A study on the thermal performance of a curved vertical venetian blind

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Abstract

A study on the thermal performance of a glass window with a curved vertical venetian blind installed is performed. The curved vertical venetian blind is considered as a nonspecular element and a diathermanous layer. The curved vertical venetian blind is installed behind the glass window as an indoor shading device. The mathematical model is developed to predict the solar heat gain through the glass window with a curved vertical venetian blind installed. The solar heat gain coefficient (SHGC) is chosen to be the thermal performance index for this study. The curved vertical venetian blind is treated as an effective layer. The shortwave and longwave optical properties of the curved vertical venetian blind are determined by using the radiosity method. The combined optical properties of the glass window and a curved vertical venetian blind is developed by combining the optical properties of the glass window and the optical properties of the curved vertical venetian blind using the matrix layer calculation method. In this study, the thermal performance predicted by the developed mathematical model is based on 6 mm single pane clear glass window and a curved vertical venetian blind with reflectivity of 0.7 and emissivity of 0.87. The study shows that the SHGC for the glass window with a curved vertical venetian blind installed is dependent on the slat angle and the vertical solar profile angle. The variation of the SHGC of the glass window with a curved vertical venetian blind installed for a specific slat angle is also dependent on the position of the sun relative to the glass window (positive value or negative value of solar vertical profile angle). In this study, it is found that the greatest reduction in the value of SHGC of the glass window with the vertical blind installed from the value of SHGC of the plain glass window is achieved when the slat angle is set at 45 degree and the solar vertical profile angle has a positive value.

Keywords: glass window, curved vertical venetian blind, solar vertical profile angle, solar heat gain coefficient.

1. Introduction

Buildings, which are located in the tropical zone near the equator, usually receive a large amount of solar radiation into the building through the glass windows. This high solar radiation turns into a high cooling load for the building. A large air conditioning system is usually required for removing the high solar cooling load from the building. To reduce the energy usage in building from the air conditioning system, the high efficiency glass in term of heat reduction should be used as the glass window for 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 such as the venetian blind besides the understanding of the thermal performance of the plain glass window. Much work has been done about the heat transmission through the glass window with venetain blind installed. But most of the works [1-10] are dealt with the flat slat horizontal blind. Chaiyapinunt and Worasinchai [11, 12] have developed a mathematical model to calculate the shortwave optical properties for a curved slat horizontal venetian blind with thickness and a mathematical model to calculate the longwave optical properties for a curved slat horizontal venetian blind by including both the effect of slat curvature and the effect of slat thickness in the mathematical model. Chaiyapinunt and Khamporn [13] have also performed a study on the effect of installing a curved horizontal venetian blind to the glass window on heat transmission to the space. All the works mentioned are specifically based on the horizontal venetian blind. In this article, the study of thermal performance of glass window with a curved vertical venetian blind installed in term of solar heat transmission is performed. The effect of slat angle and solar vertical profile angle on the thermal performance is also investigated.

2. Mathematical model for a curved vertical venetian blind

The curved vertical venetian blind in this study is modeled as an effective layer. The solar heat gain coefficient for the combined glass window and the venetian blind [13] 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 kth layer in the system. N_k is the inward – flowing fraction of the absorbed energy for kth layer in the system. θ is the incident angle. ψ is the azimuth angle (as defined in Fig. 1). The relationship between the solar vertical profile angle (the angle of incidence in a horizontal 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

$$\phi_{vs} = \tan^{-1}(\cos\psi \tan\theta) \quad (2)$$

where ϕ_{vs} is the solar vertical profile angle. In this study, the solar vertical profile angle is varied in the range from 0 to 90 degree (positive solar vertical profile angle) and 0 to -90 degree (negative solar vertical profile angle) in the horizontal plane perpendicular to the system of glass window and blind.

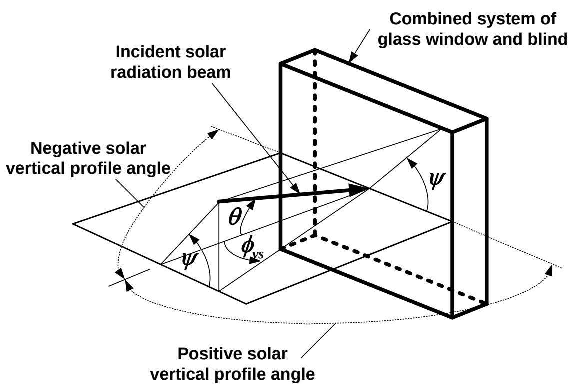


Fig. 1 The combined system of glass window and blind with the incident solar radiation.

