Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 110 (2014) 71–82

SOLAR ENERGY

www.elsevier.com/locate/solener

Heat transmission through a glass window with a curved venetian blind installed

Somsak Chaiyapinunt [a,*], Nopparat Khamporn [b]

[a] Department of Mechanical Engineering, Faculty of Engineering, Chulalongkorn University, Phayathai, Bangkok 10110, Thailand
[b] Department of Mechanical Engineering, Faculty of Engineering, Siam University, Petkasem, Bangkok 10160, Thailand

Received 9 January 2014; received in revised form 23 July 2014; accepted 30 August 2014

Communicated by: Associate Editor Mario A Medina

Abstract

This article reports a study on the effect of installing a curved venetian blind to a glass window on the solar heat transmission into the space. The mathematical model of the combined glass window and venetian blind is developed. Predicted results from the developed mathematical model are compared with the previous experimental ones to verify their accuracy. The variation of the solar heat gain coefficient (*SHGC*) with the related blind parameters (optical properties of venetian blind, slat spacing, distance between the blind and glass window, slat angle and solar profile angle) are studied. The variation of the *SHGC* in the shortwave part (*ShW SHGC*) and in the longwave part (*LoW SHGC*) with the related blind parameters are also studied. The understanding of their variation will provide the important information for the study of the thermal comfort for a person who stays near the glass window with blind. The *SHGC* can be further classified as the *SHGC* for direct solar radiation ($SHGC_D$) and the *SHGC* for diffuse solar radiation ($SHGC_d$). From the study it is found that installing a curved venetian blind to the glass window causes a significant reduction in solar heat gain compared to the plain glass window. The $SHGC_D$, $ShW\ SHGC_D$ and $LoW\ SHGC_D$ are all dependent on the slat angle and solar profile angle. The slat reflectance of the venetian blind has direct effect on the $ShW\ SHGC_D$. The slat absorptance of the venetian blind has direct effect on the $LoW\ SHGC_D$. The glass window and blind with high slat reflectance gives a lower value of $SHGC_D$ compared to the glass window and blind with low slat reflectance. The slat curvature also affects the $SHGC_D$ of the fenestration system (glass window with blind installed). The slat with more curvature (lower value of slat radius of curvature) causes more reduction in the value of $SHGC_D$ compared to the slat with less curvature. The blind with lower slat spacing yields a lower value of $SHGC_D$ compared to the blind with higher slat spacing. The effects of slat emittance and distance between the blind and the glass window on the $SHGC_D$ of the fenestration system are only appeared on the $LoW\ SHGC_D$ and such effects are quite small.

Keywords: Venetian blind; Glass window; Solar heat gain coefficient; Shortwave radiation; Longwave radiation; Thermal performance

1. Introduction

Glass windows are a common type of building envelope for most commercial buildings. They receive a plenty of heat gain into buildings from the incident solar radiation, especially in countries that are located in the tropic zone near equator. To reduce this solar heat gain and maintain thermal comfort for the occupants in the building, a large air conditioning system is usually required. The best way to reduce the solar cooling load is to prevent solar radiation from entering into the building inner space. Certain types of external shading devices such as roof overhangs, horizontal and vertical projections are preferred for

* Corresponding author.

