Effect of Installing a Curved Venetian Blind to the Glass Window on Heat Transmission

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Abstract

This article is about a study on the effect of installing a curved venetian blind to the glass window on heat transmission to the space. The curved venetian blind, whose optical properties are considered as nonspecular optical element, is modeled as an effective layer. The mathematical model of the glass window installed with a curved venetian blind is developed by using matrix layer calculation method. Empirical model of heat convection coefficient between the glass window and the venetian blind is adopted in the proposed mathematical model. The effect of diathermanous layer on the radiative heat transfer between the glass window and space behind the installed venetian blind is also considered. The predicted results from the mathematical model are verified with the experimental results. The variation of the solar heat gain coefficient and overall heat transfer coefficient, which are the key parameters used to calculate the heat transmission through the glass window installed with venetian blind to the space inside, are studied. It is found that installed the venetian blind behind the glass window significantly reduces the heat transmission through the space. The reduction in heat transmission is greatly influenced by the characteristics of the venetian blind and the glass window such as the optical properties of the slat, the slat angle, the solar profile angle and the optical properties of the glass window. It is also found that installed the high reflective blind (white blind) behind the glass window in certain slat angle and solar profile angle can reduce the solar heat gain coefficient as much as 59.7 percent compared to the plain glass window.

***Keywords**:* Glass window, Venetian blind, Solar heat gain coefficient, Heat transmission.

1. Introduction

Countries, that located in the zone near the equator, have the better opportunity compared to countries in the other part of the world in harvesting solar radiation to use as the auxiliary energy. But having high solar radiation also has certain disadvantages when considering in the aspect of building application in term of cooling load, especially building with large amount of glass window installed as building envelope. Large air conditioning systems are usually required for removing the high solar cooling load from the buildings. The best way to reduce the solar cooling load is to block the solar radiation from entering into the building inner space. Certain types of external shading device such as roof overhangs, horizontal and vertical projections are preferred to use for preventing the solar radiation from entering into the building. But with certain types of building, such as high rise office building, etc, building equipped with the external shading devices may not be preferred. In that case, installing the internal shading device behind the glass window can be another option for tenant to use for reducing heat transmission through building envelope apart from being used for controlling the light transmission and the condition of privacy. In this study, the curved venetian blind is chosen as the indoor shading device to be investigated. 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 plain glass window. Chaiyapinunt et al. [1] and Chaiyapinunt and Khamporn [2] have studied the thermal performance of different types of glass. Many research works related to the heat transmission through the glass window installed with venetian blind have been done. Research works [3-12] are only dealt with flat slat blind. Research works [13-14] are dealt with the venetian blind with arbitrary shapes. 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. Chaiyapinunt and Khamporn [17] have developed the mathematical model for the combined glass window and a curved venetian blind installed behind the glass window to calculate the thermal performance of a glass window system in term of heat gain in the part of shortwave radiation to the space. The matrix layer calculation method [4, 5] was used to combine the optical properties of the individual glass windows and the optical properties of the venetian blind to achieve the optical properties of the combined glass window and the blind. Since the optical properties of the venetian blind are dependent on several parameters, such as slat properties, slat angle and solar profile angle, 84x84 bi directional optical properties matrix was set up. The optical properties of the combined glass window and the blind shall also be formed as an 84x84 matrix as well. In this article the study of the effect of installing a curved venetian blind to the glass window on heat transmission is performed. The heat transmission through the glass window installed with a curved venetian blind in the part of longwave radiation and heat conduction shall be analyzed. The variations of the thermal performance of the glass window installed with venetian blind in term of solar heat gain coefficient and overall heat transfer coefficient on different types of glass and blind are also investigated.

2. Heat Transmission

Heat transmission through the system of glass window installed with a venetian blind can be expressed as the summation of the solar heat gain and the conduction heat gain. The expression of the heat gain can be written as

$$q = \{SHGC(\theta,\psi)\}I + U\Delta T \quad (1)$$

where q is heat gain (*W/m*^{2}). $SHGC$ is the solar heat gain coefficient. U is the overall heat transfer coefficient (*W/m*^{2}*-K*). ΔT is the temperature difference between the indoor and outdoor condition (*K*). I is the incident solar radiation, (*W/m*^{2}). θ is the solar incident angle (degree). ψ is the azimuth angle (degree).

