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Abstract

The use of venetian blinds to control solar gain through windows is common in both residential and commercial buildings, and their potential for reduction of peak cooling load and energy consumption is recognized to be large. As such, there is a strong need for models that allow a venetian blind to be included in glazing system analysis. A simplified method of calculating the “effective” solar optical properties of a venetian blind is presented. The solar optical properties of the entire blind are determined based on slat geometry and the optical properties of the slat material, and on the direction and nature (beam or diffuse) of incident radiation. The slat material optical properties are assumed to be independent of the angle of incidence, and are assumed to transmit and reflect beam radiation diffusely. As a first approximation, the slats are assumed to be flat with negligible thickness. A correction is then developed and applied that accounts for the curvature of the slat. The results of the flat and curved slat models are compared with experimental data for commercially available venetian blinds. Both models demonstrate
excellent agreement with experiments, except when the profile and slat angles are aligned. In that case, the flat slat model predicts blind transmissions that are too large. The models developed in this study provide useful input to multi-layer glazing/shading models used for rating or for building energy simulation.

Keywords: building energy simulation, fenestration, shading devices, solar optics, solar gain, heat transfer

Introduction

The modelling of energy performance for windows with shading devices (called complex fenestration) is a two step problem. In the first step, short wave (solar) radiation is considered. Generally, the effective solar-optical properties of each layer in the system needs to be measured [1,2] or predicted [3,4,5,6]. These effective properties are then used as part of a multi-layer calculation that considers layer interactions [7,8,9]. This calculation results in the systems solar transmission and absorbed solar components. The absorbed solar quantities appear as energy source terms in the second step – the heat transfer analysis. The present work is aimed at accurately modelling the effective solar properties for a louvered shading layer (venetian blind) from minimal data.

Several solar-optical models in the literature consider the effective properties of louvered shades. Parmelee and Aubele [3], Pfrommer [4], and Rosenfeld et al. [5]. Parmelee and Aubele presented a mathematical method for the determination of layer specific absorptance, reflectance, and transmission for a shade layer. Properties were determined as a function of solar position with respect to the glazing system, the optical properties of the shade material, and slat geometry (slat width, angle, and pitch ratio), and results were
presented for both direct and diffuse light. It was assumed in that analysis that the slats were flat and diffusely reflecting.

Yahoda and Wright [6] developed a set of optical property models for louvered shades. Their method requires the slat geometry and knowledge of slat surface reflectance as well as its beam-diffuse split. Furthermore, the method requires separate treatment of incident beam and diffuse radiation. For incident beam radiation, the method generates both beam-beam and beam-diffuse optical properties. The beam-beam calculations involve tracing the specularly reflected portion of incidence beam radiation until it emerges from the blind layer. Only two specular reflections were permitted by this model, after which, the ray becomes a diffuse source. This particular ray tracing technique is computationally intensive as algorithms are required to determine the fraction of incident radiation undergoing a certain number of reflections coupled with a series of geometric conditions imposed on each ray. The beam-diffuse calculations, on the other hand, involve net radiation analysis which accounts for diffuse reflections at the slat surfaces. The models can be used to calculate solar optical properties pertaining to incident beam and incident diffuse radiation, and can also be used to obtain both direct-normal and off-normal optical properties of venetian blinds at various slat angles. The models, therefore, provide useful inputs to the multi-layer glazing/shading solar optical model.

The models developed by Yahoda and Wright [6] were intended to be used in the multi-layer solar-optical calculation method developed by Wright and Kotey [9]. Their multi-layer model accounts for both beam and diffuse radiation in a complex fenestration system consisting of specular glazings and non-specular shading layers. It is an extension of an existing multi-layer model for specular glazing layers that was developed by
Edwards [10]. The method assumes that only specular and/or isotropically diffuse components of solar radiation result from the interaction of insolation with any item in a glazing/shading layer array. An expanded set of solar-optical properties is assigned to each layer accordingly. Layers that are not uniform (e.g., venetian blinds, pleated drapes) are assigned spatially averaged, or “effective”, solar-optical properties. The results of the multi-layer solar-optical calculation give the absorbed solar radiation in each layer as well as the transmitted and reflected fluxes.

