COMPARATIVE ANALYSIS OF ONE-DIMENSIONAL SLAT-TYPE BLIND MODELS

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ABSTRACT

Slat-type blinds, such as Venetian blinds, are the most commonly used shading devices for controlling solar heat gain. This study presents a comparative analysis of three one-dimensional, optical slat-type blind models suitable for building load calculations. The influence of input parameters on the predicted solar transmittance is investigated. The models are also compared to experimental data. Furthermore, the effect of the blind on building thermal loads is investigated. The results indicate that there is a need for a comprehensive optical blind model that includes advantageous features from each of the three models. In addition, a general thermal fenestration model that predicts the thermal interaction of the fenestration system having the blind with the conditioned space is needed in order to utilize one-dimensional blind models in thermal load and energy calculations.

INTRODUCTION

The use of solar shading devices is an important strategy in energy conscious building design. Correctly designed shading systems can optimally provide natural light as well as effectively reduce building heat gains and cooling requirements. However, a detailed knowledge of the optical and thermal properties of the shaidng devices is an essential prerequisite of optimal fenestration system design. It is therefore necessary to have detailed simulation models that can reliably predict and quantify the performance of shading devices for all locations and seasons.

Slat-type shading devices, such as Venetian blinds, are popular because they are relatively inexpensive and can provide occupant privacy. They can also be used to provide glare control to improve visual comfort. Typically, two models are used to characterize the fenestration system containing slat-type blinds: optical and thermal models. The optical (or solar) model determines how much solar (or short-wave) radiation is transmitted through the fenestration system, reflected back outside, and absorbed by each layer of the system. The thermal model determines thermal interactions within layers of the fenestration system, between outermost layer(s) and the outdoor environment, and between the innermost layer(s) and the indoor environment. To complete the heat transfer calculation, the thermal model needs to know the rate at which solar radiation is absorbed by each layer of the fenestration system. This information is provided by the optical model.

To estimate optical properties of the fenestration system, the current standard approach is based on the so-call multi-layer approach [Klems et al. 1995, van Dijk and Goulding 1996, and Rosenfeld et al. 2000]. With this approach, optical properties of the fenestration system can be determined as a function of the optical properties of its individual components. Optical properties of individual components of the fenestration system are inputs to the optical fenestration model and can be determined by measurements and/or detailed mathematical models. Mathematical models are preferable since they can easily be used to study the effect of input parameters on fenestration components over a range of conditions [Rosenfeld et al. 2000].

This study focuses on models used to predict solar-optical properties of slat-type blinds. The main objective is to investigate and identify weaknesses in existing optical blind models suitable for incorporating into a building simulation tool. The study compares three one-dimensional, optical blind models suitable for building load calculations [Parmelee and Aubelee 1952, Pfrommer et al. 1996, and Simmler et al. 1996] – and investigates the influence of input parameters on the solar transmittance. The models are also compared to experimental data. The effect of the blind on building thermal loads is investigated as well.

LITERATURE REVIEW

The earliest attempt to analyze optical characteristics of slat-type blinds was possibly made by Parmelee and Aubelee [1952]. They presented two optical blind models: one for a specular-reflecting slat surface and one for a diffuse-reflecting slat surface. Their models are discussed in detail in the next section. In their subsequent paper, Pamelee et al. [1953] validated their models with experimental data obtained by means of the solar calorimeter. They later used their models to develop design data for use in determining the solar heat gain [Parmelee and Vild 1953]. Several researchers [Ozisik and Schutrum 1960; Farber et al. 1963; and Collins and Harrison 2004] utilized Parmelee's models to study energy performance of various fenestration systems containing slat-type blinds.

Like Parmelee and Aubelee, Pfrommer et al. [1996] developed optical blind models for both specular- and diffuse-reflecting slat surfaces. However, they combined their two models into a single model that can describe slat surfaces that are neither purely specular nor purly diffuse. Their models are discussed in detail in the next section.

Rosenfeld et al. [2000] discussed two optical blind models recently developed by European researchers. The first model, called the WIS model developed by van Dijk and Goulding [1996], is an optical model applicable only for blinds with a diffuse-reflecting slat surface. The WIS model is conceptually similar to Simmler's model [1996], which is described in detail in the next section. The only significant difference between the two models is that slat surfaces are divided into more elements in the WIS model than in Simmler's model (i.e. 5 elements versus 2 elements). The WIS model is currently incorporated in the ISO standard [ISO 2000]. The other model, called the simple model developed by Breitenbach et al. [2001], is based on the observation that the distribution of radiation reflected from the slat is not uniform and the peak occurs at the specular-reflecting direction. Rosenfeld et al. [2000] showed that the simple model, which accounts for the quasi-specular behavior of the blind, had a better agreeement with experimental results than the WIS model, which assumes purely diffuse slat surfaces. The simple model, however, was developed specifically for product-rating purposes; hence, the model only predicts blind optical properties for direct solar radiation (e.g. the directional-hemispherical blind transmittance) and is only applicable for normal incident light. The model is therefore not suitable for incorporating in a building simulation tool.