Therefore, the solar heat gain coefficient for the combined glass window and the venetian blind can be rewritten as

$$SHGC(\phi_{vs}) = T^{fH}_{\{1,M\}}(\phi_{vs}) + \sum_{k=1}^{M} N_k A^f_{k,\{1,M\}}(\phi_{vs}) \qquad (3)$$

The solar heat gain coefficient can be further divided into the solar heat gain coefficient for direct solar radiation and the solar heat gain coefficient for diffuse solar radiation. In this study, only the solar heat gain coefficient for the direct solar radiation is considered.

The optical properties of the vertical 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 vertical blind with thickness

The slats of the vertical blind are assumed to be perfect diffusers and all the slats have the same optical properties. The whole blind assembly is represented by two consecutive vertical slats as shown in Fig. 2.

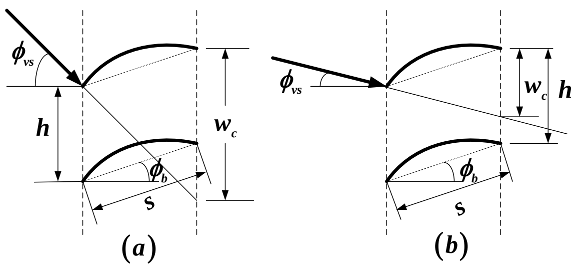


Fig. 2 Curved slat vertical blind at different solar vertical profile angle seen in the horizontal plane.

Fig. 2 shows the projected views of the blind in the horizontal plane in two sun positions. Fig. 2(a) shows the projected view of the blind at the sun position that no part of the direct radiation can directly pass through the blind without touching the slat surfaces. Fig. 2(b) shows the projected view of the blind at the sun position that there is a part of the direct radiation directly pass through the blind without touching the slat surfaces.

The optical properties of the blind can be classified as the shortwave optical properties and longwave optical properties. 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.

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 [11] as

$$\tau^f_{bl-ct,dir,dir} = 1 - \frac{w_t}{h_t} \quad \text{when } w_t \le h_t \qquad (4)$$

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 is the blocked distance from the curved slat with thickness effect. h_t is the distance between two adjacent slats which accounted for thickness effect. 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. 3.

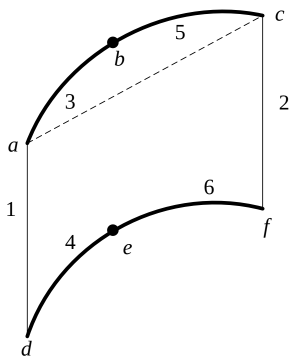


Fig. 3 Six surface closed enclosure formed by two consecutive slats.

The optical properties of the effective layer for a curves vertical venetian blind with thickness now can be evaluated according to the method proposed by Chaiyapinunt and Worasinchai [11] and can be written as

$$\tau^f_{bl-ct,dir,dif} = \tau^f_{bl-c,dir,dif}\left(1-bf\right) \quad (5)$$

$$\rho^f_{bl-ct,dir,dif} = \rho^f_{bl-c,dir,dif}\left(1-bf\right)+\rho^f_s\left(bf\right) \quad (6)$$

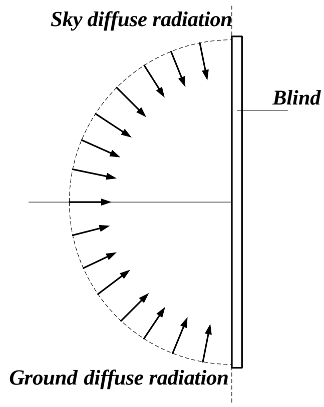
$$\alpha^f_{bl-ct,dir,dif} = 1-\tau^f_{bl-ct,dir,dir}-\tau^f_{bl-ct,dir,dif}-\rho^f_{bl-ct,dir,dif} \quad (7)$$

$$bf = \frac{t_b\cos\left(\phi_b+\phi_{vs}\right)}{\left(h+\dfrac{t_b}{\cos\phi_b}\right)\cos\phi_{vs}} \quad (8)$$

