Title

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Summary

We present in this paper a technique that can be used to indicate thermal comfort in nonresidential buildings as a function of specific fenestration system parameters. Comfort index values correlated to window design variables were derived from a data base of many simulations of a prototypical office building module using the DOE-2 energy analysis program. Four glazing types and two shading devices were combined in several ways so that a representative sampling of realistic fenestration systems were analyzed.

Past studies related to windows have been performed only incidentally to the more general concerns of what defines comfort in different environments. Windows have been shown to be a source of both cold and hot discomfort. In our study, the windows were a source of cold discomfort only where they were greater than 60% of the wall area of the module used. The primary thermal comfort issue in thermally neutral perimeter zones was found to be related to the impact of windows as a source of high intensity direct solar radiation.

For the high-intensity source, we binned the amount of direct solar radiation coming through a window for each DOE-2 simulation run. These values were correlated to level of dissatisfaction using data from Fanger (1970). The resulting annual thermal comfort index was then related to the fenestration systems' solar heat gain coefficient and area. We conclude by recommending that solar radiation bin data be generated for several weather locations and window orientations so that one could ascertain the comfort implications associated with the high-intensity source.

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Abstract

We present in this paper a technique that can be used to indicate thermal comfort in nonresidential buildings as a function of specific fenestration system parameters. Comfort index values correlated to window design variables were derived from a data base of many simulations of a prototypical office building module using the DOE-2 energy analysis program. Four glazing types and two shading devices were combined in several ways so that a representative sampling of realistic fenestration systems were analyzed. These comfort indicators are intended to be used as part of a more comprehensive design tool to analyze total window performance.

Introduction

The performance of fenestration is inherently complex involving many physical processes. Topics of research interest have primarily dealt with energy performance involving analysis of the heat and mass transfer characteristics associated with system conductance, solar optical properties, and ventilation. Much work has been accomplished to date to evaluate these phenomena. There is also a body of literature on the visual comfort aspects of fenestration. One area, however, that has not been sufficiently investigated involves the relationship between building fenestration systems and levels of thermal comfort. Past studies have been performed only incidentally to the more general concerns of what defines comfort in different environments.

The multitude of interdependent parameters associated with fenestration performance makes an all-inclusive analysis formidable, if not impossible. In order to isolate and systematically characterize the impacts of fenestration, we performed a series of sensitivity studies early in our research (Choi et al. 1983 and Johnson et al. 1983). These studies identified levels of importance for various fenestration energy performance parameters. With this basis, we were able to develop a prototypical building module and a parametric analysis procedure to study fenestration and daylighting energy performance.

These results were of considerable use and importance from a research standpoint but did not fully meet the needs for practical application in a design environment. The results format did not lend itself to convenient evaluation of tradeoffs among fenestration design options. Issues of comfort and amenity were not directly addressed. Performance data for complex shading systems was nonexistent or unreliable. It was thus necessary to undertake new work to overcome these shortcomings.

This paper presents a portion of this new work. We discuss the thermal comfort aspects of fenestration and how one can evalute a thermal comfort index as a function of various fenestration system parameters. We intend to make this procedure part of a design tool in which energy and visual comfort performance are also considered.

Model Description

The foundation of our analysis is a large data base created by hourly heat transfer simulations of a prototypical single-story commercial office building using the DOE-2 energy analysis program (Building Energy Simulation Group, 1984). Although the DOE-2 simulations were completed primarily to study the energy implications of fenestration, we modified the program source code to generate imformation that could be used in our comfort analysis. Two climate locations were analyzed: Madison, Wisconsin, and Lake Charles, Louisiana.

The module in our study has four perimeter zones consisting of ten offices, each 4.57 m (15 ft) deep by 3.05 m (10 ft) wide surrounding a central core zone of 929 m^2 (10,000 ft^2) floor area. Floor-to-ceiling height was 2.6 m (8.5 ft) with a plenum of 1.07 m (3.5 ft) height. Normal building thermal interactions included heat capacity effects and small convective/conductive transfers between the core and perimeter.