Klems [7,8] has also developed a multi-layer method that involves the measurement of bi-directional solar-optical properties for each layer in the system. The properties of the overall complex fenestration system are then built up using matrix calculations and the measured layer properties. This method is very accurate, but also computationally intensive. The larger issue with this method, however, is that there is currently no practical method by which the bi-directional property matrices can be produced en-masse for input to the matrix routine.

In the current study, the solar optical property models developed by Yahoda and Wright [6] are reevaluated. The primary intention is to eliminate the computationally intensive ray tracing techniques inherent in those models. It is anticipated that the simplified models will be highly valuable to building energy simulation, which places a strong requirement for speed on any of its sub-models. In this regard, the slats are assumed to be perfect diffusers and hence transmit and reflect diffusely any beam solar radiation that is incident in a slat. As a first approximation, the slats are assumed to be flat with negligible thickness. A secondary goal, therefore, is to increase the accuracy of the results by adding a curvature correction. Such a correction should prevent the model from over-predicting
directly transmitted irradiation when the profile and slat angles are aligned. A more recent comparison between flat and curved slat models to experimental data by Platzer [11] further suggests an increase in accuracy of curved slat models.

Methodology

Solar optical properties of a venetian blind layer are determined by considering an enclosure which is representative of an entire blind layer. Figure 1(a) shows a typical enclosure of a venetian blind where $s$ is the slat separation, $w$ is the slat width and $\phi$ is the slat angle. The optical properties of the venetian blind are functions of the slat geometry and the slat material optical properties. Optical properties pertaining to beam radiation are also dependent on the solar profile angle, $\Omega$. Some simplifications are incorporated in the models by making the following assumptions:

- The slats are flat with negligible thickness
- Incident diffuse radiation is isotropic

The following observations and inherent features of the slats also lead to further simplifications of the models:

- The slats reflect beam radiation diffusely.
- The slats transmit beam radiation diffusely if at all.

The optical property models for the venetian blind pertaining to incident beam radiation require the beam-diffuse reflectance of the upward-facing and downward-facing slat surfaces ($\rho^{s}_{u,bd}$ and $\rho^{s}_{d,bd}$) as well as the beam-diffuse transmittance of the slats ($\tau^{s}_{bd}$). For incident diffuse radiation, the diffuse-diffuse reflectance of the upward-facing and downward-facing slat surfaces is required ($\rho^{s}_{u,dd}$ and $\rho^{s}_{d,dd}$) as well as the diffuse-diffuse
transmittance of the slats ($\tau_{dd}$). From the assumption that slats are perfect diffusers, it follows that $\rho^s_{u,bd} \cdot \rho^s_{d,bd}$ and $\tau^s_{bd}$ are independent of the angle of incidence and hence $\rho^s_{u,bd} = \rho^s_{u,dd}$, $\rho^s_{d,bd} = \rho^s_{d,dd}$ and $\tau^s_{bd} = \tau^s_{dd}$. Moreover, since there is no beam-beam transmission or reflection, $\tau^s_{bb} = 0$, $\rho^s_{u,bb} = 0$ and $\rho^s_{d,bb} = 0$. Consequently, the only slat material optical properties required as inputs to the blind model are $\rho^s_{u,bd}$, $\rho^s_{d,bd}$ and $\tau^s_{bd}$.