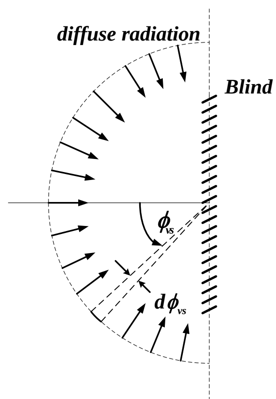
where $\tau^f_{bl-ct,dir,dif}$ is the front direct-to-diffuse transmittance of the effective layer for curved blind with thickness. $\tau^f_{bl-c,dir,dif}$ is the front direct-to-diffuse transmittance of the effective layer for curved blind without effect of thickness. $\rho^f_{bl-ct,dir,dif}$ is the front reflectance of the curved blind with thickness for direct radiation. $\rho^f_{bl-c,dir,dif}$ is the front reflectance of the curved blind without effect of thickness. 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. bf is the blind edge correction factor. ϕ_{vs} is the solar vertical 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.

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. But in this study, the analysis is performed based on the incident solar radiation on the horizontal projected plane normal to the blind surface. 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. 4.



(a) Side view



(b) Top view

Fig. 4 Distribution of diffuse radiation on the vertical venetian blind.

Fig. 4(a) shows side view of the blind with the diffuse radiation reaching the blind from every direction, both downward from the sky and upward from the ground. Fig. 4(b) shows the top view of the blind (projected view in the horizontal plane perpendicular to the blind) with the incident diffuse solar radiation.

The optical properties for diffuse radiation can expressed as

$$\tau^f_{bl-ct,sky-dif,dif}=\frac{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\left[\tau^f_{bl-ct,dir,dir}(\phi_{vs})+\tau^f_{bl-ct,dir,dif}(\phi_{vs})\right]I_{sky}(\phi_{vs})\cos\phi_{vs}\,d\phi_{vs}}{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}I_{sky}(\phi_{vs})\cos\phi_{vs}\,d\phi_{vs}} \quad (9)$$

$$\tau^f_{bl-ct,gnd-dif,dif}=\frac{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\left[\tau^f_{bl-ct,dir,dir}(\phi_{vs})+\tau^f_{bl-ct,dir,dif}(\phi_{vs})\right]I_{gnd}(\phi_{vs})\cos\phi_{vs}\,d\phi_{vs}}{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}I_{gnd}(\phi_{vs})\cos\phi_{vs}\,d\phi_{vs}} \quad (10)$$

$$\rho^f_{bl-ct,sky-dif,dif}=\frac{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\rho^f_{bl-ct,dir,dif}I_{sky}(\phi_{vs})\cos\phi_{vs}\,d\phi_{vs}}{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}I_{sky}(\phi_{vs})\cos\phi_{vs}\,d\phi_{vs}} \quad (11)$$

$$\rho^f_{bl-ct,gnd-dif,dif}=\frac{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\rho^f_{bl-ct,dir,dif}I_{gnd}(\phi_{vs})\cos\phi_{vs}\,d\phi_{vs}}{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}I_{gnd}(\phi_{vs})\cos\phi_{vs}\,d\phi_{vs}} \quad (12)$$

$$\alpha^f_{bl-ct,sky-dif,dif}=\frac{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\alpha^f_{bl-ct,dir,dif}I_{sky}(\phi_{vs})\cos\phi_{vs}\,d\phi_{vs}}{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}I_{sky}(\phi_{vs})\cos\phi_{vs}\,d\phi_{vs}} \quad (13)$$

$$\alpha^f_{bl-ct,gnd-dif,dif}=\frac{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\alpha^f_{bl-ct,dir,dif}I_{gnd}(\phi_{vs})\cos\phi_{vs}\,d\phi_{vs}}{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}I_{gnd}(\phi_{vs})\cos\phi_{vs}\,d\phi_{vs}} \quad (14)$$