By treating a curved venetian blind as an effective layer, the solar heat gain coefficient of the glass window installed with venetian blind is dependent on both the solar incident angle and azimuth angle. Fig. 1 shows the solar radiation beam incident on the combined system of glass window and a venetian blind and its related angles.

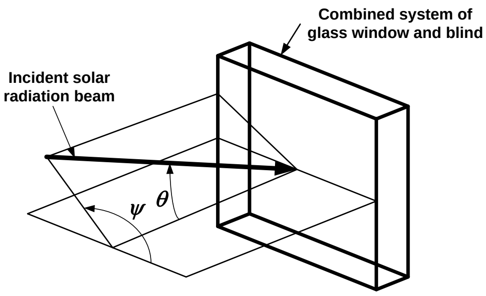

Fig. 1 The system of glass window installed with a venetian blind with the incident solar radiation.

The solar heat gain coefficient of the system of the glass window installed with venetian blind can be written as

$$SHGC(\theta,\psi) = T^{fH}_{\{1,M\}}(\theta,\psi) + \sum_{k=1}^{M} N_k A^{f}_{k,\{1,M\}}(\theta,\psi) \quad (2)$$

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. 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

$$\phi_s = \tan^{-1}(\sin\psi \tan\theta) \quad (3)$$

where ϕ_s is the solar profile angle.

The optical properties shown in the equation 2 ($T^{fH}_{\{1,M\}}$, $A^{f}_{k,\{1,M\}}$) can be solved by using the matrix layer calculation method to combine the optical properties of the glass window and of a curve venetian blind as shown in reference [17].

The convective conductance coefficients for exterior surfaces and gaps between layers can be first determined from the relations suggested by Finlayson et al. [18]. The relationship of the convective conductance coefficients for the outermost glass windows is a function of wind speed and direction and can be expressed on the windward side of the building as

For $V >$ 2 m/s $\quad h_{c,out} = 8.07V^{0.605} \quad (4)$

For $V <$ 2 m/s $\quad h_{c,out} = 12.27 \quad (5)$

On the leeward side of the building as

$$h_{c,out} = 18.64\left(0.3 + 0.05V\right)^{0.605} \quad (6)$$

where $h_{c,out}$ is the convective conductance coefficient for outermost layer, *W/(m^2-K)*. V is wind velocity (*m/s*).

The relationship for the convective conductance coefficient for the inner most layer (venetian blind) and the room air is adopted from the experimental data for natural convection between room air and a vertical plate given by Arasteh et al., [19] as

$$h_{c,in} = 1.77\left(\left|T_{s2n} - T_{room}\right|\right)^{0.25} \quad (7)$$

where $h_{c,in}$ is the convective conductance coefficient for innermost layer *(W/(m^2-K))*. T_{s2n} is the surface temperature of the innermost layer (surface *2n*) (*K*). T_{room} is the room temperature *(K)*.

The relationship for the convective conductance coefficient for the gap between two glass surfaces and the gap between the glass and the blind can be determined from the expression given by Elsherbiny et al., [20] as

$$h_{c,gap,j} = \frac{k_f Nu}{w} \quad (8)$$

$$Nu = \left[1 + \left(0.0303 Ra^{0.402}\right)^{11}\right]^{0.091} \text{ for } Ra < 2\text{x}10^5 \quad (9)$$

$$Ra = Gr \cdot \Pr$$

$$Gr = \frac{g\beta\rho^2 w^3 \Delta T}{\mu^2} \quad (10)$$

where $h_{c,gap,j}$ is the convective conductance coefficient for the gap between two glass surfaces (*W/(m^2-K)*). Nu is the gap Nusselt number. Ra is the Rayleigh number. Gr is the Grashoff number. $\Pr$ is the Prandtl number. k_f is the thermal conductivity of the gas in the gap (*W/(m-K)*). w is the width of the gas gap *(m)*. g is the gravitational acceleration (*m/s^2*). β is the coefficient of thermal expansion (1/K). ρ is the gas density *(kg/m^3)*. μ is the gas viscosity *(N-s/m^2)*. ΔT is the temperature difference across the gap *(K)*.