**Beam-Beam Solar Optical Properties**

The beam-beam transmittance of the shade layer is the ratio between the beam radiation that passes through the slat openings and the incident beam radiation. This is purely a geometric property. From Fig.1(a), the front beam-beam transmittance is

$$\tau_{f,bb} = \frac{s-h}{s}$$

(1)

It can be shown that the front beam-beam transmittance is also given by the expression,

$$\tau_{f,bb} = \frac{d-w}{de}$$

(2)

where

$$de = s \left| \frac{\cos(\Omega)}{\sin(\Omega+\phi)} \right|$$

(3)

Equations (1) to (3) are based on the assumption that the slat thickness is zero. A similar calculation can be used to obtain the back beam-beam transmittance, $\tau_{b,bb}$, by considering beam radiation incident on the back surface of the venetian blind layer. However, by
symmetry, $\tau_{b,bb}$ is readily obtained by using the same formulae for calculating $\tau_{f,bb}$ with a negative slat angle.

**Beam-Diffuse Solar Optical Properties**

The beam-diffuse calculation is subdivided into two categories depending on whether the slats are fully or partially illuminated. For fully illuminated slats, the representative enclosure comprises four surfaces as shown in Fig. 1(a). Partially illuminated slat surfaces on the other hand give rise to a six-surface enclosure as shown in Figure 1b.

**Four-Surface Model**

As shown in Figure 1a, beam radiation incident on surface $w_4$ is reflected diffusely. Furthermore, a portion of the beam radiation incident on surface $w_4$ is diffusely transmitted. Diffuse radiation present within the enclosure will also be transmitted and reflected diffusely by the slats. The following definitions apply:

- $J_i$ is the radiosity of surface $i$
- $G_i$ is the irradiance on surface $i$
- $Z_i$ is the diffuse source term due to incident beam radiation on surface $i$.

From the definitions of $J$, $G$, and $Z$, the following equations can be written:

$$J_3 = Z_3 + \rho_{d,bd}^s G_3 + \tau_{bd}^s G_4$$  \hspace{1cm} (4)

$$J_4 = Z_4 + \tau_{bd}^s G_3 + \rho_{a,bd}^s G_4$$  \hspace{1cm} (5)

$$G_i = \sum_{j=1}^{4} F_{ij} J_j \text{ for } i = 1 \text{ to } 4$$  \hspace{1cm} (6)
The view factor, $F_{ij}$, is the fraction of diffuse radiation leaving surface $i$ that is intercepted by surface $j$, and can be determined by Hottel’s crossed string rule.

Since there is no incident diffuse radiation at the front and back surfaces of the enclosure, $J_1 = J_2 = 0$. The diffuse source terms, $Z_3$ and $Z_4$ can be computed for two different cases:

If incident beam radiation, $I_{beam}$, hits the upward-facing slat surfaces, then

$$Z_3 = 	au_{bd}^i \frac{s}{de} I_{beam}$$  \hspace{1cm} (7)  

$$Z_4 = \rho_{u, bd}^i \frac{s}{de} I_{beam}$$  \hspace{1cm} (8)

If incident beam radiation hits downward-facing slat surfaces, then

$$Z_3 = \rho_{d, bd}^i \frac{s}{de} I_{beam}$$  \hspace{1cm} (9)  

$$Z_4 = \tau_{bd}^i \frac{s}{de} I_{beam}$$  \hspace{1cm} (10)

Equations (4) to (6) are solved to obtain all the radiosities $J_j$. In these equations, $I_{beam}$ is set to unity and the front beam-diffuse transmittance and reflectance of the blind layer are

$$\tau_{f, bd} = G_2$$  \hspace{1cm} (11)

$$\rho_{f, bd} = G_1$$  \hspace{1cm} (12)
Six-Surface Model

Each slat surface is divided into two segments in order to distinguish between the illuminated and shaded portions of the slat with respect to beam radiation. Following a similar methodology described for the four-surface model, the following equations are written for the six-surface model

\[
J_3 = Z_3 + \rho_{d, bd}^s G_3 + \tau_{bd}^s G_4
\]  
(13)

\[
J_4 = Z_4 + \tau_{bd}^s G_5 + \rho_{u, bd}^s G_4
\]  
(14)

\[
J_5 = Z_5 + \rho_{d, bd}^s G_5 + \tau_{bd}^s G_6
\]  
(15)

\[
J_6 = Z_6 + \tau_{bd}^s G_5 + \rho_{u, bd}^s G_6
\]  
(16)

\[
G_i = \sum_{j=1}^{6} F_{ji} J_j \quad \text{for} \ i = 1 \text{ to } 6
\]  
(17)