COMPARATIVE ANALYSIS

This study investigates three selected optical slat-type blind models – the Parmelee, Pfrommer, and EnergyPlus models [Parmelee and Aubelee 1952; Pfrommer et al. 1996; and DOE 2002] – that are suitable for use in a buidling energy simulation program. A brief overview of the Parmelee and Pfrommer models is given in the previous section. The EnergyPlus model was originally developed by Simmler et al. [1996] for the DOE-2 building energy calculation program [Winkelmann et al. 1993]. The EnergyPlus model is only applicable for blinds with diffuse-reflecting slat surfaces. In this section, fundamental calculations of the three models are compared in detail.

Common Basic Assumptions

All three models consider the blind assembly as a series of equidistant slats. The slats are assumed to be of infinite length. Then, in a theoretical analysis, the whole blind assembly is represented by two consecutive slats. The models are considered to be one-dimensional optical blind models since the models predict the amount of solar radiation transmitted through the blind assembly, but do not determine where the transmitted solar radiation falls in the room, which would require a 3-D ray tracing technique.

Calculation Procedures for Direct Solar Radiation

All three models similarly divide the calculation procedure for direct solar radiation into two parts. The first part of the calculation procedure deals with directly transmitted radiation and is purely a geometry problem. The ratio of the unobstructed solar radiation passing through the blind to the incident solar radiation is called the opening ratio by Parmelee and Aubele [1952]. This opening ratio is generally referred to as the 'direct-to-direct transmittance' of the blind [Pfrommer et al. 1996; and DOE 2002]. For flat slats of negligible thickness, all three models predict exactly the same direct-to-direct blind transmittance. However, when either slat thickness or slat curvature is accounted for, the predicted results are slightly different. Later sections discuss how the three models apply corrections to take into account slat thickness and slat curvature.

The second part of the calculation procedure deals with reflected radiation. The EnergyPlus model [DOE 2002] assumes that the slat surface is purely diffuse. Parmelee and Aubele [1952] present two optical blind models: one for a specular reflecting surface and one for a diffuse reflecting surface. Pfrommer et al. [1996] also present algorithms for both specular and diffuse reflecting surfaces but they combined the algorithms into a single model that can describe surfaces that are neither purely specular nor purely diffuse. The Pfrommer model uses a "shining factor" [Pfrommer et al. 1996], defined as the ratio between the diffuse-reflected and the total-reflected components, to specify the diffuseness of the blind slat. The shining factor is one for purely diffuse surfaces and zero for purely specular surfaces.

Both the Parmelee and Pfrommer models consider infinite reflections between slats in calculating the reflected solar radiation for purely specular slat surfaces. Parmelee and Aubele [1952] and Pfrommer et al. [1996] utilize the 2-D ray tracing technique to obtain analytical solutions for specular reflecting surfaces. A preliminary investigation showed that although the Parmelee and Pfrommer models use different formulations, the results predicted by Parmelee's specular reflecting model and Pfrommer's model using a shining factor of zero were exactly the same. In this study, the effect of specularly reflecting surfaces was not further investigated.

Using the 2-D ray tracing technique, Parmelee and Aubele [1952] and Pfrommer et al. [1996] also present their diffuse reflecting surface models in an analytical form. However, Parmelee and Aubele consider infinite reflections between slats whereas Pfrommer et al. consider only two reflections. To determine optical properties due to reflected solar radiation, the EnergyPlus model [DOE 2002] employs the net radiation method to solve (solar) radiative energy exchange within an enclosure formed by the outside opening, two slats and the inside opening. Each slat is divided into two elements (illuminated and shaded elements), which vary depending on sunlit area due to incident direct sunlight. To solve radiative energy exchange within the enclosure, only the illuminated element emits energy while all other surfaces have zero emissive power. As previously mentioned, the EnergyPlus model is conceptually silmilar to the WIS model [van Dijk and Goulding 1996], except that the WIS model divides each slat into five elements.

Predicted Direct Solar Transmission

In this study, direct-to-direct transmittance is defined as the fraction of beam solar radiation passing directly through the blind assembly without hitting the slats. Direct-to-diffuse transmittance is defined as the fraction of beam solar radiation passing indirectly through the blind assembly by reflections between the slats. Both direct-to-direct and direct-to-diffuse transmittances are mainly dependent on the profile angle defined as the angle between a plane perpendicular to the blind assembly (the normal plane) and a plane coincident with the line of sight to the sun (the line of sight plane) [Parmelee and Aubelee 1952]. Figure 1 illustrates the profile angle along with slat geometry. As shown, the slat angle is defined as the angle between the slat and the normal plane. The figure shows a downward facing blind with a positive slat angle. The slat spacing is defined as the distance from the upper surface of the upper slat to the upper surface of the lower slat while the slat width is defined as the distance of a straight line from one end of the slat to the other end as shown in Fig. 1. Using these conventions, the following analysis is for blinds havng horizontal slats.