By treating the venetian blind as an diathermanous layer (layer which the radiative heat can be transferred across the layer, i.e. the radiative heat from the surface of the inner glass can flow across the blind to the inner space), the inward–flowing fraction of the absorbed energy for *k*th layer in the system, N_k, and the overall heat transfer coefficient can be found from the concept of the resistance of the heat flow as shown in reference [21]. With the developed mathematical model, the solar heat gain coefficient and the overall heat transfer coefficient for the glass window installed with a curved venetian blind can now be determined.

3. Verification

To verify the accuracy of the mathematical developed for calculating the solar heat gain coefficient and the overall heat transfer coefficient for the combined glass window system installed with a curve venetian blind, the simulation results shall be compared with the experimental results. The experimental results for this study are obtained from the work of Collins and Harrison [22]. Collins and Harrison used a technique called solar calorimetry to test the double clear glass installed with a curved venetian blind. Fig. 2 shows the experimental apparatus that Collins and Harrison performed their work (details of the experimental apparatus can be seen from reference [22]). Two sets of venetian blind with three blind slat angle and two solar profile angles were used when performed the experiment.

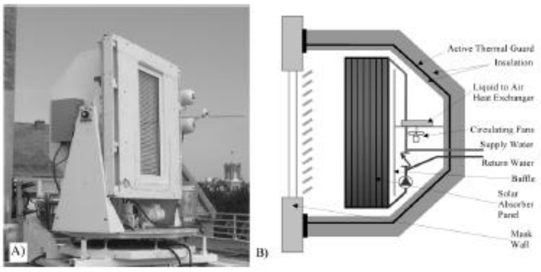

Fig. 2. Solar calorimeter (A) photo of the calorimeter and (B) cross-sectional schematic (not to scale) [22].

The glass window was composed of two panes of 3 mm clear glass with a 13 mm air gap. The blind slat had a width of 25.4 mm, thickness of 0.17 mm; and an arc length and a radius of curvature of 27.3° and 52.3 mm. The slats were separated by a pitch of 22.2 mm. One blind had a white enameled surface while the other was painted flat black. The white blind has a solar absorptance of 0.32 and hemispherical emissivity of 0.75. The black blind has a solar absorptance of 0.9 and hemispherical emissivity of 0.89. The combined conductivity of the aluminum slat and enameled coating was found to be 120 *W/m-K*. Experiment were performed for each blind at three blind slat angles of -45°, 0°, and 45° and at solar profile angles of 30° and 45°. During tests, the blinds were installed at a nominal distance (center of slat to inner glass) of 30 mm.

The simulation is done to determine the solar heat gain with the same condition used in the experiment performed by Collins and Harrison [22]. The values of solar heat gain coefficient obtained from the experiment were the solar heat gain coefficient that taking into account for direct solar radiation and diffuse solar radiation. Therefore the values of solar heat gain coefficient used for compared with the experimental results can be obtained from the following relation:

$$SHGC = \{(SHGC_D)I_D + (SHGC_d)I_d\}/(I_D + I_d) \quad (11)$$

Where $SHGC_D$ is the solar heat gain coefficient for direct solar radiation. $SHGC_d$ is the solar heat gain coefficient for diffuse solar radiation. I_D is the direct solar radiation. I_d is the diffuse solar radiation. The comparison between the experimental results and the simulation results are shown in table 1.

One can see from table 1 the agreement between the values of the simulation results and the experimental results are quite good. The greatest in the deviation is within 10 %. Unfortunately, Collins and Harrison [22] did not give the experimental results on the value of the overall heat transfer coefficient from the tests.