http://dx.doi.org/10.1016/j.solener.2014.08.041
0038-092X/

preventing the solar radiation from entering into the building. But for certain types of buildings such as high rise office buildings, external shadings are not preferred due to the external wind load. In that case, using an expensive energy efficient glass (i.e. double pane reflective glass, double pane low-e glass and triple pane low-e glass, etc.) as a building envelope is the preferred way to reduce the solar heat gain. However, when the building is actually used, occupants often install a venetian blind as an indoor shading device to reduce the glare and to maintain the privacy. The building envelope to be analyzed becomes the glass window together with blind instead of the plain glass window alone. The venetian blind is considered as diathermanous (i.e. it transmits both shortwave and longwave radiation) and nonspecular optical element. Much work has been done on heat transmission through the glass window with venetian blind installed. But most of the works (Klems, 1994a,b; Klems et al., 1996; Klems and Warner, 1997; Collins and Harrison, 2004; Pfrommer et al., 1996; Chantrasrisalai and Fisher, 2004; EnergyPlus, 2005; Yahoda and Wright, 2004) dealt with the flat slat blind. Kuhn (2006a,b) has studied the solar control system including the venetian blind with arbitrary shapes of slat and their specular properties. Wright et al. (2008) through the ASHRAE sponsored research developed a simplified method to calculate the thermal performance of the glass window with a shading device system. Chaiyapinunt and Worasinchai (2009a,b) 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 the effects of both the slat curvature and the slat thickness in the mathematical model. Chaiyapinunt and khamporn (2013) have investigated the thermal performance of a glass window with a curved venetian blind installed in the shortwave part. It is found that the solar heat gain coefficient in the part of shortwave radiation (*ShW SHGC*) is mainly affected by the slat properties, slat angle and solar profile angle. The glass window using blind with a lower value of slat reflectance, will have a smaller value of *ShW SHGC*.

In this article, the complete study of the thermal performance of the glass window with a curved venetian blind installed in term of total solar heat gain and the solar heat gain in the part of shortwave and longwave radiation is performed. The effect of certain parameters on the thermal performance of the fenestration (glass window with a curved venetian blind installed) is performed. It is believed that with a clearly understanding of the thermal performance of the glass window with a curved venetian blind installed, the need of using the expensive energy efficient glass as the building envelope can be avoided. For an energy efficient building, besides minimizing the solar heat gain through the building envelope, the thermal comfort for the occupants in the building must be maintained. Chaiyapinunt et al. (2005) and Khamporn and Chaiyapinunt (2014) have shown that the thermal discomfort for a person who sits near glass window can be classified as the discomfort from the solar radiation striking on his body (shortwave effect) and the discomfort from the glass surface temperature (longwave effect). The thermal discomfort of a person who sits near the glass window with a curved venetian blind installed can also be classified as the discomfort from the solar radiation striking on his body (shortwave effect) and the discomfort from the glass surface temperature (longwave effect), as well (Khamporn, 2012). Without a thoroughly understanding about the *ShW SHGC* and *LoW SHGC* (solar heat gain coefficient in the part of longwave) of the fenestration, it is quite possible that though the total solar heat gain is minimized, but the occupants may need more extra cool air from the air conditioning system to compensate the local discomfort from either the shortwave effect or the longwave effect (depends on which component of the solar heat gain is dominated). Therefore, the understanding about the *ShW SHGC* and *LoW SHGC* of the fenestration is also important.

2. Mathematical model for the glass window with a curved venetian blind installed

Heat transmission through the system of glass window with a curved venetian blind installed 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:

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

where q is the 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), and ψ is the azimuth angle (angle of the incident radiation measured from the horizontal axis on the plane of the glass window as shown in Fig. 1) (degree). The heat gain from solar radiation can be further classified as the heat gain from the direct solar radiation (beam solar radiation) and

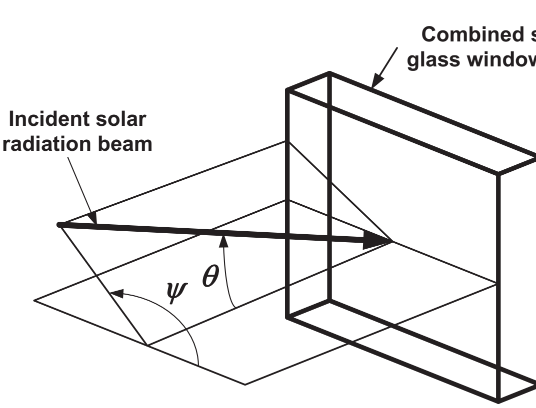

Fig. 1. The system of glass window with a venetian blind installed and the incident solar radiation. θ is the solar incident angle. ψ is the azimuth angle.

the heat gain from the diffuse solar radiation. The heat gain from solar radiation can be expressed as:

$$\{SHGC(\theta,\psi)\}I = \{SHGC_D(\theta,\psi)\}I_D + \{SHGC_d\}I_d \tag{2}$$

$$I = I_D + I_d \tag{3}$$

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 is the global solar radiation, I_D is the direct solar radiation, and I_d is the diffuse solar radiation.

