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Solar Heat Gain through Single Glass-Blind Fenestrations

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ABSTRACT

Energy-saving venetian blinds have recently been studied using a unique environmental chamber complete with artificial sun. Data from this study have enabled further confirmation of a reported methodology for calculating the shading coefficient for glass-blind systems. This methodology allows architects and engineers to use published data on solar optical properties of both vertical and horizontal blinds, such as that given in the ASHRAE Handbook - 1981 Fundamentals. At present, the guide does not provide a procedure for calculating the shading coefficient for complex window systems using data on solar optical properties. Values of shading coefficient are provided for only a few selected special glazings and "light" and "medium" colored interior blinds. Now, energy-saving blinds with a wider range of shading coefficients have been tested and their performance shown to be consistent with the recommended design procedure. Use of the method and data permits more convenient calculation of solar heat gain in buildings by extending confidence in shading coefficients.

INTRODUCTION

Energy-efficient use of windows in the design and operation of modern buildings, particularly the glass-clad variety, requires accurate input and understanding of solar heat gain through complex fenestrations. The purpose of this paper is to contribute to this understanding and to present a relatively simple but proven method for computing additional shading coefficient data, given the measured solar optical properties of the exterior glazing and the interior porous shading -- specifically, 1-inch slat horizontal venetian blinds.

DATA, COMPARISONS, AND ANALYSIS

Data

The experimental solar energy window data presented and discussed in this paper have been gathered over the past several years by the Building Technology Research Division of Davidson Laboratory at the Stevens Institute of Technology in Hoboken, New Jersey, in conjunction with several industry, government (Department of Energy) and academic research studies. The unique Environmental Simulator, designed specifically to measure shading coefficient and to permit measurement of solar optical properties of variegated surfaces, was employed to gather data on the modern 1-inch slat horizontal blinds described in Tab. 1. The experimental results are given in Tabs. 2 and 3. A detailed description of this facility has been previously reported[2] and will be expanded upon in a seminar at the Atlantic City ASHRAE meeting in January 1983. However, a brief explanation of its use follows.

Test Procedure

The Environmental Simulator consists of two thermally insulated chambers connected by an airtight removable window with 7.5 ft^2 (0.697 m^2) of exposed glass area. The interior framing provides for blinds or shading up to 34 in. (864 mm) wide by 40 in. (1016 mm) high and mounted

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2 in. (51 mm) behind and overhanging the indoor surface of the glass. Typical clearances of 1-3/8 in. (35 mm) above the blind support head and 1/4-in. (6 mm) at each side of the blind are provided in addition to the maximum blind closure limit of from 70 to 75° where 90° would be tightly closed (as can be selected with vertical blinds). Thus, air is relatively free to move through and around the sides and top of each blind, even at the closed slat setting. An adjustable artificial sun and an air-conditioning system are used in the outdoor chamber, with the solar profile or incidence angle set to 35° above the horizontal for these test data. Steady-state heat flow to the sealed calorimeter indoor room is measured by the energy removed in an instrumented chilled-water heat exchanger.

The solar optical properties for each blind are measured using a black-box interior background with the glass and its frame removed from the window opening. Solar heat gain is measurable to within ±18 Btu/hr (5 W). Average values of solar optical reflectance and transmittance are measured using pyranometers mounted close to the plane of the variegated surface. Blind angle is set and held by means of a small motor, with the angle of the middle slat used as reference. The transmittance can be measured to within ± 0.02 and reflectance to within ± 0.03.[3]

Comparison with Theory

Figure 1 shows the combined results of Tab. 3 for all three blind angles plotted as measured shading coefficient versus measured average blind reflectance for a 1/4-in. clear glass window. The dependence of shading coefficient on reflectance of the blind, ρ_i, was derived from theory in Van Dyck and Konen[4]. This relationship is based on several simplifying assumptions, where the shading coefficient (SC) is expected to be of the following form:

$$SC = 1.15 \left\{ (1 - \rho_i)\left(\frac{\tau_o}{1 - \rho_o \rho_i}\right) + N_{io}\alpha_o \left[1 + \rho_i \left(\frac{\tau_o}{1 - \rho_o \rho_i}\right)\right]\right\} \tag{1}$$

where τ_o, ρ_o, and α_o are the known transmittance, reflectance, and absorptance of the glazing. The N_{io} factor, which may be expressed as a combination of indoor, h_i, and outdoor, h_o, film coefficients of heat transfer, $h_i/(h_i + h_o)$, is the inward flowing fraction of heat absorbed by the glazing (see Fig. 2). For the relatively "still-air" test conditions in the simulator of less than 1 ft/s (0.3m/s) indoor and outdoor air velocities near the glazing, h_o would approach h_i, and N_{io} would be expected to be near 0.5. The theoretical curve of predicted shading coefficient for $N_{io} = 0.5$ is shown for comparison in Fig. 1. The agreement of the data with this curve is the subject of this paper.