Continuous-strip windows were used in the exterior wall of each perimeter zone. Four glazing types and two shading devices were combined in several ways to simulate a representative sampling of realistic fenestration systems. Glazing area was parametrically varied at 0, 15%, 30%, 45%, and 60% of the wall area. The glazing types were clear, bronze-tinted absorptive, reflective, and clear low-E. Results were obtained for single-, double-, and triple-pane units. Shading devices included a diffusing shade and a venetian blind (LBL and FSEC, 1988).

Comfort Evaluation

Of particular importance in the office environment are the effects on thermal comfort arising from asymmetric thermal radiation. Thermal radiation, in this context, not only includes that due to longwave low-temperature sources such as cold or warm surfaces (walls and windows) or radiators, but also high-intensity sources such as infrared heaters and direct solar radiation. The literature is mixed in its treatment of each of these, with an early emphasis on high-intensity sources. Lately, however, the concentration has been on longwave sources.

Analytical and experimental results used in the ASHRAE/ANSI Standard 55-1981 (Thermal Environmental Conditions for Human Occupancy) and in recommended procedures for evaluating comfort as specified in ASHRAE Fundamentals (1985) are based in varying degrees on three fundamental models of the thermal response of the human body: the Fanger model, the Pierce two-node model, and the Kansas State University two-node model (Berglund, 1978).

In general Fanger's results are more conservative than the others' and his methodology has been prepared in the form of tables and charts that are very easy to use. For these reasons, Fanger's model was used to predict comfort levels in this study. We investigated both mean radiant temperature (Fanger, 1970) and asymmetric radiant temperature effects (Fanger, 1986) for cold windows and high-intensity direct solar radiation. Radiant temperature effects from warm windows do not seem to be a problem (Fanger, 1986); however we feel that further investigations are necessary to verify the extreme temperature asymmetries deemed acceptable. This is particularly true because of the increased use of heat-absorbing glass in some geographic locations.

Low-Temperature Cold Window

Windows as a source of cold discomfort in our model occurred only for those whose area was greater than 60% of the wall area. The room temperature and all surface temperatures of the office space previously described were assumed to be at 22°C (72°F). Relative humidity was 50% and the room air velocity was 0.15 m/s (30 fpm).

Activity level was set to 1.2 met (70 W/m^2, 22 Btu/h-ft^2, 60kcal/h-m^2). These conditions are at the midpoint of the winter comfort criteria specified in the ASHRAE/ANSI Standard.

We partitioned the room into 24 equal areas and calculated MRT (Mean Radiant Temperature), PMV (Predicted Mean Vote), PPD (Percent People Dissatisfied), PLT (Plane Radiant Temperature), and RTA (Radiant Temperature Assymetries) for each node (Fanger, 1970 and 1986). We calculated the effect of a cold window by assuming the window glass surface temperature to be 0°C (32°F). For this condition at the largest window-to-wall ratio (WWR) of 0.6, the highest incremental PMV due to the MRT change from neutral was -0.2 at a location adjacent to the window. This value denotes an increase of only a few percent in PPD. If the wall were completely a window (WWR=1.0), the ΔPMV was -0.5, which represents about a 10% level of dissatisfaction.

Radiant temperature asymmetries for this glass surface temperature condition varied from 4.3°C (7.7°F) for the WWR=0.6 to 10.3°C (18.6°F) for WWR=1.0. Standard 55-1981 specifies a limit of 10°C (18°F) for cold vertical surfaces and this corresponds to about a 5% level of dissatisfaction. We also tested other winter conditions by assuming much lower glass surface temperatures, down to and including -18°C (0°F). Dissatisfaction levels greater than 10% occurred for temperatures lower than -3°C (26°F); and greater than 20% for temperatures lower than -9°C (16°F) for the WWR=1.0 window. For WWR=0.6, the level of dissatisfaction was always less than 2%, regardless of glass surface temperature.

High Intensity Direct Solar Radiation

The primary thermal comfort issue in thermally neutral perimeter zones was found to be related to the impact of windows as a source of high-intensity direct solar radiation. Past experimental testing on discomfort resulting from high-intensity sources has been concerned with subject response to infrared heating devices (ASHRAE,1985; Fanger, 1970; Gagge, et al., 1967; Berglund, 1979). Unlike the case of longwave sources discussed above and part of the ASHRAE/ANSI Standard, which were evaluated for their asymmetric characteristics, no such studies have been found in the literature that specifically dealt with high-intensity sources in this manner.