Fig. 1 shows the solar radiation beam incident on the combined system of glass window and a curved venetian blind and its related angles. By treating a curved venetian blind as an effective layer, the $SHGC_D$ for the combined glass window and the venetian blind can be written as:

$$SHGC_D(\theta,\psi) = T^{fH}_{\{1,n\}}(\theta,\psi) + \sum_{k=1}^{n} N_k A^f_{k,\{1,n\}}(\theta,\psi) \tag{4}$$

where $T^{fH}_{\{1,n\}}$ is the directional-hemispherical front transmittance of a fenestration system (combined system of glass window and blind) with n layers, $A^f_{k,\{1,n\}}$ is the directional absorptance of the kth layer in the system, and N_k is the inward-flowing fraction of the absorbed energy for kth layer in the system. The solar profile angle (the angle of incidence in a plane that is perpendicular to the window and perpendicular to the slat direction) is also introduced in this analysis. The relationship between the solar profile angle and the incident angle and the azimuth angle can be written as:

$$\phi_s = \tan^{-1}(\sin\psi \tan\theta) \tag{5}$$

where ϕ_s is the solar profile angle.

The expression of the $SHGC_D$ for a fenestration system in Eq. (4) can be further divided into the $SHGC_D$ in the shortwave part (ShW $SHGC_D$: $(T^{fH}_{\{1,n\}}(\theta,\psi))$ and the $SHGC_D$ in the longwave part (LoW $SHGC_D$: $\left(\sum_{k=1}^{n} N_k A^f_{k,\{1,n\}}(\theta,\psi)\right)$.

The parameters in the expression of the $SHGC_D$ ($T^{fH}_{\{1,n\}}$, $A^f_{k,\{1,n\}}$, N_k and U) can be determined from the mathematical model developed by Chaiyapinunt and Khamporn (2013). The slats of the curved venetian blind are assumed to be perfect diffusers. The optical properties of the venetian blind can be classified as shortwave optical properties and longwave optical properties. The optical properties of the curved venetian blind with the thickness effect can be determined by the methods suggested by Chaiyapinunt and Worasinchai (2009a,b). Then the combined optical properties of the fenestration system can be calculated by combining the optical properties of the glass window and the optical properties of the venetian blind using the matrix layer calculation method (Klems (1994a,b)). With the combined optical properties of the fenestration system, the parameters in the $SHGC_D$ ($T^{fH}_{\{1,n\}}$, $A^f_{k,\{1,n\}}$) in Eq. (4) can be now evaluated. For the inward-flowing fraction of the k^{th} layer (N_k) and the overall heat transfer coefficient (U) of the fenestration system, they can be calculated by

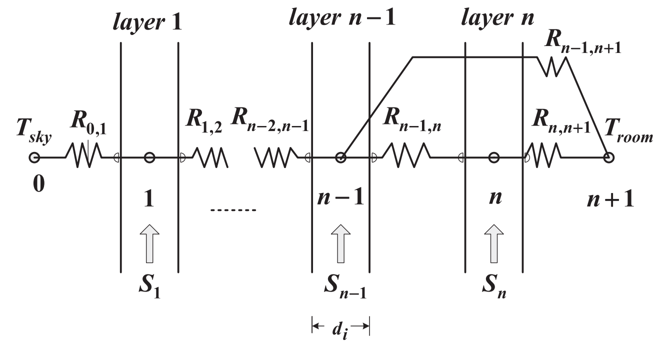

Fig. 2. The fenestration system of n layers which layer nth is the effective layer (venetian blind) and the related heat resistance network. $R_{i,j}$ is the resistance of the heat transfer between node i and node j of the fenestration system. S_i is the absorbed heat in the layer ith.