Analysis

The ASHRAE Handbook - 1981 Fundamentals,[5] lists shading coefficients for many common glazings and for "medium" and "light" venetian blinds with these glazings. However, at present, the Handbook does not provide a procedure for calculating the shading coefficient for any complex glazing system with interior shading, using the solar optical properties of the interior shading. The development and availability of energy-saving high reflectance and multicolored 1-inch horizontal blinds have required additional testing and now provide the opportunity to test newly measured performance using published ASHRAE values and other recommended design procedures.

Equation 1 was developed because of a need for a simple yet accurate method for calculating shading coefficient, using the much more easily obtainable data on solar optical properties of the adjustable interior shading that is being considered for use with a particular exterior glazing design. Confidence in the range and degree of accuracy of Eq. 1 shading coefficients will permit more convenient calculation of solar heat gain in buildings.

The overall agreement of the 40 measurements presented in Tab. 3 and shown in Fig. 1 is excellent. Their correlation coefficient is 0.978 with a sample standard error of estimate of 0.046 for measured shading coefficient as compared with predicted shading coefficient using Eq. 1 and $N_{io} = 0.5$ for the simulator test conditions. The last column in Tab. 3 gives predicted shading coefficients for standard ASHRAE 7.5-mph summer wind conditions, where $h_o = 4.0$, $h_i = 1.46$ Btu/hr·ft²·°F and $N_{io} = 0.267$. These lower values should be used for summer design comparisons and energy estimates. Similarly, for 15-mph outdoor winter wind conditions, $N_{io} = 0.196$ should be used to calculate the shading coefficient.

DISCUSSION

In the course of developing the predictive equation for computing the shading coefficient, several important simplifying assumptions were made. Following is a list of these assumptions and the reasons for making them:

1. Total direct and diffuse solar energy may be treated together as a first approximation. Under primarily direct solar illumination, diffuse and reflected solar energy are a relatively small and constant portion of the total solar energy and as a result do not influence the overall reflectance and transmittance values appreciably. The direct solar illumination shading coefficient measurements seem to agree in this study.

2. The blind is relatively porous due to closure restrictions. This permits air flow around and through the interior shading portion of the window system and allows use of the simplified indoor film coefficient shown in Fig. 2 as h_2. This pseudo-indoor film coefficient may then be used to compute N_{io} in the same manner as h_i is used for a simple window system.

3. Almost all solar energy absorbed by the interior shading device ultimately remains within the room. This allows the simplifying assumption that $N_{ii} = 1.0$, where N_{ii} is that portion of the solar energy absorbed by the interior blind of a single glass-blind fenestration that stays in the room.

The third assumption can be questioned for low reflectance/high absorptance interior blinds, where under winter conditions the blind surface temperature might conceivably be hotter than the glazing temperature. When this occurs, some net energy could be conducted and radiated back to the glazing and ultimately leave the room. Though this may be the case with low reflectance blinds, the third assumption is believed to hold fairly well for all high reflectance blinds. Moreover, the basic definition and use of shading coefficient separates thermal effects from solar energy heat gain and treats each by superposition, where the total heat gain (or loss) is

Total heat gain = solar heat gain + thermal heat gain

$$Q/A = SC \times SHGF + U(t_o - t_i) \qquad (2)$$

Thus, the shading coefficient should be measured at equal indoor and outdoor temperatures for accuracy, and thermal effects should be added later. Obviously, in the real world, indoor and outdoor temperatures are rarely equal so that net total energy flow is a combination of solar and thermal effects as shown in Eq. 2. The basic validity of this superposition relationship should be tested if any question remains as to the application of the measured shading coefficient. Precise measurement of the U-value then becomes equally important.

Further comment should be made here on the overall fit of the measured shading coefficient data to the predicted curve for $N_{io} = 0.5$ shown in Fig. 1. The fit is generally very good despite wide variations in blind slat setting, surface finish, and color for all reflectances greater than about 0.10. However, the open blind setting also appars to fit down to reflectances of 0.05 or larger. Only the closed (70 - 75°) blind settings at low reflectances of less than 0.10 show signficant, if small, deviations below the predicted values of shading coefficient. Obviously, something is occurring here that should be looked into in order to gain a better understanding of the mechanism of energy transfer.