Table. 1 The values of SHGC from the experiment [22] and simulation with I_D and I_d of 562 and 167.9 W/m^2.

Condition	$SHGC_e$	$SHGC_s$
White, 30° incidence, 0° slat	0.59	0.632
White, 45° incidence, 0° slat	0.56	0.546
White, 30° incidence, 45° slat	0.46	0.429
White, 45° incidence, 45° slat	0.44	0.403
White, 30° incidence, -45° slat	0.65	0.655
White, 45° incidence, -45° slat	0.65	0.702
Black, 30° incidence, 0° slat	0.65	0.677
Black, 45° incidence, 0° slat	No	0.618
Black, 30° incidence, 45° slat	0.64	0.607
Black, 45° incidence, 45° slat	0.64	0.591
Black, 30° incidence, -45° slat	0.68	0.712
Black, 45° incidence, -45° slat	No	0.725

Note: $SHGC_e$ is the experimental value. $SHGC_s$ is the simulation value. “No” means no data available. All the experimental values shown are within ±0.01.

4. Thermal Performance

In this study, the thermal performance of the system of glass window installed with a curved venetian blind is investigated. Two types of glass window, two types of venetian blind and three slat angles are used to study the variation of the heat transmission through the system of glass window installed with venetian blind with the solar profile angle. The solar heat gain coefficient and the overall heat transfer coefficient are used as the heat transmission indices in this study (see eq. 1). Two types of glass window are single pane clear glass and double pane clear glass. The single pane clear glass is 6 mm thick. The double pane clear glass is consisted of two 6 mm clear glass with 6 mm air gap in between. Two types of blind are white and black blind. The slat of the blind has a width of 25.4 mm and thickness of 0.17 mm. The slat has an arc length and a radius of curvature of 27.3° and 52.3 mm. The slats are separated by a pitch of 22.2 mm. The conductivity of the slat is 120 *W/m-K*. The optical properties of the glass and the blind are shown in table 2.

Table. 2 Glass and slat optical properties

Description	Solar Energy			Emissivity	
	Trn	Ref	Ab	Ef	Eb
Clear glass	0.80	0.08	0.12	0.84	0.84
2 Clear glass	0.572	0.108	note	0.84	0.84
White slat	-	0.68	0.32	0.75	0.75
Black slat	-	0.10	0.90	0.89	0.89

Note: for 2 clear glass, absorptance of 1st glass = 0.186, absorptanceof of 2nd glass = 0.134.

Trn = transmittance, Ref = reflectance, Ab = absorptance, Ef = front emittance, Eb = back emittance.

The blind is installed with a 30 mm distance from the inner glass surface. Three slat angles used in the simulation are 45, 0 and -45 degree. The inside room temperature is set at 24 °C.

Fig. 3 shows the variations of the solar heat gain coefficient of the system of single pane clear glass window and venetian blind compared with the plain clear glass of different solar profile angle. Fig. 4 shows the variations of the solar heat gain coefficient of the system of double pane clear glass window and venetian blind compared with the plain double clear glass window of different solar profile angle.

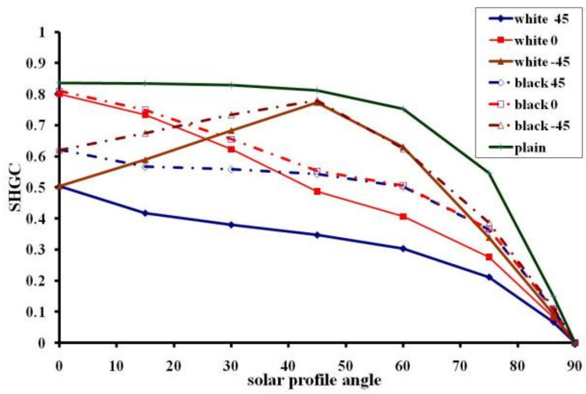

Fig. 3 Variations of the solar heat gain coefficient for single pane clear glass window and blind in different slat angles.