where $\tau^f_{bl-ct,sky-dif,dif}$ is the front transmittance of the effective layer for a curved vertical 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 vertical 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 vertical blind with thickness for direct radiation in the part which is directly passing through the blind without touching the slat at a solar vertical profile angle ϕ_{vs}. $\tau^f_{bl-ct,dir,dif}$ is the front transmittance of the effective layer for a curved vertical blind with thickness for direct radiation in the part which is incident on the slat at a solar vertical profile angle of ϕ_{vs}. $\rho^f_{bl-ct,sky-dif,dif}$ is the front reflectance of the effective layer for a curved vertical 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 vertical 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 vertical blind with thickness for direct radiation. $\alpha^f_{bl-ct,sky-dif,dif}$ is the front absorptance of the effective layer for a curved vertical 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 vertical 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 vertical 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 inward – flowing fraction factor in Eq. 1 can be evaluated from the longwave optical properties of the glass window and the curved vertical venetian blind. The detail of the development of the longwave optical properties of the blind can be found from reference [12].

3. Mathematical model for a combined glass window and the curved venetian blind

The combined optical properties of the fenestration system can be calculated by combining the optical properties of each layer (glass and venetian blind) in the system using the matrix layer calculation method [2, 3, 11]. The optical properties of the glass window and the vertical venetian blind have to rewrite in the form of bi-directional properties. 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 (see the set up method in reference [14]). 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.

4. Thermal Performance

In this study, the thermal performance of the system of glass window and a curved vertical venetian blind is investigated. A 6 mm single pane clear glass window and a curved vertical venetian blind are chosen for this study. The optical properties of the glass window and the curved vertical venetian blind are shown in table 1. The slat of the blind has a width of 100 mm and thickness of 0.3 mm. The slat has an angle of the arc length and a radius of curvature as 23.38º and 245.07 mm, respectively. The slats are separated by a pitch of 80 mm. The conductivity of the slat is 120 *W/m-K*. The blind is installed with a 70 mm distance measured from the inner glass surface to the center of the slat width. Five slat angles chosen for the simulation are 0, 30, -30, 45 and -45 degree. The inside room temperature is set at 25 ºC. The outside temperature is set at 35 ºC.

Table. 1 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
slat	-	0.70	0.30	0.87	0.87

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

Fig. 5 shows the slat alignment relative to the glass window from the horizontal projected view. Fig. 5(a) shows the vertical venetian blind with slat angle set at 0 degree. Fig. 5(b) shows the vertical venetian blind with slat angle set in the positive value (i.e. 30 and 45 degree). Fig. 5(c) shows the vertical venetian blind with slat angle set in the negative value (i.e. -30 and -45 degree).

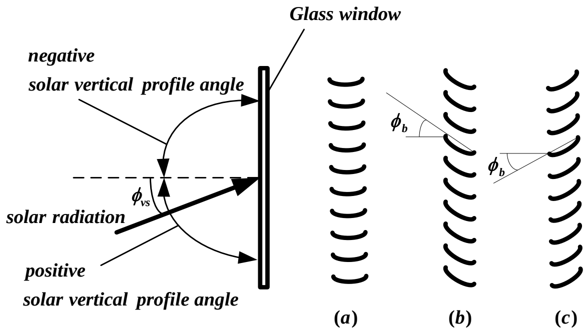


Fig. 5 Glass window and vertical venetian blind with slat setting at 0 angle, positive angle and negative angle.

The solar heat gain coefficient (SHGC) for direct solar radiation from Eq. 3 can be evaluated by using the developed mathematical model for certain value of the solar vertical profile angle. Fig. 6 shows the variations of the SHGC of the system of single pane clear glass window and vertical venetian blind with slat angle setting at 0 degree compared with the SHGC of the plain clear glass for different solar vertical profile angle. From Fig. 6, one can see that the SHGC for the plain clear glass is dependent on the solar vertical profile angle. For the positive value of solar vertical profile angle, the SHGC has the maximum value of 0.836 at 0 degree of solar vertical profile angle and the value is slowly decreased as the solar vertical profile angle is increased up to about 60 degree. Then its value is rapidly decreased to 0 at 90 degree of solar vertical profile angle. The variations of the SHGC of the clear glass window for the negative solar vertical profile angle is the same as the variations of the SHGC for the positive solar vertical profile angle.