CONCLUSIONS AND RECOMMENDATIONS

There is excellent agreement between the experiment and the predictive theory, particularly in the case of high reflectance blinds with $N_{io} = 0.5$ taken for the simulator window surface conditions. This agreement instills confidence that the appropriate simplifications have been selected for the single glass-blind system.

To improve agreement and provide more understanding of the solar heat-flow phenomenon, it is suggested that a research effort be directed towards studying the heat-transfer interchange effect on the N_{io} value, particularly with low-reflectance blinds. Although there would appear to be only a small gain in accuracy of energy-use prediction, this area could be important if the method can be extended to predict the shading coefficient for interior shading with insulating glasses. Indeed, determining the shading coefficient of double or triple glazing with interior reflective shading is still a valid energy research objective, when clear glazing with high transmittance is considered.

New energy-efficient vertical blinds, which allow more complete closure than horizontal blinds, have shown very high reflectance values and would be expected to provide correspondingly low shading coefficients based on the predictive equation. This should be verified by test, since air flow around a closed vertical blind would be expected to differ somewhat from that developed with a horizontal blind. Similarly, nonporous shades or other interior devices may cause variations in the N_{io} portion of glass-absorbed energy that passes to the room.

There is much to gain in overall year-round building energy consumption through proper design and selection of glazing and adjustable interior decorative shading devices. The results of this study show that lower shading coefficients may now be used in energy calculations and design schemes for certain energy-efficient glazing systems. Variations in the shading coefficient can even be attempted where warranted with an additional degree of confidence in the engineering values used.

REFERENCES

1. R.L. Van Dyck and T.P. Konen, "The Stevens-Levolor Environmental Simulator and the Study of Interior Shading for Energy Efficient Windows" (Paper delivered to ASME Solar Energy Division Conference, Reno, Nevada, April 27-May 1, 1981), p. 597.

2. R.L. Van Dyck and T.P. Konen, Energy Conservation Through Interior Shading of Windows: An Analysis, Test and Evaluation of Reflective Venetian Blinds (Berkeley, CA: Lawrence Berkeley Laboratory, U. of California, Energy and Environment Division, 1982) LBL-14369 also (Hoboken, NJ: Davidson Laboratory, Stevens Institute of Technology 1982) TR-2083.

3. R.L. Van Dyck and T.P. Konen, Energy Conservation, p. 34.

4. R.L. Van Dyck and T.P. Konen, Energy Conservation, pp. 5-9.

5. ASHRAE Handbook - 1981 Fundamentals Volume, Chapter 27, Tabs. 34 and 37.

TABLE 1
Description of Experimental Venetian Blinds

Blind No.[a]	Color Upper Surface/Lower Surface (convex/concave)	Surface Finish Upper Surface/Lower Surface (convex/concave)[b]
1	Aluminum/aluminum	High gloss/high closs - no protective coating
2	Aluminum/aluminum[c]	High gloss/high gloss
3	Aluminum/black[c]	High gloss/satin
4	White/white	Glossy/glossy
5	Off white/off white	Satin/satin
6	Light green/light green	Glossy/glossy
7	Aluminum/aluminum	Polished/polished
8	Light tan/light tan	Glossy/glossy
9	Medium tan/medium tan	Satin/satin
10	Chrome/chrome[c]	Fine ripple/fine ripple
11	Chrome/black[c]	Fine ripple/satin
12	Dark brown/dark brown	Satin/satin
13	Black/aluminum[c]	Satin/high gloss
14	Black/chrome[c]	Satin/fine ripple

NOTE: All blinds are 1-inch width with 0.8-inch spacing (open)

[a] Arranged in order of decreasing reflectance for closed blinds.

[b] "Glossy" and "Satin" refer to typical painted surface finishes as seen by the eye.

[c] These blinds received a special protective coating.