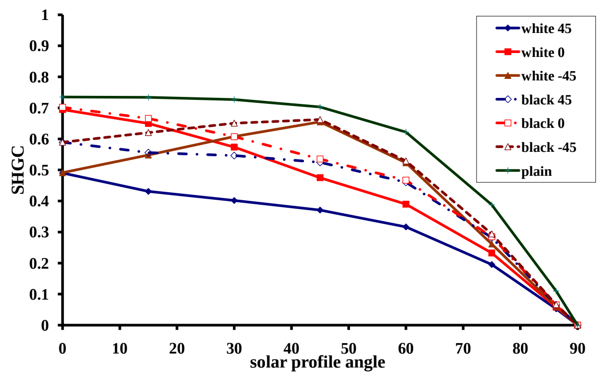

Fig. 4 Variations of the solar heat gain coefficient for double pane clear glass window and blind in different slat angles.

From Fig. 3, one can see that the solar heat gain coefficient for the plain clear glass is dependent on the solar profile angle. It has the maximum value of 0.836 at zero solar profile angle and the value is slowly decreased as the solar profile angle is increased up to about 60 degree. Then its value is rapidly decreased to 0 at 90 degree of solar profile angle. When the blind is installed behind the glass window the value of the solar heat gain coefficient of the combined glass window system is decreased compared to value of the plain glass window. The variations of the solar heat gain coefficient of the combined glass window system are dependent on slat angle. At 45º slat angle the value of the solar heat gain coefficient is at 0.5036 at 0º solar profile angle. The value of the solar heat gain coefficient is continuously decreasing when the solar profile angle is increasing. For 0º slat angle, the value of the solar heat gain coefficient is at 0.801 at 0º solar profile angle. The value of the solar heat gain coefficient is continuously decreasing when the solar profile angle is increasing. For -45 º slat angle, the value of the solar heat gain coefficient is at 0.5044 at 0º solar profile angle. The value of the solar heat gain coefficient is continuously increasing when the solar profile angle is increasing until it reaches 45º. Then the solar heat gain coefficient is continuously decreased when the solar profile angle is further increased. The explanation of the increasing of the solar heat gain coefficient for the case of -45º slat angle is that when the solar profile angle is increasing from 0 to 45º, more solar radiation beam can be penetrated through the blind into the room. Once the solar profile angle is greater than 45º the slat starts to block the solar radiation beam from entering into the room causing the value of solar heat gain coefficient to decrease.

The effect of slat optical properties on the solar heat gain coefficient can be observed in Fig. 3 from results of white blind (solid line) and black blind (dot line) case. The white blind has high slat reflectance (0.68) compared to the black blind (0.10). The blind with high slat reflectance (low absorptance) gives the value of solar heat gain coefficient lower than the value of solar heat gain coefficient for the blind with low slat reflectance (high absorptance). Among three slat angles, the effect of the slat optical properties on the solar heat gain coefficient is clearly seen in 45º slat angle case.

For the case of double pane clear glass window in Fig. 4, the variations of the solar heat gain coefficient of the glass system installed with blind are in the similar pattern with the single pane glass window in Fig. 3. The reduction of the solar heat gain coefficient of the glass window system compared to the plain double pane glass is less than the case of glass window system of single pane glass. The reason is that a single pane clear glass has the value of transmittance higher than the double pane clear glass. When installing a high reflectance venetian blind (white blind) behind the single pane clear glass, part of the direct and diffuse solar radiation transmitted through the glass incident on the blind will reflect back through the glass to outside. The heat transmission through the glass system therefore is reduced. For double pane clear glass which has lower transmittance than the single pane clear glass, the capability of letting the reflected radiation from the blind passing through the glass window to outside is lesser than the single pane clear glass. Therefore the reduction in heat transmission of the double pane glass window with blind is lesser than the single pane glass window system.

Table 3 and table 4 show the reduction in percentage of the solar heat gain coefficient for the glass window installed with venetian blind compared to the plain glass window.

Table. 3 The reduction in percentage of SHGC for the single pane glass window with venetian blind compared to the single pane glass.

