A Thermal Performance Study of a Glass Window Installed with a Curved Venetian Blind

Somsak Chaiyapinunt[*1] and Nopparat Khamporn[1]

[1] Department of Mechanical Engineering, Faculty of Engineering, Chulalongkorn University, Phayathai, Bangkok 10330, Thailand

*Corresponding Author: E-mail, somsak.ch@chula.ac.th Telephone Number, 662 2186610 Fax. Number 662 2522889

Abstract

This article is about a study of thermal performance of glass window installed with a curved venetian blind in term of heat gain in the part of shortwave radiation to the space. The curved venetian blind, whose optical properties are considered as nonspecular element, is modeled as an effective layer. The mathematical model of the combined glass window and venetian blind is developed by combining the mathematical model of glass window and the mathematical model of a curve venetian blind using matrix layer calculation method. The experiment is performed in a test room to measure the heat gain due to solar radiation passing through the glass window installed with a curved venetian blind. The results from the developed model are compared with the experimental results. The agreement between the predicted results and the experimental results is good. It is found that installing a curved venetian blind to the clear glass window causes a significant reduction in heat gain compared to the plain glass window. It is also found that the heat gain through glass window installed with a venetian blind in the part of shortwave radiation is mainly affected by the slat properties, slat angle and solar profile angle.

Keywords*:* Venetian blind, Glass window, Heat gain, Shortwave radiation, Thermal performance.

1. Introduction

Thailand, which is located in the tropical zone near the equator, has weather that is hot and humid for most of the year. There is plenty of solar radiation available to harvest as the auxiliary energy for generating electricity, drying agriculture products and any other applications relating to solar energy. But at the same time, having high solar radiation also has certain disadvantages. It also imposes high cooling load to the building, especially building with large amount of glass window installed as building envelop. Large air conditioning systems are usually required for removing the high solar cooling load from the buildings. To reduce the energy usage in building from the air conditioning system, the high efficiency glass in term of heat reduction should be used for building glass window. But Chaiyapinunt et al. [1] and Chaiyapinunt and Khamporn [2] have shown that choosing a proper glass window for the building, one has to consider the thermal performance of glass window not only in term of heat transmission but also in term of thermal comfort. Thoroughly understanding of the thermal performance of glass is essential for designing an energy efficient building. But when the building is actually in use, people tend to install an indoor shading device such as a venetian blind or a drapery behind the glass window to control the light transmission and the condition of privacy. Therefore to really design an energy efficient building, one needs to understand the thermal performance of the combined glass window and the indoor shading device besides the understanding of the thermal performance of the plain glass window. The venetian blind is chosen as an indoor shading device to be investigated for this study. The glass is the substance whose optical properties are specular, while the optical properties of the venetian blind are considered nonspecular. Therefore, it is much more complex in modeling the venetian blind for calculating its thermal performance when compared to the glass window. Much work has been done about the heat transmission through the glass window installed with venetain blind. But most of the works [3-12] are dealt with the flat slat blind. Khun [13, 14] has studied on the solar control system including the venetian blind with arbitrary shape of slat and its specular properties. Chaiyapinunt and Worasinchai [15, 16] have developed a mathematical model to calculate the shortwave optical properties for a curved slat venetian blind with thickness and a mathematical model to calculate the longwave optical properties for a curved slat venetian blind by including both the effect of slat curvature and the effect of slat thickness in the mathematical model from the beginning. With an accurate model for the optical properties of the curved venetian blind, the thermal performance of glass window installed with a curved venetian blind can be accurately predicted. In this article the study of thermal performance of glass window installed with a curved venetian blind in term of heat gain in the part of shortwave radiation to the space is performed. The effect of slat properties, slat angle and solar profile angle on the thermal performance are also investigated.

2. Mathematical Model for a Curved Venetian Blind

The venetian blind in this study is modeled as an effective layer. Fig.1 shows the example of the fenestration system having a venetian blind installed as an interior shading device.

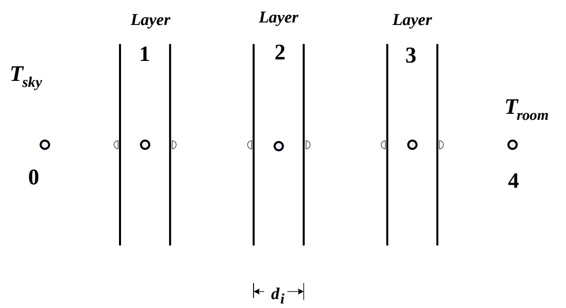

Fig. 1 The blind is modeled as an effective layer (layer 3) behind the double glass window (layer 1 and 2).