using the method of heat balance. Fig. 2 shows the fenestration system of n layers in which layer nth is the effective layer (venetian blind) and the related heat resistance network. The overall heat transfer coefficient and the inward-flowing fraction of the fenestration system of n layers can be expressed as:

$$U = \frac{\sum_{i=n-1}^{n} R_{i,i+1} + R_{n-1,n+1}}{\left[R_{n-1,n+1}\left(\sum_{i=0}^{n} R_{i,i+1}\right) + \left(\sum_{i=0}^{n-2} R_{i,i+1}\right)\left(\sum_{i=n-1}^{n} R_{i,i+1}\right)\right]} \tag{6}$$

For layer kth which $k = 1, n-1$.

$$N_k = U\sum_{i=0}^{k-1} R_{i,i+1} \tag{7}$$

For layer kth which $k = n$.

$$N_k = U\left[\sum_{i=0}^{k-1} R_{i,i+1} + \frac{R_{k-1,k}\sum_{i=0}^{k-2} R_{i,i+1}}{R_{k-1,k+1}}\right] - \frac{R_{k-1,k}}{R_{k-1,k+1}} \tag{8}$$

where $R_{i,j}$ is the heat resistance (in the mode of conduction, convection and radiation) between node i and node j of the fenestration system. The heat resistance between node i and node j of the fenestration system can be written as:

$$R_{i,j} = \frac{1}{h_{c,out} + h_{r,out}} + \frac{0.5d_1}{k_1} \quad \text{for } i = 0 \text{ and } j = 1 \tag{9}$$

$$R_{i,j} = \frac{1}{h_{c,in} + h_{r,in}} + \frac{0.5d_n}{k_n} \quad \text{for } i = n \text{ and } j = n+1 \tag{10}$$

$$R_{i,j} = \frac{1}{h_{c,gap\,i,j} + h_{r,gap\,i,j}} + \left(\frac{0.5d_i}{k_i} + \frac{0.5d_j}{k_j}\right) \quad \text{for } i = 1, n-1 \text{ and } j = 2, n \tag{11}$$

$$R_{i,j} = \frac{1}{h_{r,across\,n-1,n+1}} + \frac{0.5d_n}{k_n} \quad \text{for } i = n-1 \text{ and } j = n+1 \tag{12}$$

where $h_{c,p}$ is the convective heat transfer coefficient in the p space where p = out, in and gap i, j (out = outside air condition, in = inside air condition and gap i, j = air in the gap between the layer ith and jth), $h_{r,p}$ is the radiative heat transfer coefficient in the p space where p = out, in and gap i, j (out = outside air condition, in = inside air condition, gap i,j = air in the gap between the layer ith and jth and across $n-1$, $n+1$ = air from layer $n-1$th to layer

$n+1$th), k_i = thermal conductivity of the layer ith, d_i = thickness of the layer ith, 0 refers to the outside air condition, and $n+1$ refers to the indoor air condition.

Since the diffuse solar radiation incident on the vertical surface is composed of diffuse solar radiation from the sky and diffuse solar radiation reflected from the ground (shown in Fig. 3), the *SHGC* for the diffuse solar radiation ($SHGC_d$) can be calculated from the integration of the $SHGC_D$ over the sky components of the sky solar radiation and ground reflected components of the ground reflected solar radiation.

$$SHGC_d = \frac{\int_0^{\frac{\pi}{2}} SHGC_D(\phi_s) I_{sky}(\phi_s)\cos\phi_s\, d\phi_s}{\int_0^{\frac{\pi}{2}} I_{sky}(\phi_s)\cos\phi_s\, d\phi_s} + \frac{\int_{-\frac{\pi}{2}}^{0} SHGC_D(\phi_s) I_{grd}(\phi_s)\cos\phi_s\, d\phi_s}{\int_{-\frac{\pi}{2}}^{0} I_{grd}(\phi_s)\cos\phi_s\, d\phi_s} \tag{13}$$

where $SHGC_d$ is the solar heat gain coefficient for diffuse solar radiation, I_{sky} is the direct solar radiation from the sky, and I_{grd} is the direct solar radiation reflected from the ground.