TABLE 2

Measured Solar Optical Properties
of Experimental Venetian Blinds
(35° Solar Incidence)

Blind No.	Slat Position	Transmittance τ_i	Reflectance ρ_i	Absorptance α_i
1	Closed	.050	.710	.240
2	Closed	.030	.670	.300
	45°	.190	.460	.350
	Open	.730	.040	.230
3	Closed	.020	.650	.330
	45°	.040	.450	.510
	Open	.630	.020	.350
4	Closed	.051	.602	.347
	45°	.110	.495	.395
	Open	.483	.216	.301
5	Closed	.042	.589	.369
	45°	.108	.477	.415
	Open	.442	.197	.361
6	Closed	.034	.503	.463
	45°	.108	.375	.517
	Open	.544	.148	.308
7	Closed	.036	.498	.466
	45°	.120	.381	.499
	Open	.570	.069	.361
8	Closed	.035	.444	.521
	45°	.080	.340	.580
	Open	.499	.134	.367
9	Closed	.021	.316	.663
	45°	.052	.229	.719
	Open	.399	.097	.504
10	Closed	.024	.316	.660
	45°	.058	.219	.723
	Open	.482	.046	.472
11	Closed	.017	.312	.671
	45°	.025	.231	.744
	Open	.496	.013	.491
12	Closed	.015	.089	.896
	45°	.026	.065	.909
	Open	.434	.020	.546
13	Closed	.020	.070	.910
	45°	.050	.040	.910
	Open	.410	.010	.580
14	Closed	.006	.062	.932
	45°	.032	.041	.927
	Open	.407	.014	.579

TABLE 3

Comparison of Measured and Predicted Shading Coefficients
(35^o Incidence, 1/4-In. Clear Glass,
1-in. Wide Interior Blinds)

Blind No.	Slat Position	Blind Reflectance ρ_I	Still Air (N_{io} = .5) SC_M*	SC_P*	Summer (N_{io} = .267) SC_P
1	Closed	.710	.41	.41	.35
2	Closed	.670	.44	.44	.38
	45^o	.460	.63	.61	.56
	Open	.040	.92	.94	.90
3	Closed	.650	.47	.46	.40
	45^o	.450	.63	.62	.57
	Open	.020	.92	.96	.92
4	Closed	.602	.55	.50	.44
	45^o	.495	.66	.59	.53
	Open	.216	.80	.81	.76
5	Closed	.589	.53	.51	.45
	45^o	.477	.68	.60	.55
	Open	.197	.79	.82	.78
6	Closed	.503	.58	.58	.52
	45^o	.375	.67	.68	.63
	Open	.148	.84	.86	.82
7	Closed	.498	.56	.58	.53
	45^o	.381	.71	.68	.63
	Open	.069	.92	.92	.88
8	Closed	.444	.60	.63	.57
	45^o	.340	.71	.71	.66
	Open	.134	.84	.87	.83
9	Closed	.316	.66	.73	.68
	45^o	.229	.77	.80	.75
	Open	.097	.88	.90	.86
10	Closed	.316	.66	.73	.68
	45^o	.219	.80	.81	.76
	Open	.046	.92	.94	.90
11	Closed	.312	.69	.73	.68
	45^o	.231	.80	.80	.75
	Open	.013	.90	.96	.92
12	Closed	.089	.83	.91	.86
	45^o	.065	.85	.92	.88
	Open	.020	.90	.96	.92
13	Closed	.070	.86	.92	.88
	45^o	.040	.88	.94	.90
	Open	.010	.93	.96	.92
14	Closed	.062	.83	.93	.88
	45^o	.041	.85	.94	.90
	Open	.014	.90	.96	.92

*Subscripts: M = measured in simulator. P = predicted based on measured blind reflectance, ρ_I, where glass τ_o = .77, ρ_o = .08, and α_o = .15.