In any fenestration system which composed of glasses only, the solar heat gain coefficient is dependent only on the incident angle. But when installed the venetian blind (which its optical properties are considered nonspecular) to the glass window, the solar heat gain coefficient of the glass windows installed with the venetian blind becomes much more complex. It has an additional variable, the azimuth angle (angle of the incident radiation measured from the horizontal axis on the plane of the glass window). The solar heat gain coefficient for the combined glass window and the venetian blind can be written as

$$SHGC(\theta,\psi) = T^{fH}_{\{1,M\}}(\theta,\psi) + \sum_{k=1}^{M} N_k A^{f}_{k,\{1,M\}}(\theta,\psi) \quad (1)$$

where $SHGC$ is the solar heat gain coefficient of a fenestration system with *M* layers. $T^{fH}_{\{1,M\}}$ is the directional-hemispherical front transmittance of the system. $A^{f}_{k,\{1,M\}}$ is the directional absorptance of the *k*th layer in the system. N_k is the inward – flowing fraction of the absorbed energy for *k*th layer in the system. θ is the incident angle. ψ is the azimuth angle. The relationship between the solar profile angle (solar profile angle is the angle of incidence in a plane that is perpendicular to the window and perpendicular to the slat direction) and the incident angle and the azimuth angle can be written as

$$\phi_s = \tan^{-1}(\sin\psi \tan\theta) \quad (2)$$

where ϕ_s is the solar profile angle.

Therefore the optical properties of the combined glass window and a venetian blind are essential in determining the heat transmission through the fenestration system from the solar radiation. The optical properties of the blind, when treated as the effective layer, can be determined from the mathematical model described in the following section.

2.1 Optical properties for a curved slat blind with thickness

The optical properties of the venetian blind (considered as an effective layer) are dependent mainly on slat properties, slat angle, nature of interreflection of the radiation between the slat surfaces and solar profile angle. The slats are assumed to be perfect diffusers and all the slats have the same optical properties. The whole blind assembly is represented by two consecutive slats as shown in Fig. 2. The optical properties of the blind can be classified as the shortwave optical properties and longwave optical properties [15, 16]. Only shortwave optical properties (transmittance, reflectance and absorbtance) will be considered in this study. The shortwave optical properties of the effective layer are further classified as the optical properties for direct radiation and the optical properties for diffuse radiation.

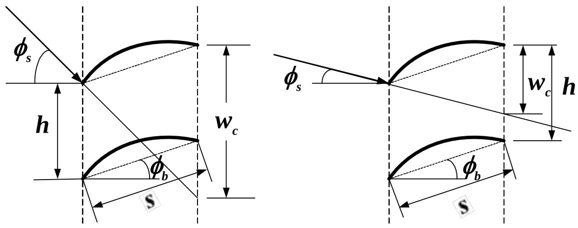

Fig. 2 Curved slat blind at different solar profile angle.

2.1.1 Optical properties for direct radiation

The optical properties for direct radiation can be further separated into two components. The first component is the transmittance due to the part of the direct radiation which is directly passing through the blind without touching the slat surfaces (direct-to-direct transmittance). The second component is the transmittance due to the part of the direct radiation which is interreflected between two adjacent slats (direct-to–diffuse transmittance).

The first component of the transmittance can be calculated from the relationship developed by Chaiyapinunt and Worasinchai [15] as

$$\tau^{f}_{bl-ct,dir,dir} = 1 - \frac{w_t}{h_t} \qquad \text{when } w_t \le h_t \qquad (3)$$

where $\tau^f_{bl-ct,dir,dir}$ is the front direct-to-direct transmittance of the effective layer for the curved slat blind with thickness.

$$w_t = w_c + t_b \cos\phi_b - t_b \sin\phi_b \tan\phi_s \tag{4}$$

$$h_t = h + t_b / \cos\phi_b \tag{5}$$

where w_t is the blocked distance from the curved slat with thickness effect. w_c is the blocked distance from the curved slat without thickness effect. ϕ_s is the solar profile angle of the solar radiation incident on the blind. ϕ_b is the slat angle. h is the distance between two adjacent slats. t_b is the slat thickness. Fig. 3 shows the geometry of curved blind with thickness at different slat angles.

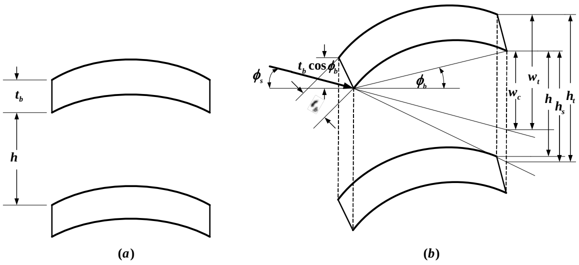

Fig. 3 Geometry of a curved blind with thickness at different slat angle.

The second component of the optical properties for direct radiation is the properties in the part that the direct radiation indirectly passed through the blind by reflections between the slats are calculated by using radiosity method on a 6 surface closed enclosure as shown in Fig. 4.

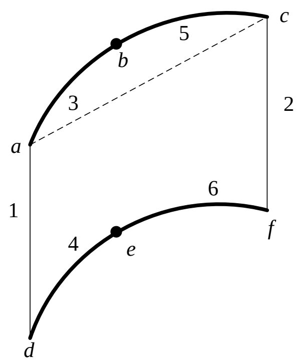

Fig. 4 Six surface closed enclosure formed by two consecutive slats.