3. Verification of the mathematical model

To verify the accuracy of the developed mathematical model for calculating the *SHGC* for the glass window with a curved venetian blind installed, the predicted results from the simulation shall be compared with the experimental ones. The accuracy of the developed mathematical model in the part that is used for calculating the *ShW SHGC* has been verified by comparing the predicted results with the experimental one in the work of Chaiyapinunt and Khamporn (2013). The agreement is quite good. Unfortunately, the existing test room used in the work of Chaiyapinunt and Khamporn (2013) is not suitable for measuring the total heat gain through the fenestration system. Therefore the previous experimental results by Collins and Harrison (2004) are chosen for the comparison. Collins and Harrison used a technique called solar calorimetry to test the double clear glass window with a curved venetian blind installed. The experiment was performed in the Solar Calorimetry Laboratory (SCL) which is located on the roof of the mechanical engineering building at Queen's university (44.14° latitude, 76.49° longitude). The SCL is equipped with the tracking system which made the SCL capable of tracking the sun with the accuracy of ±1°. The details of the experimental apparatus can be seen from Collins and Harrison (2004). Two sets of venetian blind with three blind slat angles and two solar profile angles were used when the experiment was performed.

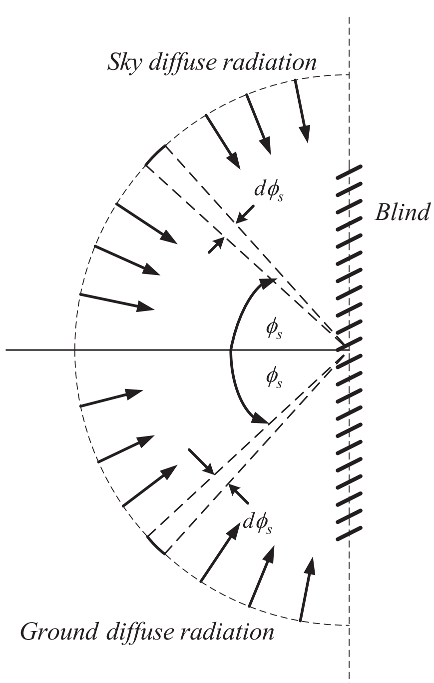

Fig. 3. Distribution of the diffuse solar radiation on the blind.

The glass window used in the work of Collins and Harrison (2004) 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 widow surface) of 30 mm.

The experimental results were grouped and plotted by using the term defined as the efficiency of the glazing system. The efficiency of the glazing system was expressed as:

$$\eta = \frac{Q_{input}}{A_f I} = SHGC - U_f \frac{\Delta T_{i,o}}{I} \tag{14}$$

where η is the thermal efficiency of the glazing system. Q_{input} is the heat input from the incident solar radiation on the test window (W/m^2). A_f is the window's projected area (m^2). I is the incident solar radiation (W/m^2). *SHGC* is the solar heat gain coefficient. U_f is the total overall heat transfer coefficient (W/m^2 K). $\Delta T_{i,o}$ is the inside and outside temperature difference (K).

By plotting the efficiency of the glazing system, η and $\Delta T_{i,o}/I$ on the same graph, the *SHGC* can be achieved from the intercept of the trend line on the $\Delta T_{i,o}/I$ axis. For one certain test condition (one type of blind, one solar profile angle and one slat angle), at least six data points were needed. The calorimetric results of solar performance for a window and a venetian blind were presented in Table 1.

The incident solar radiation in the components of direct radiation and diffuse radiation were chosen from the

Table 1
The values of *SHGC* and U_f from the experiment (Collins and Harrison (2004)).