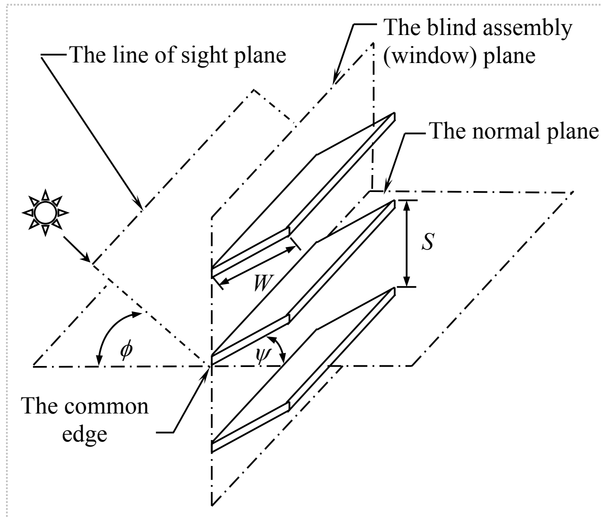

Figure 1 Profile Angle and Slat Geometry (ϕ = the profile angle, ψ = the slat angle, S = the slat spacing, W = the slat width)

Overall optical characteristics of the blind assembly are primarily dependent on the slat angle. Other parameters including slat spacing, slat width, slat reflectance, slat thickness, and slat curvature have a secondary effect on the overall optical characteristics of the blind. Figure 2 illustrates the influence of the slat angle on the blind transmittances. The different profiles for direct-to-direct and direct-to-diffuse transmittances are characteristic of upward facing, downward facing and fully open (horizontal) blinds.

As shown in Fig. 2a for 0° (fully open) and –45° (upward facing) slat angle cases, the peak value of the direct-to-direct transmittance (for the blind having flat slats with zero thickness) is equal to one occurring when the sum of the profile angle and the slat angle is zero. At the same profile angle, the direct-to-diffuse transmittance is then equal to zero as shown in Fig. 2b. Conversely, the peak value of the direct-to-diffuse transmittance occurs at the same profile angle when the direct-to-direct transmittance becomes zero for all three slat angles.

Since all three models predict the same direct-to-direct transmittance, only one set of results is presented in Fig. 2a. As shown in Fig. 2b, the Pfrommer model tends to predict a lower direct-to-diffuse transmittance than the other two models for all slat angles. This is due to the fact that the Pfrommer model considers only two reflections between the slats. On the other hand, both EnergyPlus and Parmelee models predict nearly identical results for all slat angles indicating that the net radiation method employed in the EnergyPlus model and the 2-D ray tracing technique with infinite reflections between slats used in the Parmelee model are equivalent.

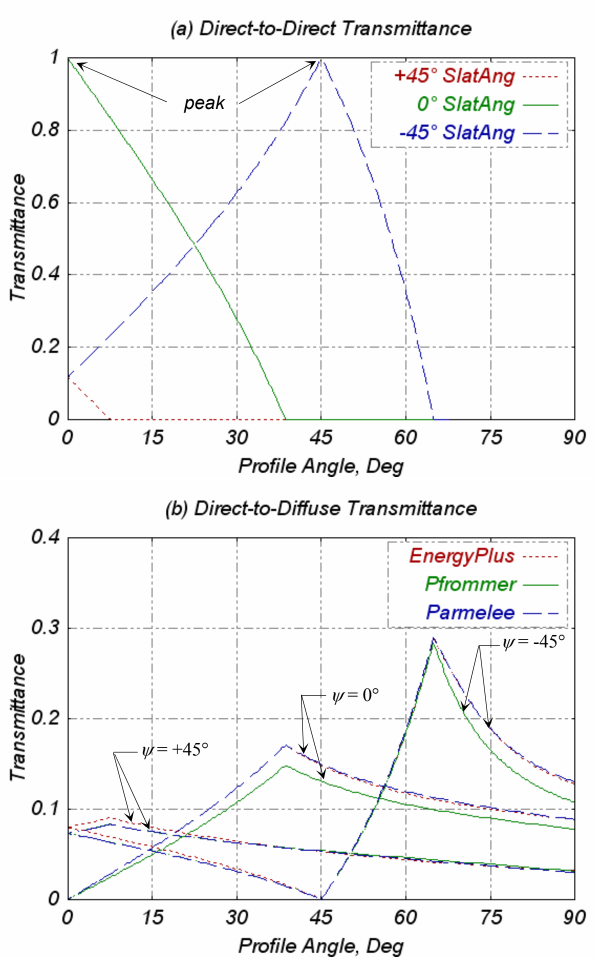

Figure 2 Effect of Slat Angle (for Flat Slat with Zero Thickness, and Slat Reflectance of 0.5): (a) Direct-to-Direct Transmittance, (b) Direct-to-Diffuse Transmittance

As the slat reflectance increases, the effect of the two-reflection treatment in the Pfrommer model becomes more pronounced. Figure 3 shows that there is little difference between the models for a reflectance of 0.1, but a peak error of nearly 25% in the direct-to-diffuse transmittance for a reflectance of 0.9.