The transmittance due to the part of the direct radiation which is interreflected between two adjacent slats (direct-to–diffuse transmittance) can be calculated from a unit of direct radiation flux incident on the blind from the front side as the irradiation on surface 2. It can be written as [15]

$$\tau^f_{bl-c,dir,dif} = G_2 \tag{6}$$

$$\rho^f_{bl-c,dir,dif} = G_1 \tag{7}$$

where $\tau^f_{bl-c,dir,dif}$ is the front direct-to-diffuse transmittance of the effective layer. $\rho^f_{bl-c,dir,dif}$ is the front direct-to-diffuse reflectance. G_1 is the irradiation on surface 1. G_2 is the irradiation on surface 2.

The effect of the slat thickness can be determined from the geometry shown in Fig. 3. It can be written as

$$bf = \frac{t_b \cos(\phi_b + \phi_s)}{\left(h + \dfrac{t_b}{\cos\phi_b}\right)\cos\phi_s} \tag{8}$$

where bf is the blind edge correction factor.

The optical properties of the effective layer for a curves venetian blind with thickness now can be written as

$$\tau^f_{bl-ct,dir,dif} = \tau^f_{bl-c,dir,dif}(1-bf) \tag{9}$$

$$\rho^f_{bl-ct,dir,dif} = \rho^f_{bl-c,dir,dif}(1-bf) + \rho^f_s(bf) \tag{10}$$

$$\alpha^f_{bl-ct,dir,dif} = 1 - \tau^f_{bl-ct,dir,dir} - \tau^f_{bl-ct,dir,dif} - \rho^f_{bl-ct,dir,dif} \tag{11}$$

where $\tau^f_{bl-ct,dir,dif}$ is the front direct-to-diffuse transmittance of the effective layer for curved blind with thickness. $\tau^f_{bl-ct,dir,dir}$ is the front direct-to-direct transmittance of the curved blind with thickness. $\rho^f_{bl-ct,dir,dif}$ is the front reflectance of the curved blind with thickness for direct radiation. ρ^f_s is the front reflectance of the slat. $\alpha^f_{bl-ct,dir,dif}$ is the front absorptance of the curved blind with thickness for direct radiation.

2.1.2 Optical properties for the diffuse radiation

The diffuse radiation is reaching the blind from every direction, both downward from the sky and upward from the ground. The optical properties for diffuse radiation are separated into optical properties calculated from the sky radiation and optical properties from the ground reflected radiation. They can be determined by integrating the optical properties obtained from the direct radiation in certain direction over the sky and ground element as shown in Fig. 5. The optical properties for diffuse radiation can expressed as

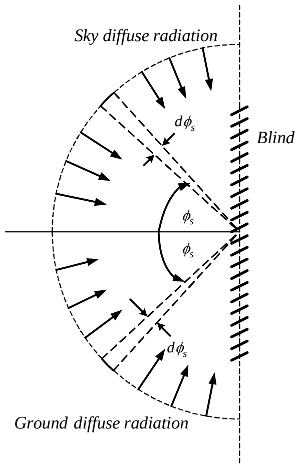

Fig 5 Distribution of diffuse radiation on the blind.

$$\tau^f_{bl-ct,sky-dif,dif} = \frac{\int_0^{\frac{\pi}{2}} \left[\tau^f_{bl-ct,dir,dir}(\phi_s) + \tau^f_{bl-ct,dir,dif}(\phi_s)\right] I_{sky}(\phi_s)\cos\phi_s d\phi_s}{\int_0^{\frac{\pi}{2}} I_{sky}(\phi_s)\cos\phi_s d\phi_s} \tag{12}$$

$$\tau^f_{bl-ct,gnd-dif,dif} = \frac{\int_{-\frac{\pi}{2}}^{0} \left[\tau^f_{bl-ct,dir,dir}(\phi_s) + \tau^f_{bl-ct,dir,dif}(\phi_s)\right] I_{gnd}(\phi_s)\cos\phi_s d\phi_s}{\int_{-\frac{\pi}{2}}^{0} I_{gnd}(\phi_s)\cos\phi_s d\phi_s} \tag{13}$$

$$\rho^f_{bl-ct,sky-dif,dif} = \frac{\int_0^{\frac{\pi}{2}} \rho^f_{bl-ct,dir,dif} I_{sky}(\phi_s)\cos\phi_s d\phi_s}{\int_0^{\frac{\pi}{2}} I_{sky}(\phi_s)\cos\phi_s d\phi_s} \tag{14}$$

$$\rho^f_{bl-ct,gnd-dif,dif} = \frac{\int_{-\frac{\pi}{2}}^{0} \rho^f_{bl-ct,dir,dif} I_{gnd}(\phi_s)\cos\phi_s d\phi_s}{\int_{-\frac{\pi}{2}}^{0} I_{gnd}(\phi_s)\cos\phi_s d\phi_s} \tag{15}$$