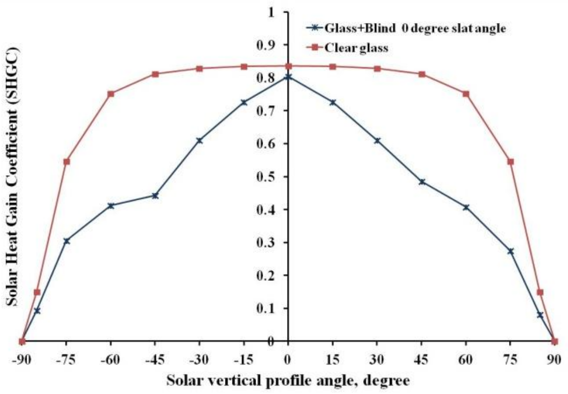


Fig. 6 Variations of the SHGC for a single pane clear glass window and a clear glass window with vertical venetian blind installed with slat angle setting at 0 degree.

When the blind is installed behind the glass window the value of the SHGC of the combined glass window system is decreased compared to value of SHGC of the plain glass window. The value of the SHGC of the combined glass window system is 0.804 at solar vertical profile angle equal to 0 degree. The value of the SHGC is continuously decreasing when the solar vertical profile angle is increasing. The variations of the SHGC is the same for both the positive and negative value of solar vertical profile angle when the solar profile angle is in the range of 0 to 30 degree and 0 to -30 degree. The effect of the curvature of the blind is clearly seen when the solar vertical profile angle is greater than 30 and -30 degree. The value of SHGC at the positive solar vertical profile angle becomes different from the SHGC at the negative solar vertical profile angle.

Figs. 7 and 8 show the variations of the SHGC of the system of single pane clear glass window and vertical venetian blind at 30 degree and -30 degree of slat angle compared with the SHGC of the plain clear glass for different solar vertical profile angle. When the blind having the slat angle set at 30 degree is installed behind the glass window the value of the SHGC of the combined glass window system is decreased compared to value of SHGC of the plain glass window. The SHGC is 0.604 at solar vertical profile angle equal to 0 degree. The value of the SHGC is continuously decreasing when the solar vertical profile angle is increasing. The value of the SHGC is decreasing to 0 at solar vertical profile angle of 90 degree. When the solar vertical profile angle has the negative value, the SHGC is still further increasing and reaching the maximum value at solar vertical profile angle equal to -30 degree. Blind in this position (30 degree slat angle) is aligned with the direction of the beam normal solar radiation. Most of the solar radiation is passing through the glass window into the room causing the SHGC reached the maximum value at this slat position. When the solar vertical profile angle is further increased in the negative value, the value of the SHGC is decreasing resulted from the blockage of the blind from the solar radiation. The value of the SHGC is reduced to 0 at solar vertical profile angle of -90 degree. The reduction of the SHGC resulted from installing the blind behind the glass window is obvious when the blind is in the position that the solar vertical profile angle has positive value.

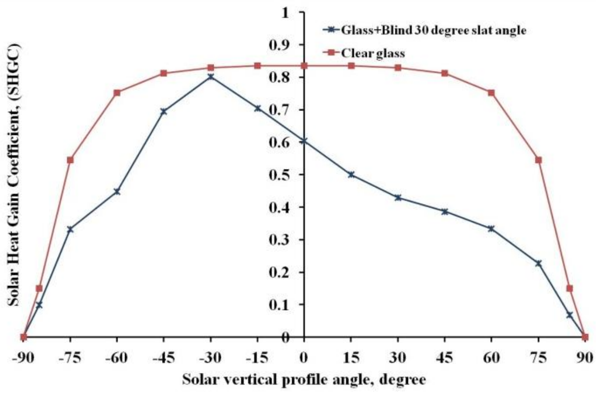


Fig. 7 Variations of the SHGC for a single pane clear glass window and a clear glass window with vertical venetian blind installed with slat angle setting at 30 degree.

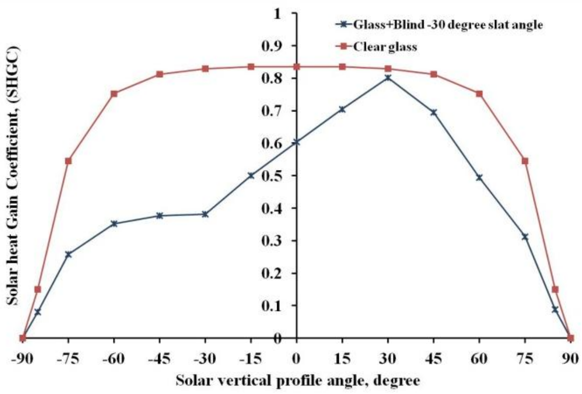


Fig. 8 Variations of the SHGC for a single pane clear glass window and a clear glass window with vertical venetian blind installed with slat angle setting at -30 degree.