Condition	*SHGC*	U_f (W/m^2 K)
White, 30° incidence, 0° slat	0.59 ± 0.01	3.64 ± 0.68
White, 45° incidence, 0° slat	0.56 ± 0.01	4.50 ± 0.63
White, 30° incidence, 45° slat	0.46 ± 0.01	4.76 ± 0.46
White, 45° incidence, 45° slat	0.44 ± 0.01	4.74 ± 0.44
White, 30° incidence, −45° slat	0.65 ± 0.01	4.50 ± 0.85
White, 45° incidence, −45° slat	0.65 ± 0.01	4.66 ± 0.71
Black, 30° incidence, 0° slat	0.65 ± 0.01	2.74 ± 0.91
Black, 45° incidence, 0° slat	No data	No data
Black, 30° incidence, 45° slat	0.64 ± 0.01	5.20 ± 1.07
Black, 45° incidence, 45° slat	0.64 ± 0.01	4.42 ± 0.58
Black, 30° incidence, −45° slat	0.68 ± 0.01	3.28 ± 0.96
Black, 45° incidence, −45° slat	No Data	No Data

Collins and Harrison's experiment to be used in the simulation from the developed mathematical model. The chosen incident solar radiations are shown in Table 2.

The simulation from the developed mathematical model is performed to determine the solar heat gain by setting the operating condition the same as the experiment performed by Collins and Harrison (2004). The values of *SHGC* obtained from the experiment were the *SHGC* that taking into account for direct solar radiation and diffuse solar radiation. Therefore the values of *SHGC* used for comparison with the experimental results can be obtained from the following relation:

$$SHGC = \{(SHGC_D)I_D + (SHGC_d)I_d\}/(I_D + I_d) \tag{15}$$

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, and I_d is the diffuse solar radiation. The predicted results from the simulation are compared with the experimental ones as shown in Table 3.

One can see from Table 3 that the agreement between the predicted results and the experimental ones are quite good. The average deviation is around 3–6% and the largest in the deviation is 8.75%. With the verification results shown in Table 3 along with the verification results of the *ShW SHGC* of the combined glass window and blind performed by Chaiyapinunt and Khamporn (2013), one can be confident in using the developed mathematical model to analyze the thermal performance of the glass window with the venetian blind installed especially in the part of *SHGC*. Though Collins and Harrison (2004) gave the values of the total overall heat transfer coefficient (U_f) from the tests, they are the value of *U* for the fenestration system and the wood-frame. Unfortunately, the authors did not give the value of *U* of the frame, and stated clearly that *U* of the glass window could not be determined. Therefore, the verification of the predicted value of *U* could not be done in this study.

Table 2
The chosen values of the incident solar radiation from the experiment used in the simulation.

Condition	I_D (W/m^2)	I_d (W/m^2)
White, 30° incidence, 0° slat	701.61	164.58
White, 45° incidence, 0° slat	504.48	163.42
White, 30° incidence, 45° slat	759.53	166.73
White, 45° incidence, 45° slat	606.44	181.14
White, 30° incidence, −45° slat	730.72	160.40
White, 45° incidence, −45° slat	592.67	167.16
Black, 30° incidence, 0° slat	754.73	177.03
Black, 45° incidence, 0° slat	No data	No data
Black, 30° incidence, 45° slat	650.11	240.45
Black, 45° incidence, 45° slat	643.21	160.82
Black, 30° incidence, −45° slat	719.82	191.34
Black, 45° incidence, −45° slat	No data	No data

4. Thermal performance

In this study, the thermal performance of the glass window with a curved venetian blind installed is carefully investigated. The variation of the *SHGC* with the related parameters (optical properties of venetian blind, slat spacing, distance between the blind and glass window, slat angle and solar profile angle) are studied from the predicted results.

The glass window chosen for this study is the 6 mm clear glass window. The blind chosen for this study has a slat width of 25.4 mm and thickness of 0.3 mm. The slat has a radius of curvature of 71.5 mm. The slats are separated by a distance of 20 mm. The conductivity of the slat is 120 W/m K. The reflectance of the slat is chosen to be 0.6 (slat absorptance of 0.4). The emittance of the slat is 0.87. The blind is installed at a 40 mm distance from the inner glass window surface to the center of the blind. Table 4 shows the optical properties of the chosen glass window and blind.