$$\alpha^f_{bl-ct,sky-dif,dif} = \frac{\int_0^{\frac{\pi}{2}} \alpha^f_{bl-ct,dir,dif} I_{sky}(\phi_s)\cos\phi_s d\phi_s}{\int_0^{\frac{\pi}{2}} I_{sky}(\phi_s)\cos\phi_s d\phi_s} \tag{16}$$

$$\alpha^f_{bl-ct,gnd-dif,dif} = \frac{\int_{-\frac{\pi}{2}}^{0} \alpha^f_{bl-ct,dir,dif} I_{gnd}(\phi_s)\cos\phi_s d\phi_s}{\int_{-\frac{\pi}{2}}^{0} I_{gnd}(\phi_s)\cos\phi_s d\phi_s} \tag{17}$$

where $\tau^f_{bl-ct,sky-dif,dif}$ is the front transmittance of the effective layer for a curved blind with thickness for diffuse radiation which comes from the sky. $\tau^f_{bl-ct,gnd-dif,dif}$ is the front transmittance of the effective layer for a curved blind with thickness for diffuse radiation which comes from the ground. $\tau^f_{bl-ct,dir,dir}$ is the front transmittance of the effective layer for a curved blind with thickness for direct radiation in the part which is directly passing through the blind without touching the slat at profile angle ϕ_s. $\tau^f_{bl-ct,dir,dif}$ is the front transmittance of the effective layer for a curved blind with thickness for direct radiation in the part which is incident on the slat at profile angle ϕ_s. $\rho^f_{bl-ct,sky-dif,dif}$ is the front reflectance of the effective layer for a curved blind with thickness for diffuse radiation which comes from the sky. $\rho^f_{bl-ct,gnd-dif,dif}$ is the front reflectance of the effective layer for a curved blind with thickness for diffuse radiation which comes from the ground. $\rho^f_{bl-ct,dir,dif}$ is the front reflectance of the effective layer for a curved blind with thickness for direct radiation. $\alpha^f_{bl-ct,sky-dif,dif}$ is the front absorptance of the effective layer for a curved blind with thickness for diffuse radiation which comes from the sky. $\alpha^f_{bl-ct,gnd-dif,dif}$ is the front absorptance of the effective layer for a curved blind with thickness for diffuse radiation which comes from the ground. $\alpha^f_{bl-ct,dir,dif}$ is the front absorptance of the effective layer for a curved blind with thickness for direct radiation. I_{sky} is the radiation intensity of the diffuse radiation which comes from the sky. I_{gnd} is the radiation intensity of the diffuse radiation which comes from the ground.

The detail of the development of the shortwave optical properties can be found from reference [15].

3. Mathematical Model for a Combined Glass Window and the Curved Venetian Blind

The effective layer which has the shortwave optical properties (developed in section 2) shall be treated as another layer of the fenestration system. The combined optical properties of the fenestration system can be calculated by combing the optical properties of each layer (glass and venetian blind) in the system using matrix layer calculation method [4, 5]. The expressions for the optical properties of the combined glass window and venetian blind system can be written as

$$T^{fH} = u^T \cdot \Lambda \cdot T^f_{M,\{1,M\}} \tag{18}$$

$$R^{fH} = u^T \cdot \Lambda \cdot R^f_{M,\{1,M\}} \tag{19}$$

where $u^T = \{1 \quad 1 \quad \ldots \quad 1\}$ (20)

$$\Lambda_i = \begin{Bmatrix} \Delta\Omega_i^1 \cos(\theta_i^1) & 0 & \ldots & 0 \\ 0 & \Delta\Omega_i^2 \cos(\theta_i^2) & \ldots & 0 \\ \ldots & \ldots & \ldots & 0 \\ 0 & 0 & \ldots & \Delta\Omega_i^N \cos(\theta_i^N) \end{Bmatrix} \tag{21}$$

where T^{fH} is the directional-hemispherical front transmittance of the fenestration system. R^{fH} is the directional-hemispherical front reflectance of the fenestration system. $T^f_{M,\{1,M\}}$ is the bi-directional front transmittance of the fenestration system with M layers. $R^f_{M,\{1,M\}}$ is the bi-directional front reflectance of the fenestration system with M layers. u^T is the auxiliary row vector. Λ is the propagation matrix. $\Delta\Omega$ is the solid angle. The additional expressions for the optical properties can be written as

$$T^f_{M,\{1,M\}} = T^f_M \cdot \left(1 - \Lambda \cdot R^b_{M-1,\{1,M-1\}} \cdot \Lambda \cdot R^f_M\right)^{-1} \cdot \Lambda \cdot T^f_{M-1,\{1,M-1\}} \tag{22}$$

$$R^f_{M,\{1,M\}} = R^f_{M-1,\{1,M-1\}} + \begin{bmatrix} T^b_{M-1,\{1,M-1\}} \cdot \left(1 - \Lambda \cdot R^f_M \cdot \Lambda \cdot R^b_{M-1,\{1,M-1\}}\right)^{-1} \\ \cdot \Lambda \cdot R^f_M \cdot \Lambda \cdot T^f_{M-1,\{1,M-1\}} \end{bmatrix} \tag{23}$$