Solar profile angle, degree	% Reduction in SHGC				
	0	15	30	45	60
White 45	39.76	49.96	54.14	57.23	59.67
White 0	4.16	12.13	24.89	39.95	46.01
White -45	39.66	29.45	17.57	4.72	16.29
Black 45	25.73	32.14	32.66	33.09	33.35
Black 0	3.13	10.29	20.99	31.92	32.71
Black -45	25.76	19.16	11.47	3.88	17.06

Table. 4 The reduction in percentage of SHGC for the double pane glass window with venetian blind compared to the double pane glass.

Solar profile angle, degree	% Reduction in SHGC				
	0	15	30	45	60
White 45	33.31	41.27	44.73	47.24	49.08
White 0	5.48	11.47	21.09	32.42	37.31
White -45	33.16	25.33	16.38	6.83	15.87
Black 45	19.84	24.25	24.83	25.38	25.98
Black 0	4.48	9.26	16.46	23.85	24.89
Black -45	19.84	15.46	10.49	5.76	14.93

The magnitude of the reduction of the solar heat gain coefficient is mainly dependent on the type of the blind, the slat angle and the solar profile angle. For slat angle of 45 and 0 degree, the reduction in solar heat gain coefficient for the glass window with blind compared with the plain glass window is increased with the solar profile angle. Only at -45 degree slat angle, the reduction in solar heat gain coefficient for the glass window with blind compared with the plain glass window is decreased as the solar profile angle increased until the solar profile angle reaching 45 degree. The reduction in solar heat gain coefficient starts to increase when the solar profile angle is further increased. Installed venetian blind to the single pane clear glass window yields more reduction in solar heat gain coefficient compared to the double pane glass window in the same operating condition. The white blind at the solar profile angle of 60 degree and slat angle of 45 degree gives the maximum value in the percentage of reduction for the solar heat gain coefficient value compared to the plain clear glass in both the single plain clear glass and double plain clear glass.

Fig. 5 shows the variations of the overall heat transfer coefficient of the system of glass window and venetian blind compared with the plain glass (single pane clear and double pane clear glass window).

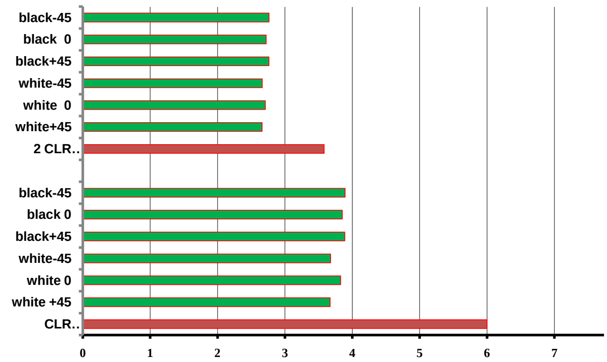

Fig. 5 Variations of the overall heat transfer coefficient for single pane glass window (CLR) with blind and double pane glass window (2CLR) with blind at different slat angles.

The overall heat transfer coefficient for the glass window is reduced when installed the blind behind the glass window as can be seen in Fig. 5. The effect of the slat angle and slat optical properties on the value of the overall heat transfer coefficient of the glass window installed with the venetian blind are quite negligible.

5. Conclusion

From the study, installing the venetian blind behind the glass window can significantly reduce the heat transmission into the space. The reduction in heat transmission comes from the reduction in the value of the solar heat gain coefficient and the overall heat transfer coefficient. It is also found that the solar heat gain coefficient of the glass system is dependent on the solar profile angle. By setting the blind at different slat angle, the value of the solar heat gain coefficient is different. The blind with a higher reflectance when installed to a higher transmittance glass window will give a better thermal performance in term of heat reduction. For this specific case, by installing a high reflective venetian blind (white blind) behind the single pane clear glass window, the solar heat gain coefficient is reduced as much as 59.7 percent compared to the solar heat gain coefficient of the plain clear glass (at slat angle of 45 degree and solar profile angle of 60 degree).

6. Acknowledgement

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