When the blind with slat angle setting at -30 degree is installed behind the glass window the value of the SHGC of the combined glass window system is decreased compared to value of the SHGC of the plain glass window. The value of the SHGC is increasing to the maximum value when the solar vertical profile angle equal to 30 degree. Blind in this position (-30 degree slat angle) is aligned with the direction of the beam normal solar radiation. Most of the solar radiation is passing through the glass window into the room causing the SHGC reached the maximum value at this slat position. When the solar vertical profile angle is further increased in the positive value, the value of the SHGC is decreasing resulted from the blockage of the blind from the solar radiation. The value of the SHGC is reduced to 0 at solar vertical profile angle of 90 degree. When the solar vertical profile angle has the negative value, the SHGC is still further decreasing and reaching the value of 0 at solar vertical profile angle equal -90 degree. The reduction of the SHGC from the installing the blind at slat angle equal to -30 degree behind the glass window is obvious when the blind is in the position that the solar vertical profile angle has negative value.

Figs. 9 and 10 show the variations of the SHGC of the plain clear glass window and the SHGC of the clear glass window with blind at slat angle equal to 45 and -45 degree with solar vertical profile angle, respectively. The variations of the SHGC with the solar vertical profile angle is similar to the case of the blind having slat angle set at 30 degree and -30 degree as shown in Figs 7 and 8. The different is in the amount of the reduction in the SHGC of the glass window and blind system compared to the SHGC of the plain glass window. The effect of blind curvature can be seen from the irregular pattern of the SHGC at the solar vertical profile angle around -15 to -30 degree as shown in Fig. 9.

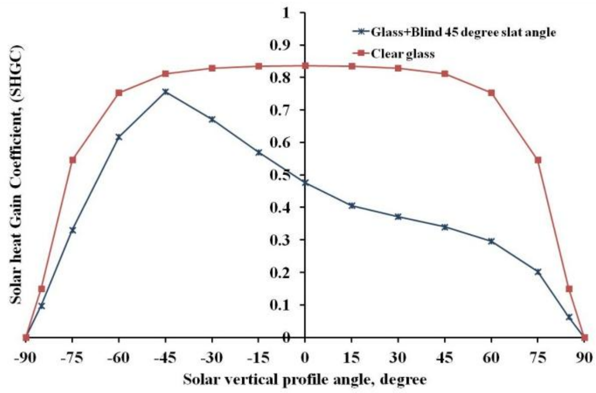


Fig. 9 Variations of the SHGC for a single pane clear glass window and a clear glass window with vertical venetian blind installed with slat angle setting at 45 degree.

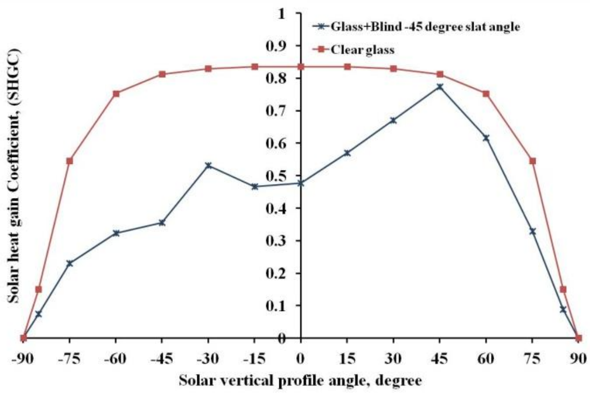


Fig. 10 Variations of the SHGC for a single pane clear glass window and a clear glass window with vertical venetian blind installed with slat angle setting at -45 degree.