Calculation Procedures for Diffuse Solar Radiation

Two primary sources are usually treated in the calculation of diffuse solar radiation: the sky and the ground. In the Parmelee model, a hemisphere in front of the blind assembly is used to represent the sky and ground. The upper half of the hemisphere represents the sky while the lower half of the hemisphere represents the ground. Both the sky and the ground are subdivided into a number of small patches. The diffuse radiation leaving each patch is then treated as direct radiation emitted from the center of the patch to the center of the hemisphere where the blind assembly is located. Consequently, the same procedure used to calculate the direct solar radiation is used to calculate diffuse radiation from each patch. The blind transmittances of the sky (or ground) diffuse solar radiation can thus be determined as the ratio of the total solar radiation transmitted through the blind assembly to the total insolation from the sky (or ground) patches

The sky and ground are also considered as separate sources of diffuse solar radiation in the Pfrommer model. Unlike the Parmelee model, however, the hemisphere representing the sky and ground is divided into horizontal slices instead of patches. The diffuse radiation leaving each slice is treated as the direct radiation emitted from the center of the slice to the center of the hemisphere. A uniform irradiance from the sky and ground slices is used in the Pfrommer model to calculate blind transmittances for diffuse solar radiation. It is important to note that the Pfrommer model was developed for blinds with horizontal slats only. For horizontal slats, all points on the same horizontal sky (or ground) slice have the same profile angle [Pfrommer et al. 1996]. The blind transmittance of diffuse solar radiation can then be determined by integrating along the profile angle. Pfrommer [1995] provides analytical solutions for their diffuse solar radiation model.

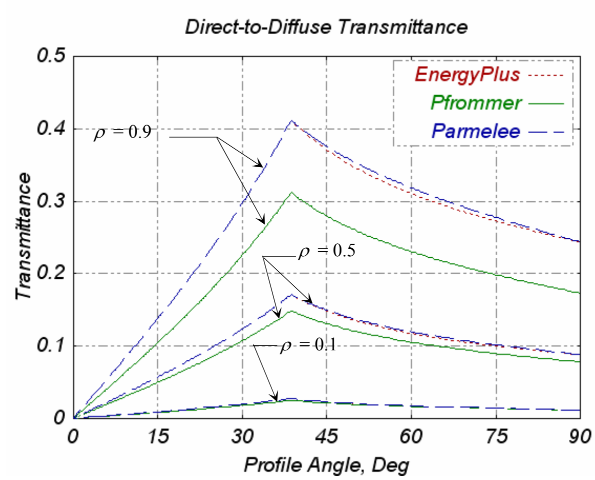

Figure 3 Effect of Slat Reflectance on Direct-to-Diffuse Transmittance (for Flat Slat with Zero Thickness, and Slat Angle of 0°)

Unlike the other two models, the EnergyPlus model does not differentiate between the diffuse solar radiaiton from the sky and the ground. The EnergyPlus model uses the net radiation method for both direct and diffuse solar radiation by specifying energy sources of different magnitudes and at different locations [DOE 2002]. For diffuse solar radiation, each slat is equally divided into two segments. A unit energy source is only applied to the fictitious outside surface while a zero energy source is applied to all other surfaces. The net radiation method is then used to solve diffuse radiative energy balance within the enclosure.

Predicted Diffuse Solar Transmission

To compare the models in this study, all three models predict two blind transmittances for diffuse solar radiation: sky-diffuse and ground-diffuse transmittances. The sky-diffuse transmittance is defined as a fraction of diffuse solar radiation from the sky passing directly and indirectly through the blind assembly. The ground-diffuse transmittance is defined as a fraction of diffuse solar radiation from the ground passing directly and indirectly through the blind assembly. Because the EnergyPlus model does not differentiate between the diffuse solar radiation from the sky and ground, values of sky-diffuse and ground-diffuse transmittances predicted by the EnergyPlus model are always the same.

Diffuse transmittances are plotted as a function of the slat angle in Fig. 4. As shown, the EnergyPlus model predicts a single diffuse transmittance curve because it does not differentiate between the sky-diffuse and the ground-diffuse transmittances. On the other hand, the Parmelee and Pfrommer models predict two curves: one for the sky-diffuse transmittance and one for the ground-diffuse transmittance. As expected, both the Parmelee and Pfrommer models predict higher ground-diffuse transmittance for the blind opened downward (positive slat angle) and higher sky-diffuse transmittance for the blind opened upward (negative slat angle). The three models predict the same sky-diffuse and ground-diffuse transmittances only for fully opened blinds (slat angle of 0°) when the slat opening's view to the sky and ground are equal.

The effect of slat reflectance on diffuse transmittance is shown in Fig. 5. The results are shown for fully opened blinds (slat angle of 0°). As shown, the three models predict similar values of diffuse transmittance for low slat reflectance. Similar to previous results, the two-reflection algorithm used in the Pfrommer model results in a 10% under-prediction of the diffuse transmittance relative to other models at high values of slat reflectance.