4.1. Effect of the slat angle and solar profile angle

The variation of the *SHGC* with the slat angle and solar profile angle are studied. Fig. 4 shows the variation of the $SHGC_D$ and *ShW* $SHGC_D$ of the fenestration system (clear glass window with blind) with the solar profile angle when the slat angle is set at 0°, 45° and −45° compared with the $SHGC_D$ of the plain clear glass window. The 0° slat angle refers to the position that the slat is parallel to the ground. The 45° slat angle refers to the position that the slat edge facing the inner glass window surface is pointing down to the ground making an angle of 45° to the horizontal direction. The −45° slat angle refers to the position that the slat edge facing the inner glass window surface is pointing up to the sky making an angle of 45° to the horizontal direction. It can be clearly seen that the $SHGC_D$ and *ShW* $SHGC_D$ of the glass window with blind and the $SHGC_D$ of the plain glass window are also dependent on the solar profile angle. The curve with solid line in the figure represents the $SHGC_D$. The curve with dotted line in the figure represents the *ShW* $SHGC_D$. Therefore the difference between the curve with solid line and curve with dotted line represents

Table 3
The values of *SHGC* from the experiment and from the simulation.

Condition	$SHGC_e$	$SHGC_s$	Deviation	Percentage (%)
White, 30° incidence, 0° slat	0.59 ± 0.01	0.616	-0.026 ± 0.01	−4.41
White, 45° incidence, 0° slat	0.56 ± 0.01	0.532	0.028 ± 0.01	5.00
White, 30° incidence, 45° slat	0.46 ± 0.01	0.435	0.025 ± 0.01	5.43
White, 45° incidence, 45° slat	0.44 ± 0.01	0.410	0.030 ± 0.01	6.82
White, 30° incidence, −45° slat	0.65 ± 0.01	0.632	0.018 ± 0.01	2.77
White, 45° incidence, −45° slat	0.65 ± 0.01	0.671	-0.021 ± 0.01	−3.23
Black, 30° incidence, 0° slat	0.65 ± 0.01	0.668	-0.018 ± 0.01	−2.77
Black, 30° incidence, 45° slat	0.64 ± 0.01	0.599	0.041 ± 0.01	6.41
Black, 45° incidence, 45° slat	0.64 ± 0.01	0.584	0.056 ± 0.01	8.75
Black, 30° incidence, −45° slat	0.68 ± 0.01	0.686	0.006 ± 0.01	0.88

Note: $SHGC_e$ is the experimental value. $SHGC_s$ is the predicted value from the simulation.

Table 4
Glass and blind optical properties.

Description	Thickness mm	Solar energy			Visible		Emissivity	
		Trn	Ref	Ab	Trv	Rev	Ef	Eb
Clear	6.0	0.801	0.069	0.130	0.883	0.076	0.84	0.84
Blind	0.3	–	0.6	0.4	–	–	0.87	0.87

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

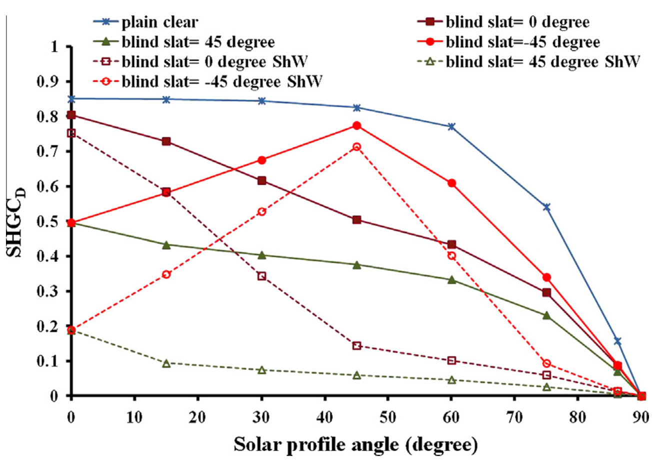

Fig. 4. $SHGC_D$ and *ShW* $SHGC_D$ of the clear glass window with blind when the slat angle is set at 0°, 45° and −45° compared with the $SHGC_D$ of plain clear glass window.