5. Conclusion

From the study, installing the curved vertical venetian blind behind the glass window can significantly reduce the heat transmission in the part of solar radiation into the space. It is also found that the SHGC for direct solar radiation of the glass window system is dependent on the solar vertical profile angle. It is also found from this study that the solar vertical profile angle could have positive and negative value. By setting the blind at a positive slat angle, the reduction of the SHGC is dominated when the sun is in the position that the solar vertical profile angle is at negative value. By setting the blind at a negative slat angle, the reduction of the SHGC is dominated when the sun is in the position that the solar vertical profile angle is at positive value. For this study, the greatest reduction in solar heat gain in the part of direct solar radiation can be achieved when setting the slat angle to be 45 degree providing that the glass window is facing in the direction that the solar vertical profile angle is in the positive value. Therefore, using curved vertical venetian blind for reducing solar heat gain into the building, one has to aware of the orientation of the glass window to the sun (solar vertical profile angle) in setting the proper slat angle. In this article, the study of the thermal performance of the glass window with the curved venetian blind installed is only limited to the case of a clear glass window and one typical blind. The additional works are required to study for the effect of other related parameters (i.e. the system optical properties, etc.) on the thermal performance for the glass window with the curved vertical venetian blind installed.

6. Acknowledgement

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7. References

[1] Klems, J.H. (1994). A new method for predicting the solar heat gain of complex

fenestration systems: 1. Overview and Derivation of the Matrix Layer Calculation. *ASHRAE Transactions 100*, *1*: pp. 1065 - 1072.

[2] Klems, J.H. (1994). A new method for predicting the solar heat gain of complex fenestration systems: 2. Detailed Description of the Matrix Layer Calculation. *ASHRAE Transactions 100*, *1*: pp. 1073 - 1086.

[3] Klems, J.H., Warner, J. L., Kelley, G. O. (1995). ASHRAE solar heat gain project 548-RP, Final report: A new method for predicting the solar heat gain of complex fenestration systems. E.O. Lawrence Berkeley National Laboratory, *Technical Report LBL-36995*.

[4] Klems, J.H., Warner, J.L. and Kelley, G. O. (1996). A comparison between calculated and measured SHGC for complex glazing systems. *ASHRAE Transactions 102*, *1*: pp. 931 - 939.

[5] Klems, J.H. and Warner, J.L. (1997). Solar heat gain coefficient of complex fenestrations with a venetian blind for differing slat tilt angles. *ASHRAE Transactions 103, 1*, pp. 1026 – 1034.

[6] Collins, M.R. and Harrison, S.J. (2004). Estimating the solar heat and thermal gain from a window with an interior venetian blind. *ASHRAE Transactions 110, Part 1*, pp. 486 - 500.

[7] Pfrommer, P., Lomas, K.J. and Kupke CHR. (1996). Solar radiation transport through slat-type blinds: A new model and its application for thermal simulation of buildings, *Solar Energy*. 57, 2,. pp. 77 - 91.

[8] Chantrasrisalai, C. and Fisher, D.E. (2004). Comparative analysis of one-dimensional slat-type blind models, *Simbuild 2004*, *IBPSA-USA National Conference*, Boulder, CO, August 4-6.

[9] EnergyPlus, (2005). *EnergyPlus Engineering Reference: The Reference to EnergyPlus Calculation*, April.

[10] Yahoda, D.S. and Wright, J. L. (2004). Methods for calculating the effective longwave radiative properties of a venetian blind layer, *ASHRAE Transactions 110 Part 1*, pp. 463 - 473.

[11] Chaiyapinunt, S and Worasinchai, S. (2009). Development of a mathematical model for a curved venetian blind with thickness, *Solar Energy,* Vol 83 No.7, pp. 1093 – 1113.

[12] Chaiyapinunt, S and Worasinchai, S. (2009). Development of a model for calculating the longwave optical properties and surface temperature of a curved venetian blind, *Solar Energy*, Vol 83 No.6, pp. 817 – 831.

[13] Chaiyapinunt, S. and Khamporn, N. (2011). Effect of installing a curved venetian blind to the glass window on heat transmission, paper presented in *The Second TSME International Conference on Mechanical Engineering*, 19 - 21 October, 2011, Krabi, Thailand.

[14] Chaiyapinunt, S. and Khamporn, N. (2010). A Thermal performance study of a glass window installed with a curved venetian blind, paper presented in *The First TSME International Conference on Mechanical Engineering*, 20 - 22 October, 2010, Ubon Ratchathani, Thailand.