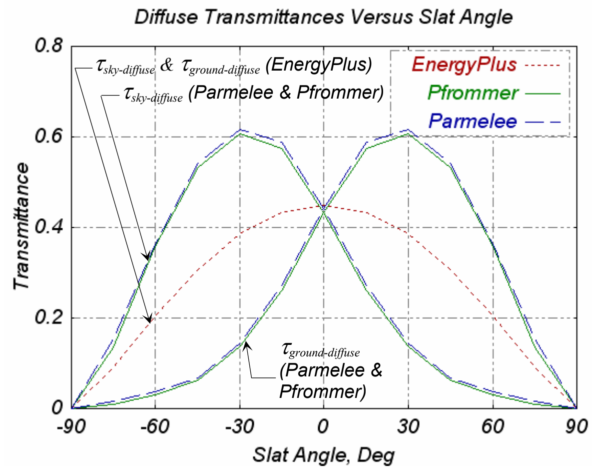

Figure 4 Effect of Slat Angle on Diffuse Transmittance(s) (for Flat Slat with Zero Thickness, and Slat Reflectance of 0.5)

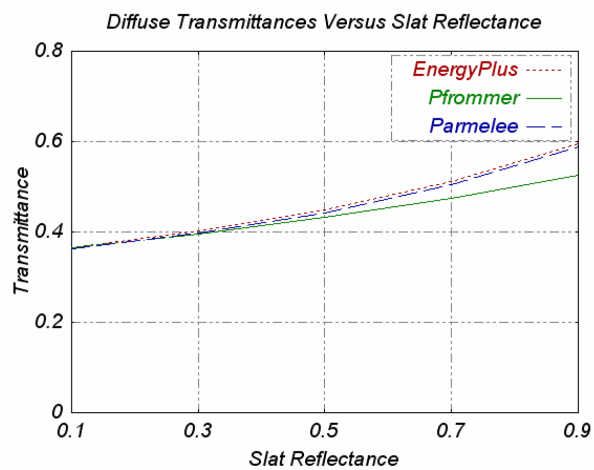

Figure 5 Effect of Slat Reflectance on Diffuse Transmittance(s) (for Flat Slat with Zero Thickness, and Slat Angle of 0°)

Corrections for Slat Thickness

In previouse sections, the calculation procedures assume flat slats with zero thickness. This assumption may introduce a non-trivial error in the results, especially for wood blinds. Only the Parmelee and EnergyPlus models have corrections to take slat thickness into account. Both models define the correction factor for slat thickness as a fraction of the shaded area due to slat thickness. The Parmelee model [Parmelee and Aubele 1952] applies the correction factor only to direct-to-direct and direct-to-diffuse transmittances. Since the calculation procedures for direct solar radiation are utilized to determine blind transmittances for diffuse solar radiation in the

Parmelee model, slat thickness is implicitly accounted for without applying any additional correction to the diffuse transmittances. On the other hand, the EnergyPlus model applies the correction factor to all blind transmittances [DOE 2002].

Figure 6 compares flat, zero thickness slats with flat slats having a slat thickness to slat spacing (T/S) ratio of 0.1. The error associated with neglecting the slat thickness can be as high as 15% for the peak direct-to-direct transmittance. As shown in Fig. 6a, both Parmelee and EnergyPlus models predict exactly the same direct-to-direct transmittances for the 0° slat angle case, but they predict different results for other slat angles depending on the profile angle (the EnergyPlus correction predicts zero direct-to-direct transmittance at all profile angles for the +45° slat angle case). Likewise, the two models predict almost identical direct-to-diffuse transmittances for the 0° slat angle case but they predict quite different results for other slat angle cases as illustrated in Fig. 6b.

Corrections for Slat Curvature

As previously mentioned, the flat slat assumption is used in all three models. Only the Pfrommer model has corrections to account for the effect of slat curvature, and those corrections are only applied to the direct-to-direct and direct-to-diffuse transmittances [Pfrommer 1995].

Figure 7 compares flat, zero thickness slats with curved slats having a slat curvature radius to slat width (R/W) ratio of 1.0. The figure shows results predicted by the Pfrommer flat and curved slat models. As shown, the slat curvature can have a significant effect on both the direct-to-direct and the direct-to-diffuse transmittances depending on the slat and profile angles. The slat curvature has no effect on the direct-to-direct transmittance for +45° slat angle case. However, the curvature correction reduces the peak direct-to-direct transmittance by more than 15% for both 0° and –45° slat angle cases.

COMPARISON WITH EXPERIMENTAL DATA

In this section, the models are compared with experimental data for a west-facing fenestration system with an internal blind [Chantrasrisalai and Fisher 2004]. The primary metric used in this comparison is the total solar transmittance defined as the ratio of total solar radiation transmitted through the fenestration system to total insolation on the outside of the fenestration system. Figure 8 shows measured solar transmittance for white curved-slat blinds oriented at three different slat angles along with results predicted by the three models. The left hand region presents diffuse solar transmittance (in the morning, no incident direct solar radiation on the west-facing fenestration system) while the right hand region shows total solar transmittance.

As shown in the left hand region of Fig. 8, the Parmelee and Pfrommer diffuse models correctly predict the shape of the measured diffuse solar radiation while the EnergyPlus diffuse model does not. The disagreement of the EnergyPlus model is primarily due to neglecting the sky and the ground as separate sources of diffuse solar radiation. Although the EnergyPlus model predicts constant diffuse solar transmittance, discrepancies between the model and measured data are mostly less than 0.05 for all three slat-angle cases.