Because there is no incident diffuse radiation on the front and back surfaces of the enclosure, \(J_1 = J_2 = 0\). Also, for the configuration shown in Fig. 1(b), surfaces \(w_5\) and \(w_6\) are shaded from beam radiation and therefore the source terms, \(Z_5 = Z_6 = 0\). The diffuse source terms, \(Z_3\) and \(Z_4\) are computed using Eqs. (7) to (10). After solving Eqs. (13) to (17) for all the \(J_j\) terms, the front beam-diffuse transmittance and reflectance are calculated from Eqs. (11) and (12).

A similar analysis is used to determine the back beam-diffuse transmittance and reflectance of the blind by considering beam radiation incident on surface \(w_2\) in Figs. 1(a)
and 1(b). However, by symmetry, $\tau_{b, bd}$ and $\rho_{b, bd}$ are readily obtained by using the same formulae for calculating $\tau_{f, bd}$ and $\rho_{f, bd}$ with a negative slat angle.

**Diffuse-Diffuse Solar Optical Properties**

The diffuse-diffuse transmittance and reflectance of the blind are calculated using the four-surface model shown in Fig.1(c). For diffuse radiation incident on the front surface of the enclosure, $I_{diff}$, the following equations can be written

\[ J_i = I_{diff} \quad (18) \]

\[ J_2 = 0 \quad (19) \]

\[ J_3 = \rho_{d, dd}^s G_3 + \tau_{dd}^s G_4 \quad (20) \]

\[ J_3 = \rho_{d, dd}^s G_3 + \tau_{dd}^s G_4 \quad (21) \]

\[ G_i = \sum_{j=1}^{4} F_{ij} J_j \quad \text{for } i = 1 \text{ to } 4 \quad (22) \]

Equations (18) to (22) are solved to obtain all the radiosities. In solving these equations, $I_{diff}$ is set to unity and the front diffuse-diffuse transmittance and reflectance are

\[ \tau_{dd} = G_2 \quad (23) \]

\[ \rho_{f, dd} = G_i \quad (24) \]

Recall that $\rho_{w, bd}^s = \rho_{w, dd}^s$, $\rho_{d, bd}^s = \rho_{d, dd}^s$ and $\tau_{bd}^s = \tau_{dd}^s$. 

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The back diffuse-diffuse reflectance is calculated in a similar manner by setting \( J_2 = I_{\text{diff}} = 1 \) and \( J_1 = 0 \). However, by symmetry, \( \rho_{b,dd} \) are readily obtained by using the same formulae for calculating \( \rho_{f,dd} \) with a negative slat angle.

**Curvature Correction**

One deficiency inherent in solar optical models for venetian blinds is the flat-slat, zero-thickness assumption. Under this assumption, there is 100% transmission as the profile angle (\( \Omega \)) and slat angle (\( \phi \)) come into line (i.e., as \( \Omega + \phi \) approaches zero). In reality, most aluminum, steel and polymer-based venetian blinds have slats that are curved to provide longitudinal rigidity, and this curvature blocks some solar radiation.

Figure 2 shows the effect of slat curvature for cases where \( \Omega + \phi \geq 0 \). In the topmost comparison, the blockage of both the flat and curved slats would be identical. While slat curvature will effect reflected-thru irradiation, the projected cross section of the slat is identical in both cases. In the bottom case, there will be a significant difference in the projected cross section. Between these two angles, the curvature should provide some additional blockage of irradiation.