$$T^b_{M,\{1,M\}} = T^b_{M-1,\{1,M-1\}} \cdot \left(1 - \Lambda \cdot R^f_M \cdot \Lambda \cdot R^b_{M-1,\{1,M-1\}}\right)^{-1} \cdot \Lambda \cdot T^b_M \tag{24}$$

$$R^b_{M,\{1,M\}} = R^b_M + \begin{bmatrix} T^f_M \cdot \left(1 - \Lambda \cdot R^b_{M-1,\{1,M-1\}} \cdot \Lambda \cdot R^f_M\right)^{-1} \\ \cdot \Lambda \cdot R^b_{M-1,\{1,M-1\}} \cdot \Lambda \cdot T^b_M \end{bmatrix} \tag{25}$$

where $T^b_{M,\{1,M\}}$ is the bi-directional back transmittance of the fenestration system with M layers. $R^b_{M,\{1,M\}}$ is the bi-directional back reflectance of the fenestration system with M layers. T_i^f is the bi-directional front transmittance of a specific layer (layer *i*). T_i^b is the bi-directional back transmittance of a specific layer (layer *i*). R_i^f is the bi-directional front reflectance of a specific layer (layer *i*). R_i^b is the bi-directional back reflectance of a specific layer (layer *i*).

The absorbtance of the specific layer in the *M* layers of the fenestration system can be written as

$$\begin{aligned} A^f_{i;M} = & \left[A_i^f \cdot \left(1 - \Lambda \cdot R^b_{i-1,\{1,i-1\}} \cdot \Lambda \cdot R^f_{(M-i+1),\{1,M\}}\right)^{-1} \cdot \Lambda \cdot T^f_{i-1,\{1,i-1\}}\right] \\ & + \left[A_i^b \cdot \left(1 - \Lambda \cdot R^f_{(M-i),\{i+1,M\}} \cdot \Lambda \cdot R^b_{i,\{1,i\}}\right)^{-1} \cdot \Lambda \cdot R^f_{(M-i),\{i+1,M\}} \cdot \Lambda \cdot T^f_{i,\{1,i\}}\right] \end{aligned} \tag{26}$$

$$\begin{aligned} A^b_{i;M} = & \left[A_i^b \cdot \left(1 - \Lambda \cdot R^f_{(M-i),\{i-1,M\}} \cdot \Lambda \cdot R^b_{i,\{1,i\}}\right)^{-1} \cdot \Lambda \cdot T^b_{M-i,\{i+1,M\}}\right] \\ & + \begin{bmatrix} A_i^f \cdot \left(1 - \Lambda \cdot R^b_{i-1,\{1,i-1\}} \cdot \Lambda \cdot R^f_{(M-i+1),\{i,M\}}\right)^{-1} \\ \cdot \Lambda \cdot R^b_{i-1,\{1,i-1\}} \cdot \Lambda \cdot T^b_{M-i+1,\{i,M\}} \end{bmatrix} \end{aligned} \tag{27}$$

where $A^f_{i;M}$ is the directional front absorptance of the layer *I* in the *M* layers system. $A^b_{i;M}$ is the directional back absorptance of the layer *I* in the *M* layers system. A_i^f is the directional front absorptance of individual layer *i*. A_i^b is the directional back absorptance of individual layer *i*.

In order to determine the combined optical properties of the fenestration system, the propagation matrix has to be set up with different values of incident angle and azimuth angle. For this study, the incident angle is considered as the increment of 15 degree (0, 15, 30, 45, 60, 75, 90 degree) and the azimuth angle is considered as the increment of 30 degree (0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330 degree) to complete the hemisphere of the irradiation. Therefore the bi-directional optical properties of each layer will form an 84x84 matrix. Then the optical properties of the combined fenestration system can be determined from the expression described above.

3. Experiment

The test room is constructed with a tested window of 0.9x1.1 m facing west. The room is located on the fourth floor of Hans Buntli building, Mechanical Engineering Department, Chulalongkorn University. The room is constructed as a double wall room with 2 inch fiber glass in between to minimize the heat transfer. The west wall is constructed with aluminum cladding as the exterior surface and gypsum board as the interior surface with 2 inch fiber glass in between. The inside surfaces of the test room are painted black. Fig. 6 shows the layout and dimensions of the test room. Two pyranometers (Kipp&Zonen, model CMB 6B) and a shading ring are used to measure the incident global solar radiation and diffuse solar radiation. Another pyranometer is used to measure the transmitted solar radiation through the glass window and a venetian blind. Figs. 6 and 7 show the pyranometers installed outside and inside the test room to measure the solar radiation.

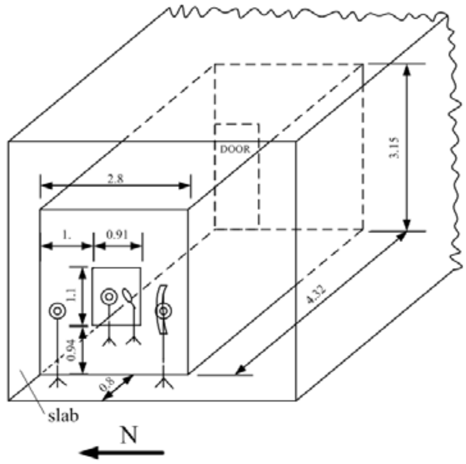

Fig. 6 Layout of the test room.