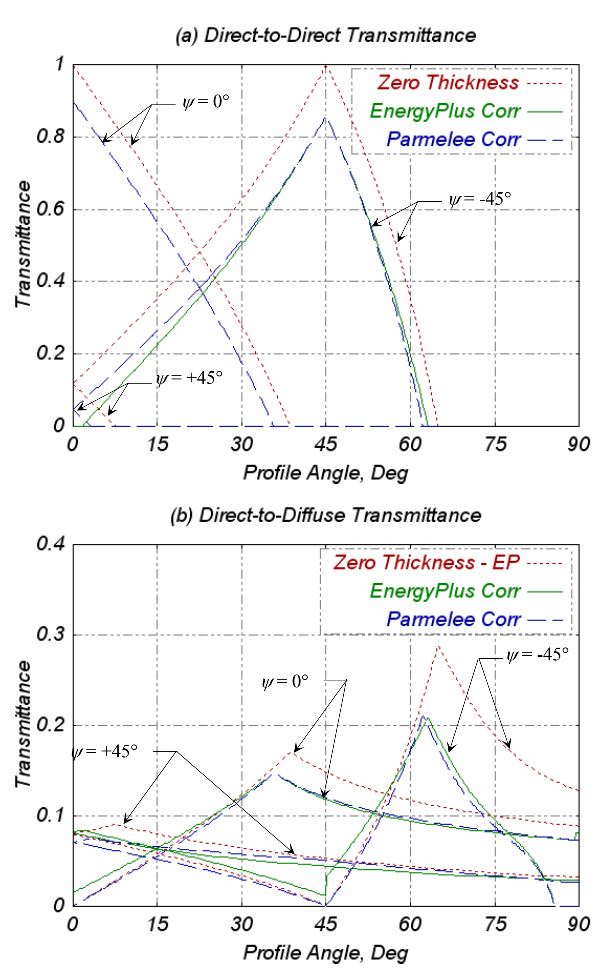

Figure 6 Effect of Slat Thickness (for Flat Slat with T/S Ratio of 0.1 and Slat Reflectance of 0.5): (a) Direct-to-Direct Transmittance, (b) Direct-to-Diffuse Transmittance

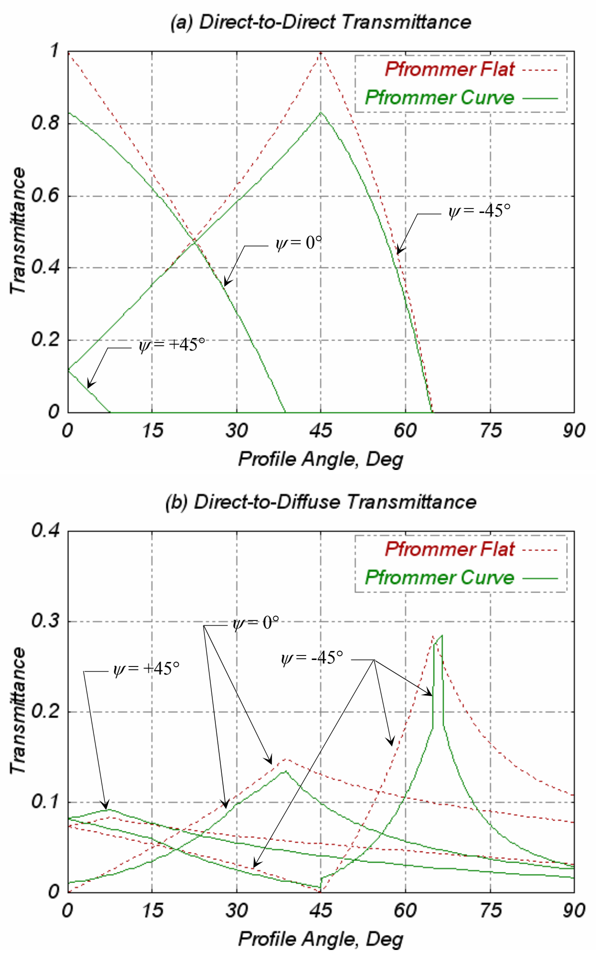

Figure 7 Effect of Slat Curvature (for Curved Slat with R/W Ratio of 1.0 and Slat Reflectance of 0.5): (a) Direct-to-Direct Transmittance, (b) Direct-to-Diffuse Transmittance