The effect of the flat-slat zero-thickness combination on the blind's properties is clearly demonstrated by comparing model results to experiments (Jiang and Collins [12]). The model predicts 100% transmission when \( \Omega + \phi = 0 \), and comes into better agreement with experimental results as \( \Omega + \phi \) move away from zero. When \( \Omega + \phi \) is sufficiently large, the flat-slat, zero-thickness assumption no longer has a significant impact on the predicted results. In comparing the experiments of Jiang and Collins [12] and the model results of Kotey and Wright [13], modeled predictions can be as much as 10% greater than
measurements when $\Omega + \phi = 0$. This translates into higher solar gain predictions by models having flat slat assumption built into them. Practically, this over prediction applies over a range of about $\Omega + \phi = \pm 13$ deg.

In developing a curvature correction, the slat is first assumed to be a perfect arc of radius, $r$, and included angle, $\theta_s$ (Fig. 3). The radius and included angle can be determined in a number of ways. It is suggested, however, that the thickness of curvature, $t$, and the actual width, $w$, be measured. $\theta_s$ and $r$ can then be solved using

$$r \sin(\theta_s/2) = w/2 \quad r \cos(\theta_s/2) = r - t \quad (25)$$

For the 15mm blind slats used in this study, $\theta_s = 26.6^\circ$ and $r = w/0.46$.

The first step in developing a curvature correction is to determine when the slat curvature has an effect on the slat's blockage. The assumption of the slat as a perfect arc makes this calculation relatively easy. As can be seen in Fig. 3, the curvature of the slat will have an impact when the profile angle, $\Omega + \phi$, is between $\pm \theta_s/2$. Mathematically

$$|\Omega + \phi| < \theta_s/2 \quad (26)$$

Once the need for a curvature correction is confirmed, the second step is to locate the $x$ and $y$ coordinates for a number of intermediate calculation points (Fig.4). The need for these points will be demonstrated. The coordinate system is defined such that the $x$-direction is always along the slat (AB) while the $y$-direction is perpendicular to it. The origin is located at the centre of the circle that would be created if the slat arc continued.
for 360°. In keeping with this coordinate system, the incident direction is the profile angle.

- Point A: is the leading edge of the slat (side towards the irradiation). It is located at

\[ x_A = r \sin(-\theta_s/2) \quad y_A = r \cos(-\theta_s/2) \]  \hspace{1cm} (27)

- Point B: is the trailing edge of the slat (side away from the irradiation). It is located at

\[ x_B = r \sin(\theta_s/2) = -x_A \quad y_A = r \cos(\theta_s/2) = y_B \]  \hspace{1cm} (28)

- Point C: is the point where the ray is tangent to the slat surface. It is located at

\[ y_C = r \cos(\phi + \Omega) \]

\[ x_C = \sqrt{r^2 - y_C^2} \text{ for } \Omega + \phi > 0 \]  \hspace{1cm} (29)

\[ x_C = -\sqrt{r^2 - y_C^2} \text{ for } \Omega + \phi < 0 \]

- Point D: is the intersection of a ray that passes point A (top lit: \( y = mx + b_A \)) or B (bottom lit: \( y = mx + b_B \)) and the radial line from point C (\( y = -x/m \)). In the case of a top-lit slat, therefore,

\[ x_D = \frac{y_A - mx_A}{1 - \frac{1}{m}} \]

\[ y_D = mx_D + b_A = -\frac{1}{m} x_D \]  \hspace{1cm} (30)

where \( m = -x/y \) is the slope of the incident ray with respect to the coordinate axis.

For a bottom-lit slat,
\[ x_D = \frac{y_B - mx_B}{\frac{1}{m} - m} \]

\[ y_D = mx_D + b_B = -\frac{1}{m} x_D \quad (31) \]

and \( m = x/y \). To avoid a division by zero error, when \( m = 0 \) (at \( \Omega + \phi = 0 \)), \( x_D = 0 \) and \( y_D = y_A \).

