.

Birdsall, B., Buhl. W.F., Ellington, K.L., Erdem, A.E. and Winkelmann, F.C. 1990. Overview of the DOE-2 Building Analysis Program. Simulation Research Group, Lawrence Berkeley National Laboratory, Berkeley, California, USA.

Windows and Daylighting Group (http://windows.lbl.gov). 1999. RESFEN-A PC Program for Calculating the Heating and Cooling Energy Use of Windows in Residential Buildings. Lawrence Berkeley National Laboratory, Berkeley, California, USA.

Windows and Daylighting Group (http://windows.lbl.gov). 1999. WINDOW+5-software under development., Lawrence Berkeley National Laboratory, Berkeley, California, USA.