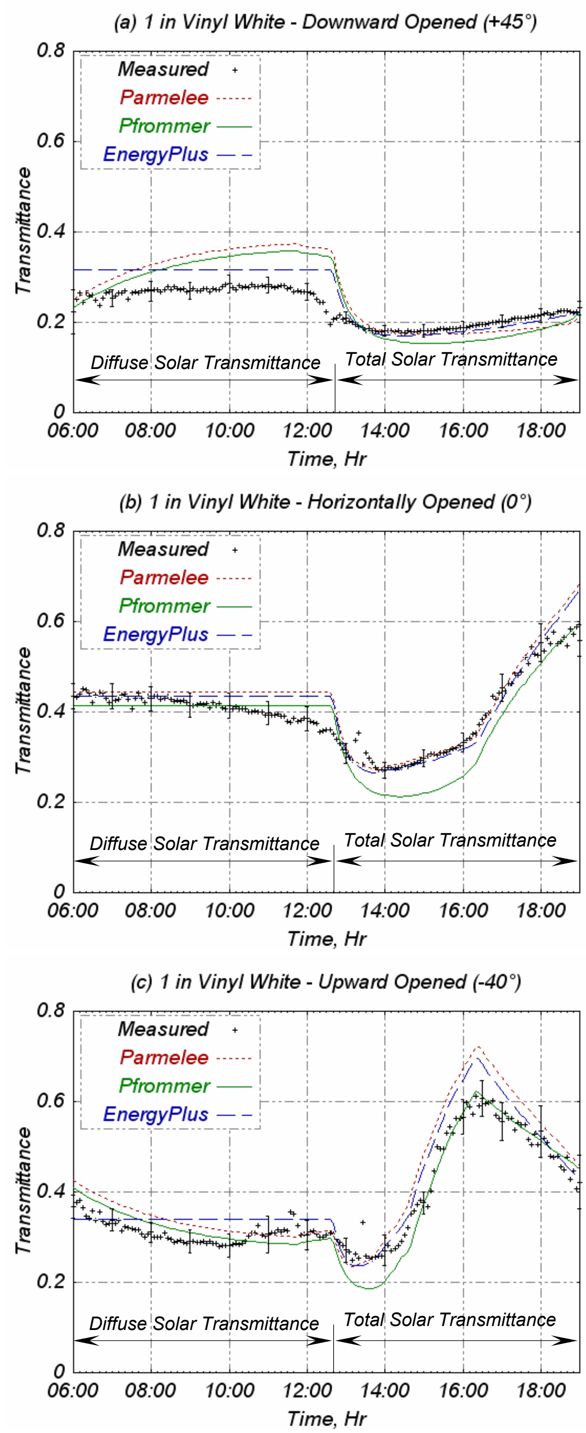

Figure 8 Experimental Comparison Results: a) Downward Opened (+45°), b) Horizontally Opened (0°), and c) Upward Opened (–40°).

As shown in Figs. 8b and 8c, diffuse solar transmittance predicted by the Parmelee and the Pfrommer models for fully opened and upward opened blinds is mostly well within the range of the experimental uncertainty. However, both models tend to over-predict measured data for downward opened blinds. As shown in Fig. 8a, the discrepancy between predicted and measured results is more than 0.05 from 9 a.m. to 12 p.m. This is likely an accumulated effect of two model simplifications. First, the isotropic assumption of diffuse irradiance distributions does not correctly predict the change in the sky brightness and the shadow cast by the test building for downward facing blinds. Second, neglecting slat curvature in both the Parmelee and the Pfrommer diffuse models leads to the over prediction of diffuse transmittance and would affect this configuration as well as the other two.

For total solar transmittance, all three models correctly predict the shape of measured profiles as shown in the right hand region of Fig. 8. Overall, the models predict measured values quite well - mostly within the range of the experimental uncertainty. Model deficiencies, however, result in large discrepancies in particular cases. For instance, the discrepancy between both the Parmelee and EnergyPlus models and measured data for the upward opened blind is about 0.10 at the peak solar transmittance as shown in Fig. 8c. This substantial disagreement is mainly due to neglecting the slat curvature. On the other hand, the Pfrommer model, which has a slat curvature correction, agrees well with measured data during that period. In addition, the Pfrommer model, which considers only the first two diffuse reflections on the slats, tends to under-predict measured transmittance when a large amount of beam solar radiation is transmitted by reflections. As shown in Fig. 8b, the discrepancy between the Pfrommer model and experimental data is more than 0.05 from 1:30 to 4:00 p.m. During the same time period, both the Parmelee and the EnergyPlus model, which consider infinite reflections, predict well within the experimental uncertainty range.

Discrepancies between the predicted and experimental results can be due to the uncertainty in measuring the input parameters as well. The uncertainty associated with the slat angle, for example, was estimated to be about 5° by observing the time of peak solar transmittance for the upward opened blind case.

EFFECT OF BLINDS ON BUILDING THERMAL LOADS

One important application of one-dimensional blind models is in building load calculation procedures. Chantrasrisalai et al. [2003] showed that the use of opened downward blinds in two office sized, highly glazed test cells reduced peak cooling loads by more than 25%. To demonstrate the ability of the heat balance (HB) method to handle interior shading devices for cooling load calculations, a thermal parameter estimation approach was used along with optical blind models. Chantrasrisalai et al. [2003] found that, for curved-slat blinds opened downward (+45° slat angle), the differences between the three optical blind models investigated in this study resulted in discrepancies in the predicted peak loads between the three models of less than 2%. The comparisons between measured loads and predicted results using the Pfrommer model are shown in Fig. 9.

Although discrepancies between the models, for blinds opened downward case, have a trivial effect on the predicted peak loads, the blind model inputs, particularly the setting of the blind itself, may have a significant impact on the thermal load. The blind position may affect both the magnitude and the time of the peak cooling load. To illustrate the effect of blind position on the cooling load, predicted cooling load results for the blind opened upward (-45°) are also plotted in Fig. 9. As shown, changing the slat angle from +45° to –45° may result in a 7% and 12% increase in the predicted peak cooling loads for the heavy and light buildings, respectively. The difference between peak loads predicted by the Pfrommer curved- and flat-slat models for upward facing (–45°) blinds is 3% and 5% for the heavy and light buildings, respectively. Thus, while the models do have a significant effect on the peak cooling load, the blind position is clearly the dominant effect.