- Point E: is found in the same way as point D, except that a ray passing Point B is used in the top-lit case, and a ray passing point A is used in the bottom-lit case. For the top-lit slat, therefore,

\[ x_E = \frac{y_B - mx_B}{\frac{1}{m} - m} \]

\[ y_E = mx_E + b_B = -\frac{1}{m} x_E \quad (32) \]

where \( m \) is equal to \(-x/y\). For a bottom-lit slat,

\[ x_E = \frac{y_A - mx_A}{\frac{1}{m} - m} \quad (33) \]

and \( m = x/y \). To avoid a division by zero error, when \( m = 0 \) (at \( \Omega + \phi = 0 \)), \( x_E = 0 \) and \( y_E = y_A \).

- Point F: is the intersection of a ray passing point E, and the slat itself. For a top-lit slat
\[ x_F = x_B - |x_B - x_E| \cdot 2 \]

\[ y_F = \frac{x_F}{m} \tag{34} \]

where \( m \) is equal to \(-x/y\). For a bottom-lit slat,

\[ x_F = x_A + |x_A - x_E| \cdot 2 \]

\[ y_F = -\frac{x_F}{m} \tag{35} \]

It is desirable to continue to use the existing solution engine (flat slat model) in an adapted form. To do so, however, some further understanding of the existing solution engine is required. In the original calculation, the length of the region that is directly irradiated along the slat (\( de^* \)) is determined. In applying the curved assumption, it is first necessary to 'flatten' the irradiated portion of the curved slat. The coordinate definition presented in Fig. 5 makes this a relatively simple process. The length \( de^* \) is approximately the \( \Delta x \) of the lit surface. In doing this, it is assumed that the effect of curvature on the first diffuse reflection is not significant. A more significant concern is the physical meaning of \( de^* \) in the original model. When \( de^* \) is less than \( w \), the beam-beam transmission is set to zero. Likewise, when \( de^* \) is greater than \( w \), beam-beam transmission is \((de^* - w)/de^*\). Due to the curved slat, however, \( de^* \) can be less than \( w \), while beam-beam transmission still exists. Two measures are required to account for this. A beam-beam transmission can still be calculated based on the projected thickness of the slat in a plane perpendicular to the direction of irradiation. More significantly, however, is that for \( de^* < w \), the original calculation assumes 100% of the irradiation is on the slat.
Therefore, when sending a value of $de^*$ that is less than $w$, knowing that beam-beam transmission still exists, it is a simple matter of multiplying the results of the solution routine by the percentage of irradiation that actually falls on the slat.

For a top-lit slat, the aforementioned modifications are fairly simple to implement. When $\Omega + \Phi < 0$

$$de^* = x_c - x_A$$  \hspace{1cm} (36)$$

$$\tau_{f,bb} = \frac{s \cos(\Omega) - L_{CD}}{s \cos(\Omega)}$$  \hspace{1cm} (37)$$

$$\Lambda = \frac{L_{CD}}{s \cos(\Omega)}$$  \hspace{1cm} (38)$$

All results from the solution routine, fed $de^*$, are subsequently multiplied by weighting, $\Lambda$. $L_{CD}$ is the distance between Points C and D, and is given by

$$L_{CD} = \sqrt{(x_c - x_D)^2 + (y_c - y_D)^2}$$  \hspace{1cm} (39)$$

A bottom-lit slat is slightly more complex due to the fact that it will be irradiated both on the top and bottom of the slat surface. In this case, Eqs. (37) and (39) can still be used to determine beam-beam transmission. For the irradiation on the slat top, $de_1^*$ is still given by Eq. (36), and the weighting factor becomes

$$\Lambda_1 = \frac{L_{CE}}{s \cos(\Omega)}$$  \hspace{1cm} (40)$$

For the irradiation falling on the underside of the slat,

$$de_2^* = x_b - x_f$$  \hspace{1cm} (41)$$

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\[ A_2 = \frac{L_{DE}}{s \cos(\Omega)} \]  

(42)

Here, \( L_{DE} \) and \( L_{CE} \) are the distance between points D and E, and C and E respectively, and are calculated in a similar manner to which \( L_{CD} \) was determined. Further, the results that come from the solution engine are multiplied by the associated weighting factor, and then summated. The beam-diffuse transmission, for example, is given by

\[
\tau_{f,\text{bd}} = A_1 \tau_{f,\text{bd},1} + A_2 \tau_{f,\text{bd},2} 
\]

(43)

where \( \tau_{f,\text{bd},1} \) and \( \tau_{f,\text{bd},2} \) are the values output from the original solution engine.