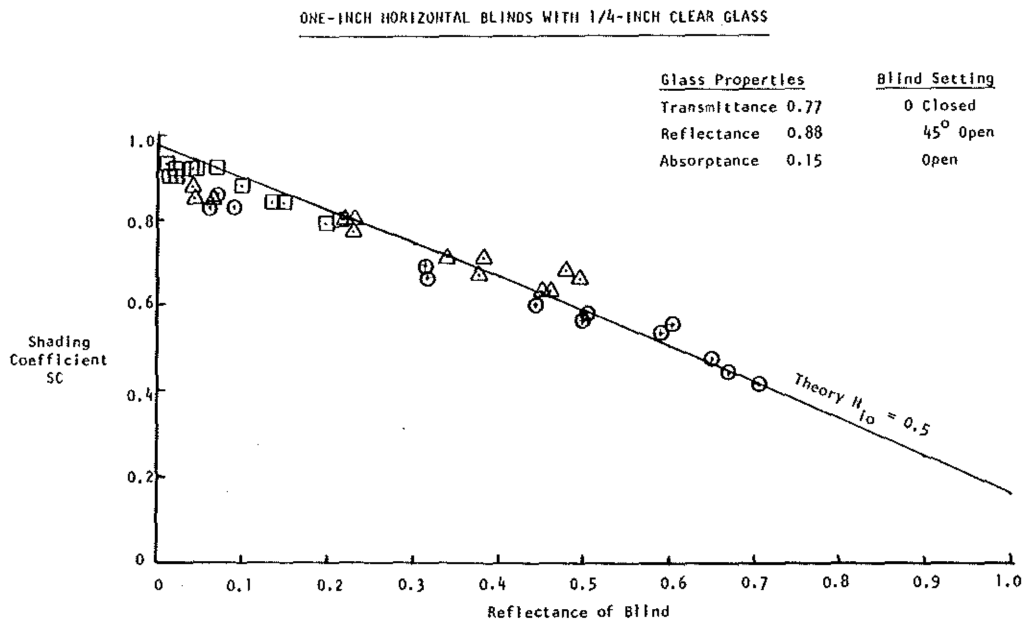

Figure 1. *Shading coefficient vs. reflectance simulator measured values in "still air"*

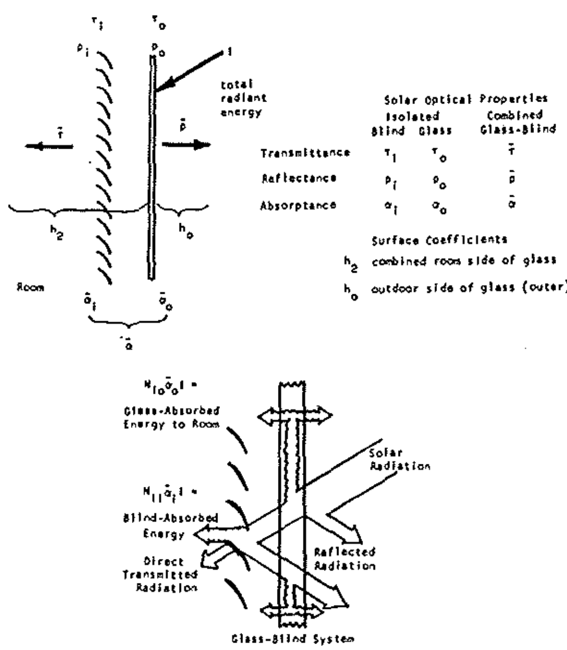

Figure 2. *Heat transfer through the glass-blind system*

Discussion

J.H. Klems, Lawrence Berkeley Lab., Berkeley, CA: How did you mount your thermocouples for measuring surface temperatures?

R.L. Van Dyck: Our thermocouples are mounted flat on the surface, unshielded, with a small piece of transparent tape. We do not report these measurements because no standards have been established. We recommend that a standard shielding and mounting procedure be adopted, particularly for surfact temperature measurements to be made in direct sunlight. Insolation values must also be correlated with these measurements.

R.H. McEntire, DAE Engineers, Logan UT: Please clarify how reflectance on horizontal axis is determined?

Van Dyck: The average solar reflectance is measured directly with a miniature pyranometer mounted close to the vertical plane of the window, first facing toward the blind (with a particular slat setting and solar incidence angle) and then turned 180 degrees to face the sun. A black nonreflecting background is mounted on the room-side of the fenestration during the solar optical measurements. The pyranometer axis is normal to the plane of the window and is centered in front of it. Our window is 36 in. x 42 in. and the pyranometer sensor is between one the two inches out from the surface to be measured.

$$\text{Reflectance} = \frac{\text{Reading facing surface}}{\text{Reading facing sun}}$$

H.F. Wu, Architecture Research Lab., Univ. of Michigan, Ann Arbor: Was there any variation of shading coefficient value due to different kinds of venetion blind with respect to blind position?

Van Dyck: Yes there are significant differences in shading coefficient for different colored blinds at different slat settings to the sun because of different reflectance values, as shown in Fig. 1. Only 1-in. width horizontal blinds are reported on here. Vertical blinds and porous shades will show similar effects, again depending on average solar reflectance values.

The same horizontal blind is representad by three different points plotted in Fig. 1. These are also listed in Tab. 3 as SC_M in still air ($N_{io} = 0.5$) for three values of ρ_i, measured at each of three slat settings for the 35 degree solar incidence angle tested.