For the high-intensity source, we used the DOE-2 program to bin the amount of direct solar radiation coming through a window. These values were correlated to level of dissatisfaction using data from Fanger (1970). An overall annual comfort index was then calculated using the following expression:

$$TC = \sum_{i=1}^{NB} X_i \ (1.0 - PPD_i)$$

where X is the decimal percent hours at a solar heat gain level and PPD is the decimal percent dissatisfied at that level. Subscript (i) represents a summation over the number of solar bins (NB). Table 1 shows the bins used and corresponding PPD values. The highest (best) index is 1.0, corresponding to a zero level of dissatisfaction. The lowest (worst) index is 0.0. This would occur if the transmitted solar radiation exceeded 473 W/m^2 (150 Btu/hr-ft^2) during 100% of the occupied hours.

We related these calculated TC values to the fenestration systems' solar heat gain coefficients, S_g, using regression analysis. S_g is defined as the ratio of the transmitted and inward-flowing absorbed solar radiation to the incident radiation. An exponential function was derived so that at a solar heat gain of zero, the TC index was at its maximum or most comfortable level of 1.0, and at large values of solar heat gain, the index was at its lowest level or most uncomfortable, i.e.:

$$TC = \alpha_1 \cdot e^{\alpha_2 S_g}$$

where α_1 and α_2 are regression coefficients, shown in Table 2 for two locations, Madison and Lake Charles.

The TC index above does not account for the total amount of solar radiation transmitted through the window, only the amount per unit area. For area variations, we used a proportional relationship under the assumption that the largest window corresponds to the largest level of discomfort (minimum TC index for the range of fenestrations systems analyzed). A comparison between fenestration systems is obtained using the minimum TC value and maximum window area as follows:

$$I_{TC} = 1.0 - \{ [(1-TC)/(1-TC_{min})] \ [A_g/A_{gmax}] \}$$

where A_g is the window area and I_{TC} is the normalized comfort index and its value varies between 0.0 and 1.0.

Conclusions

This paper documents an approach for evaluating the comfort impacts associated with varying fenestration system parameters primarily under the influence of direct solar radiation. We present a method of evaluation in which it was shown that an annual comfort index could be determined by knowing the fenestration system solar heat gain coefficient and aperture size. Conclusions reached are as follows:

a. If the assumption is made that an HVAC system or other active or passive system is available for maintaining a comfortable environment under most conditions, then thermal comfort in commercial office building perimeter spaces is an issue only in terms of asymmetric solar radiation.

b. For windows of area less than 60% of the wall, it appears that discomfort due to a cold window is not a problem. Only with the use of a large (all facade), cold window will any significant amount of discomfort be experienced for occupants adjacent to the window. Although past research has indicated that warm walls do not affect comfort, we feel that additional research is warranted to evaluate the use of heat-absorbing glass in warm environments.

c. For high-intensity sources such as solar radiation through windows, we recommend that solar radiation bin data be generated for a number of weather locations and window orientations. These data would consist of the number of hours at particular radiation levels for various solar altitudes and azimuths. From such information, one could ascertain the effects on mean radiant temperatures and comfort in perimeter-zone spaces.

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TABLE 1

PERCENT PEOPLE DISSATISFIED AT A PARTICULAR SOLAR BIN LEVEL

Solar Bin W/m^2 ($Btu/hr\text{-}ft^2$)	Percent Dissatisfied
567- (180-)	100
473-567 (150-180)	100
378-473 (120-150)	70
284-378 (90-120)	50
189-284 (60- 90)	40
95-189 (30- 60)	20
63- 95 (20- 30)	10
32- 63 (10- 20)	10
3- 32 (1- 10)	5
less than 3 (1)	5

TABLE 2

REGRESSION COEFFICIENTS: THERMAL COMFORT INDEX

		Madison	Lake Charles
α_1	N	1.0	1.0
	S	.981	.975
	E	.972	.961
	W	.965	.978
α_2	N	0.0	0.0
	S	-.198	-.144
	E	-.123	-.097
	W	-.111	-.133
r^2		.868	.864

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