At high slat angles (venetian blind in an almost closed position), double blockage could occur when curvature correction is applied to the flat slat model as the profile angle (\( \Omega \)) and slat angle (\( \phi \)) come into line (i.e., as \( \Omega + \phi \) approaches zero). Under such conditions, curvature correction gives negative values for beam-beam transmission as well as meaningless values for beam-diffuse transmission and reflection. The problem is easily remedied by setting the beam-beam transmission to zero and using the flat slat model to calculate the beam-diffuse transmission and reflection.

**Slat Thickness Correction**

No attempt was made to correct for slat thickness since the slats of venetian blinds are generally very thin. Furthermore, for very thin slats (with a typical slat thickness to spacing ratio of 0.012), slat thickness correction models developed by Parmelee and Aubele [8] and EnergyPlus [3] show a minimal effect on the effective optical properties of the blind.
Results and Discussion

The simplified solar optical models described in the previous section were used to calculate the effective solar optical properties of a light-colored venetian blind. The slat width, the slat spacing and the slat angle are $w = 15.0$ mm, $s = 12.5$ mm and $\phi = 45^0$, respectively. The slat surface reflectivity ($\rho_{s,dd}$ and $\rho_{d,dd}$) is 0.673 while the slat transmittance, $\tau_{dd}$ is zero (Jiang and Collins [12]).

Figure 6 shows plots of effective solar optical properties versus profile angle of incident beam radiation. The front effective optical properties pertaining incident beam radiation are shown in Fig. 6(a) while the back effective optical properties are shown in Fig. 6(b). With the exception of the beam-beam reflectance which is assumed to be equal to zero, all the optical properties are dependent on the solar profile angle. As seen in Fig. 6(a), the peak value of the beam-beam transmittance occurs at a profile angle of $-45^0$ when the edges of the slats are aligned with the incident beam radiation and $\Omega + \phi = 0$. For a model which assumes that the slats are flat with negligible thickness, this peak value of transmittance would be equal to 1.0. However, by correcting for slat curvature, the peak value was estimated to be 0.92. The beam-diffuse transmittance and the beam-diffuse reflectance, on the other hand, approach zero at a profile angle of $-45^0$ as expected. This is because when the edges of the slats are aligned with the incident beam radiation, only small portions of the projected surface area of the curved slats are illuminated. Hence the net radiation that leaves the blind enclosure both in the forward direction (transmitted) and the backward direction (reflected) are expected to be very small. The beam-diffuse transmittance peaks at two profile angles corresponding to a beam-beam transmittance of zero as seen in Fig. 6(a). A similar trend is depicted in Fig. 6(b) for the back effective
optical properties of the blind. By observation, the plots for the back effective optical properties are mirror images of the front effective optical properties about the y-axis (profile angle equal to zero). This is not surprising since by symmetry, the back effective optical properties are obtained by using the same formulae for calculating the front effective optical properties with a negative slat angle, and the slats have the same reflectance on both sides.