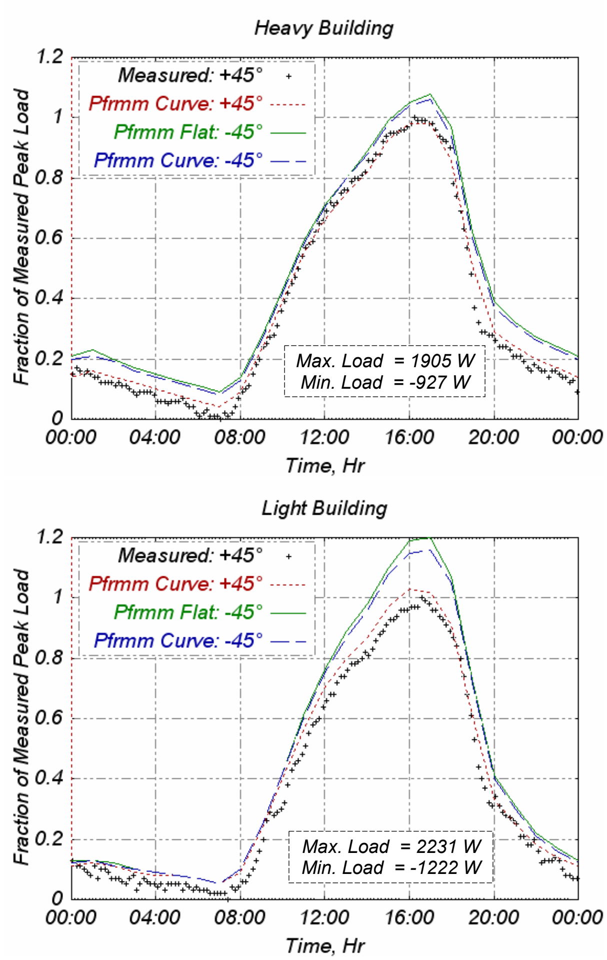

Figure 9 Load Comparisons: (a) Heavy Building, and (b) Light Building

Although the results predicted by the thermal parameter estimation approach show good agreements with measured cooling loads for the case with blinds opened downward (slat angle of +45°), they rely on measured data to estimate the net heat transfer rate from the fenestration system to the space [Chantrasrisalai et al. 2003]. General thermal fenestration models are needed to predict thermal performance of the fenestration system containing blinds so that they can be used in conjunction with the optical models in building load calculations.

CONCLUSIONS

In conclusions, the study theoretically and numerically compares three existing optical blind models suitable for building thermal load calculations. Overall, the three models predict similar results for horizontal-slat blinds having flat slats with zero thickness. However, the Pfrommer model tends to predict lower results than the other models when reflections between the slats become important (e.g. high slat reflectance) due to the two-reflection algorithms used in the model. Also, the Pfrommer model, which does not have a thickness correction, can significantly over-predict the results for flat-slat blinds when the slat thickness is non-trivial. Likewise, the EnergyPlus and Parmelee models, which do not correct for slat curvature, can substantially over-predict the direct-to-direct transmittance for curved-slat blinds.

The study also investigates the influence of input parameters on solar blind transmittances predicted by the models. These parameters include slat angle, slat reflectance, slat thickness, and slat curvature. The optical characteristics of the blinds are primarily dependent on the slat angle, which not only affects the magnitude of the blind transmittance but also changes the shape of the transmittance curve. Other parameters have a secondary effect on the blind transmittance and do not affect the shape of the transmittance curve.

In addition, the models are compared to measured data obtained by an in-situ experimental procedure. Overall, all three models show fairly good agreements with experimental data. For diffuse solar transmittance, results predicted by Parmelee and Pfrommer models reasonably follow the experimental profiles. However, the EnergyPlus model, which does not differentiate the sky and the ground as separate sources of diffuse solar radiation, does not correctly predict the shape of measured diffuse profiles. For total solar transmittance, all three models correctly predict the shape of the experimental profiles. However, both Parmelee and EnergyPlus models tend to over-predict measured data due to neglecting slat thickness while the Pfrommer model tends to under-predict measured data due to neglecting infinite reflections between slats. As illustated, the disagreements between predicted and measured data is due to known model deficiencies and the uncertainty in input parameters.

Furthermore, the study investiages the effect of the blind on building thermal loads. The cooling load procedure employing the blind models showed that differences in the models do not have a significant impact on cooling load calculations for downward facing blinds. Although simplifications in the models introduced errors of up to 5% in the cooling load for upward facing blinds, the most significant factor was the orientation of the blind, which showed up to a 12% difference in peak cooling load between upward facing and downward facing blinds.

In summary, all three of the models studied have deficiencies that are significant enough to justify additional enhancements. The EnergyPlus and Parmelee models require a slat curvature calculation, and the Pfrommer model requires a thickness calculation. In general, there is a need for a complehensive optical blind model that includes features from each of the three models studied. In addition, a general thermal fenestration model that predicts the thermal interaction of the fenstration system containing the blind with the conditioned space is needed in order to utilize one-dimensional blind models in thermal load and energy calculations.

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