Fig. 7 Two pyranometers and a shading ring.

Fig. 8 Pyranometer used for measuring the transmitted solar radiation.

4. Comparison with Experimental Data

To verify the accuracy of the mathematical model for the optical properties of the fenestration system (glass window installed with a venetian blind), the experiment is performed in the test room with a 6 mm clear glass window installed with a 25.4 mm (1 inch) venetian blind. The blind is made of aluminum with a slat curvature radius of 71.5 mm and 0.3 mm thickness. The slat color is cream. The slat width measured on projected flat plane is 25.2 mm. The spacing between two consecutive slats is 20 mm. The distance between the glass inside surface and the center of the blind width is 40 mm. The optical properties of the glass window and the slat properties are shown in table1.

Table. 1 Glass and slat optical properties

Description	Visible t		Solar Energy		
	Trn	Ref	Trn	Ref	Ab
Clear glass	89	8	80	8	12
Slat	-	-	-	71	29

Note:: Trn = transmittance, Ref = reflectance, Ab = absorptance

The test is performed on February 7, 2010. The slat angle is set as 0 degree. Fig. 9 shows the incident global solar radiation, incident diffuse solar radiation and transmitted solar radiation varying with time. Since the building is facing west, only the diffuse solar radiation can be measured in the morning. The direct solar radiation is incident on the glass window surface starting from the time of 13:00. The maximum global solar radiation occurs at the time about 16:00. The variation of the measured transmitted solar radiation with time has the similar pattern with the incident global solar radiation but having smaller magnitude. The fluctuating pattern of the measured transmitted radiation between the time of 16:00 and 18:00 is the result of the alternate sunlit and shaded band from the blind on the sensor. The actual transmitted solar radiation should be obtained by averaging the fluctuating signals.

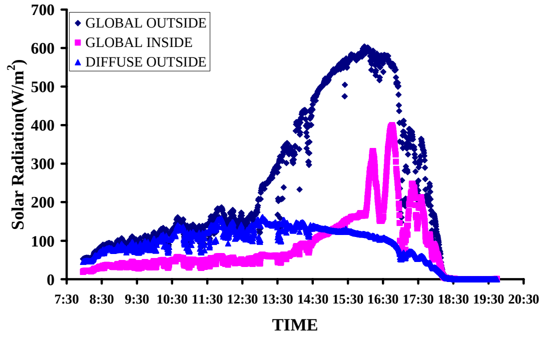

Fig. 9 Incident solar radiation and transmitted solar radiation over the tested window system.

The predicted transmitted solar radiation can be determined from the relationship developed in section 2 as

$$I_{trans} = T^{fH}_{\{1,M\}} I_{direct} + T^{fH}_{\{1,M\},diff,sky} I_{diff,sky} + T^{fH}_{\{1,M\},diff,grnd} I_{diff,grnd} \tag{28}$$

where I_{trans} is the transmitted solar radiation. I_{direct} is the incident direct radiation. $I_{diff,sky}$ and $I_{diff,grnd}$ are the incident diffuse solar radiation from the sky and from the ground. $T^{fH}_{\{1,M\}}$, $T^{fH}_{\{1,M\},diff,sky}$ and $T^{fH}_{\{1,M\},diff,grnd}$ are the directional-hemisphere front transmittance of the fenestration system for direct radiation, diffuse radiation from the sky and diffuse radiation from the ground. Fig. 10 shows the comparison between the predicted transmitted solar radiation and the measured transmitted solar radiation. The agreement on the measured values and predicted values between the time of 13:00 and 18:00 is quite good. But in the morning, the predicted values seem to have higher value than the measured value in some periods. The discrepancy in those periods is probably resulted from inaccuracy of measurement and the optical transmittance in the diffuse radiation part.

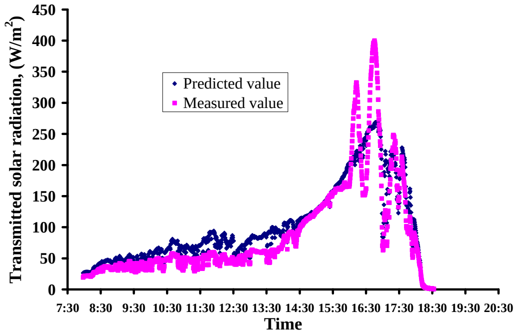

Fig. 10 Comparison between the predicted transmitted solar radiation and measured transmitted solar radiation.