Figure 7 shows the variation of the effective optical properties with slat angle for incident diffuse radiation. In this particular simulation, the front effective optical properties have the same values as the back effective optical properties and hence only the front effective optical properties plots are shown in Fig. 7. As expected, the effective diffuse-diffuse reflectance of the blind increases with increasing slat angle while the diffuse-diffuse transmittance decreases with increasing slat angle. The maximum reflectance is obtained when the slat angle is equal to ±90°. Since the slats are opaque, it is expected that the effective transmittance of the blind goes to zero at slat angles equal to ±90°. However, the four-surface model chosen in this study gives a false effective transmittance because the slats overlap when the slat angle is equal to ±90°. This false transmittance can easily be remedied by using a six-surface model as observed by Yahoda and Wright [14]. Nonetheless, a four-surface model with inherent simplifications will produce the desired accuracy for building energy simulation since commercially available blinds cannot be closed beyond slat angles greater than ±75°. The minimum value of the effective diffuse-diffuse reflectance is obtained when the blind is fully opened blind (slat angle equal to zero) with a correspondingly high (maximum) diffuse-diffuse transmittance.
Consideration will now turn to the comparison between experimental results and the simplified optical property models discussed in the previous section. The experiments were performed using the Broad Area Illumination – Integrating Sphere (BAI-IS) located at the University of Waterloo's Solar Thermal Research Laboratory (Fig. 8). The BAI-IS operates in a similar manner to other integrating spheres with a few key differences. The test sample is typically far larger than the sphere aperture and is fully illuminated by the light source. The sphere itself is 50 cm in diameter and has a 5 cm diameter aperture. With these modifications, it is possible to test materials that have relatively large scale non-homogeneity. Full details of the BAI-IS and test methodology can be found in [2,12,15].

Slats from a commercially available mini-blind were employed for this experiment. The slats were 15 mm wide, 0.17 mm thick, and white in color. Small slats were chosen because of the size of the slat in relation to the integrating sphere aperture. The more slats in the aperture area, the more homogenous the sample becomes. To cover a broader range of cases, a set of flat black slats were produced by spraying black paint over the original white slats. The black slats represent an extreme condition, and it was used solely to test the capabilities of the model. The total specular and diffuse solar properties of the slats were found to be $\rho_s=0.3$ and $\rho_d=12.3$ for the black slats; and $\rho_s=1.9$ and $\rho_d=65.4$ for the white slats. Details of the test samples can be found in [2,12].

Figure 9 shows the results of this curvature correction applied to the total transmittance through the blinds. It is imperative to note that the total transmittance used in this context is the sum of the beam-beam and the beam-diffuse transmittance. In all cases, the
predicted total transmittance using the curved slat model falls more closely in line with experimentally determined results than the flat slat model.

**Conclusions**

The importance of modelling complex fenestration systems in annual energy simulation programs lies in the need to predict the energy savings potential for various shading devices. In the current study, simplified models are used to calculate the effective solar optical properties of venetian blinds by considering an enclosure which is representative of the entire blind layer. The slats are assumed to transmit and reflect beam radiation diffusely. In addition, the optical properties of the slats are assumed to be independent of the angle of incidence. As a first approximation, the slats are assumed to be flat with negligible thickness. A novel curvature correction is then applied to the flat slat model. The results of the flat slat and the curved slat models are compared with experimental results on commercially available venetian blinds. The curved slat model matches the experimental results more closely than the flat slat model. The simplified calculation procedures therefore produce results that can serve as useful input to building load, and annual energy calculation and rating tools.

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**Nomenclature**

\[ \phi \]  \quad \text{Slat angle}
\( \theta_s \) Angle formed between two radii of curvature that intercepts the edges of the slats

\( \Omega \) Profile angle

\( \rho \) reflectance

\( \tau \) transmittance

\( G \) Irradiation

\( F_{ij} \) View factor from surface \( i \) to surface \( j \)

\( J \) Radiosity

\( Z \) Diffuse source term due to beam radiation

\( r \) Radius of the arc formed by a curved slat surface

\( t \) Thickness of slat curvature

\( w \) Slat width

\( s \) Slat spacing

\( I \) Incident radiation

Subscripts

\( b \) effective back property of blind layer

\( bb \) beam-to-beam property

\( beam \) beam radiation

\( bd \) beam-to-diffuse property

\( d \) downward side property of blind material

\( dd \) diffuse-to-diffuse property

\( diff \) diffuse radiation

\( f \) effective front property of blind layer
upward side property of blind material

Superscripts

s  slat material

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