5. Thermal performance

The thermal performance of the fenestration system installed with venetian blind in term of heat gain due to solar radiation can be divided into the part of shortwave radiation and longwave radiation. In this study, the effect of the slat properties, slat angle and solar profile angle on the transmitted shortwave radiation shall be investigated. Fig. 11 shows the shortwave transmittance for the direct radiation of the plain clear glass and the clear glass with blind (blind with optical properties shown in table 1) at -45, 0 and +45 degree of slat angle. The shortwave transmittance of the clear glass is decreased as the solar profile angle is increased. The shortwave transmittance is sharply decreased when solar profile angle is in the range of 60 to 90 degree. For blind with slat angle of 0 degree, the value of transmittance is 0.755 at 0 degree of solar profile angle. The transmittance is sharply decreased as the solar profile angle is increased from 0 to 45 degree. When the blind slat angle is set at 45 degree, the value of transmittance is reduced to 0.215 at solar profile angle of 0 degree. When the blind slat angle is set at -45 degree, the value of the transmittance is increasing to maximum value at solar profile angle of 45 degree (most of the direct solar radiation pass through the blind into the space). The value of the transmittance is decreased as the solar profile angle is increasing further from 45 degree.

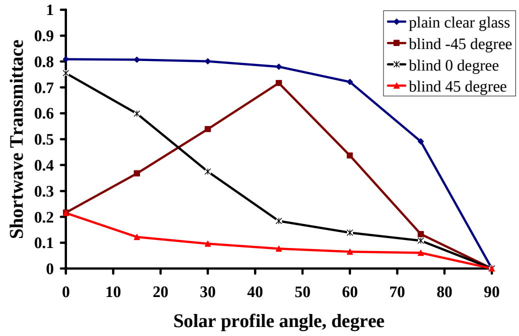

Fig. 11 Shortwave transmittance of the clear glass window with blind in different slat angle.

The effect of the slat reflectance on the shortwave transmittance of the clear glass with blind set at 0 degree slat angle is shown in Fig. 12. The slat which has a lower value of reflectance, will have a smaller value of shortwave transmittance.

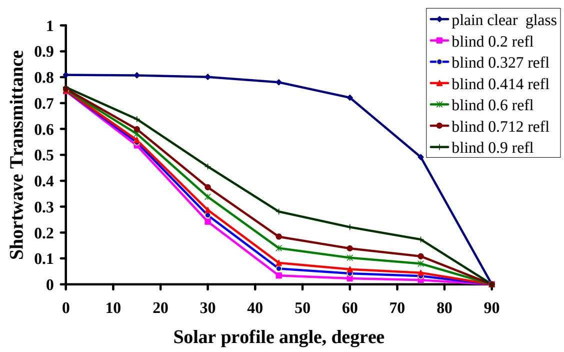

Fig. 12 Shortwave transmittance of the clear glass window with blind in different slat reflectance when blind slat angle is set at 0 degree. refl=reflectance.

The effect of the slat distance (range from 10 mm to 25 mm) on the shortwave transmittance of the clear glass with blind set at 0 degree slat angle is shown in Fig. 13. From the Fig. 13, decreasing the distance between the two slats causes the value of the shortwave transmittance to increase.

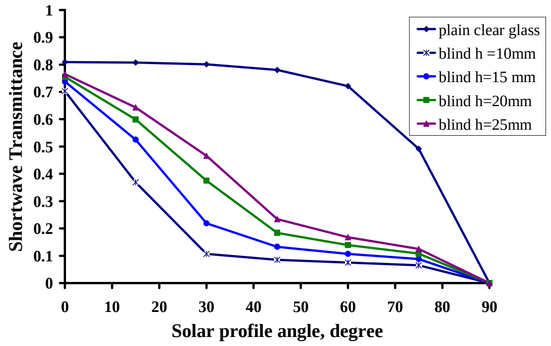

Fig. 13 Shortwave transmittance of the clear glass window with blind in different slat distance blind slat angle is set at 0 degree. h=slat distance.

The effect of the slat curvature on the shortwave transmittance is also investigated and shows the results in Fig. 14. The slat curvature is referred by its radius of curvature. The radius of curvature of the slat range from 25 mm to 200 mm are investigated. The effect of slat curvature on the shortwave transmittance is not pronounced as the effect of the other parameters investigated. The blind with the smaller radius of curvature gives the smaller value of transmittance.

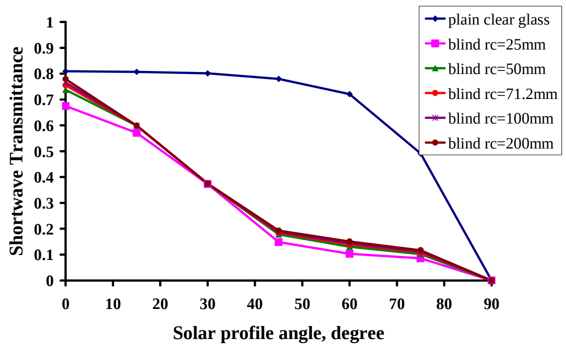

Fig. 14 Shortwave transmittance of the clear glass window with blind in different slat curvature when blind slat angle is set at 0 degree. rc=radius of curvature.

The effect of the investigated parameters on the shortwave transmittance are also studied on the shortwave diffuse transmittance of the clear glass with blind. For slat angle of 0 degree, the value of the shortwave diffuse transmittance from the sky and from the ground are the same. Fig. 15 shows the comparison between the value of diffuse transmittance of plain clear glass and clear glass with blind in different reflectance, different slat distance and different slat curvature. The effect of the investigated parameters on the diffuse transmittance are similar to the effect of the same investigated parameters on the shortwave transmittance. The slat with higher reflectance will give higher value of the diffuse transmittance. The higher the slat distance will give higher value of the diffuse transmittance. The greater value of slat radius of curvature will give a greater value of the diffuse transmittance.

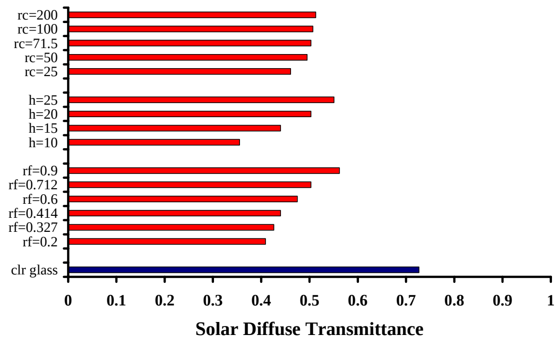

Fig. 15 Shortwave diffuse transmittance of clear glass window with blind of different slat properties when blind slat angle is set at 0 degree.

The effect of using blind to the different kind of glass window is also investigated. Figs. 16 and 17 show the shortwave transmittance of the grey glass with blind and reflective glass with blind at different slat angle (the optical properties of the grey glass and reflective glass are shown in table 2). It is found that effect of the slat angle and solar profile angle on the shortwave transmittance of the fenestration system (with grey glass and reflective glass) are similar to the effect of the slat angle and solar profile angle on the shortwave transmittance of the clear glass and blind system. The difference is only on the magnitude of the shortwave transmittance.

Table. 2 Glass optical properties

Description	Visible t		Solar Energy		
	Trn	Ref	Trn	Ref1	Ref2
Grey glass	56.8	5.8	41.9	5.1	5.1
Reflective glass	40.2	10.7	31.4	10.3	25.4

Note:: Trn = transmittance, Ref = reflectance, Ref*i* = reflectance at surface *i*.

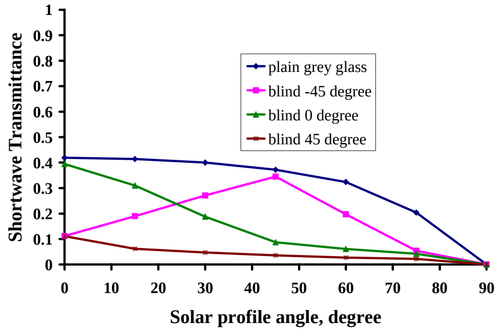

Fig. 16 Shortwave transmittance of the grey glass window with blind in different slat angle.

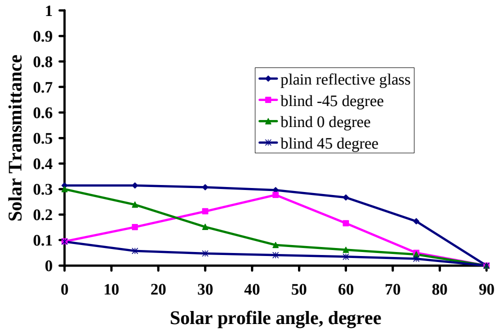

Fig. 17 Shortwave transmittance of the reflective glass window with blind in different slat angle.

6. Conclusion

The thermal performance of the glass window installed with a venetian curved blind in the part of shortwave radiation is investigated. The shortwave optical properties of a curved venetian blind with thickness are developed. The shortwave optical properties of the glass window system are developed by combining the optical properties of the glass and the blind using the matrix layer calculation. The accuracy of the mathematical model is verified by comparing the predicted transmitted radiation with the measured transmitted radiation. The agreement is quite good when there is direct solar radiation incident on the glass window surface. Installing the blind to the plain glass window system causes the decreasing of heat gain in the part of shortwave solar radiation. The amount of reduction in shortwave transmittance is mainly dependent on the slat angle and solar profile angle. It is also found that the slat which has a lower value of reflectance, will have a smaller value of shortwave transmittance. The slat distance is also affected on the shortwave transmittance. The effect on the slat curvature on the shortwave transmittance is small when compared to the effect of other parameters. The effect of the investigated parameters on the diffuse solar transmittance are similar to the effect on the shortwave transmittance. When installed blind to different kind of glass window other than clear glass window, it is found that the thermal performance is similar to the case of clear glass window. Understanding the effect of the investigated parameters on the shortwave and diffuse transmittance would help in using the proper venetian blind to control the heat gain to the space. In this study, only the heat gain in part of shortwave radiation is studied. To determine the total heat gain to the space the conduction heat gain and the heat gain in the part of longwave radiation have to be included.

7. Acknowledgement

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