the *LoW* $SHGC_D$. The $SHGC_D$ of the plain clear glass window is decreased as the solar profile angle is increased. Then it is sharply decreased as the solar profile angle is in the range of 60–90°. When the blind is installed behind the glass window the value of $SHGC_D$ of the fenestration system is decreased compared to the value of $SHGC_D$ of the plain clear glass window. The variations of the $SHGC_D$ of the fenestration system are dependent on the slat angle. For 0° slat angle, the value of $SHGC_D$ is 0.8044 at 0° solar profile angle. The value of $SHGC_D$ is continuously decreasing when the solar profile angle is increasing. For 45° slat angle, the value of $SHGC_D$ is 0.4956 at 0° solar profile angle. The value of $SHGC_D$ is continuously decreasing when the solar profile angle is increasing. For −45° slat angle, the value of $SHGC_D$ is 0.4959 at 0° solar profile angle. The value of $SHGC_D$ is continuously increasing when the solar profile angle is increasing until it reaches 45°. Then the value of $SHGC_D$ is continuously decreasing when the solar profile angle is further increased. The explanation of the increasing of the $SHGC_D$ for the case of −45° slat angle is that when the solar profile angle is increased from 0° to 45°, more solar radiation bean can penetrate through the blind into the room. Once the solar profile angle is greater than 45° the slat starts to block the solar radiation beam from entering into the room causing the value of $SHGC_D$ to decrease.

The variations of the *ShW* $SHGC_D$ and *LoW* $SHGC_D$ with the slat angle and solar profile angle can also be studied from the curves with the dotted line and the difference area between the curve with solid line and the curve with dotted line as shown in Fig. 4. The variations of the *ShW* $SHGC_D$ with the solar profile angle when the slat angle set at 0°, 45° and −45° are similar to the case of $SHGC_D$. For the case of blind with slat angle set at 45°, the value of *LoW* $SHGC_D$ (the difference between the curve with solid line and curve with the dotted line) is quite constant over the range of the solar profile angle considered (0–90°). For 0° slat angle, the value of *LoW* $SHGC_D$ is continuously increasing when the solar profile angle is increasing until it reaches 45°. Then the value of *LoW* $SHGC_D$ becomes quite constant when the solar profile angle is in the range of 45–75°. Then the value of *LoW* $SHGC_D$ is decreased to 0 when the solar profile angle is increasing to 90°. For −45° slat angle, the value of *LoW* $SHGC_D$ is continuously decreasing when the solar profile angle is increasing until it reaches 45°. Then the value of *LoW* $SHGC_D$ is increasing again when the solar profile angle is increasing. Therefore it can be concluded that setting the blind in the position that blocks the direct solar radiation (beam radiation) (i.e. solar profile angle in the range of 0–75° for 45° slat angle, solar profile angle in the range of 30–75° for 0° slat angle and solar profile angle of 0° for −45° slat angle) causes the solar heat gain to the space to be dominated by the part of longwave radiation. When the blind is set to be aligned with the direct solar radiation (i.e. solar profile angle of 0° for 0° slat angle and solar profile angle of 45° for −45° slat angle) the solar heat gain to the space is dominated by the part of shortwave radiation.

The variations of the $SHGC_d$, $ShW\ SHGC_d$ and $LoW\ SHGC_d$ with the slat angle can be studied from Fig. 5. The blind with the slat angle set at 45° gives the lowest value of the $SHGC_d$ and $ShW\ SHGC_d$ compared to the blind at other considered positions. The blind with the slat angle set at 0° gives the highest value of the $SHGC_d$ and $ShW\ SHGC_d$ compared to the blind at other considered positions. The $SHGC_d$ of the plain clear glass window is dominated by the $ShW\ SHGC_d$.

4.2. Effect of the slat optical properties

Effect of the slat optical properties (reflectance, absorptance and emittance) on the $SHGC_D$ of the fenestration system is investigated. Since the summation of the slat reflectance and slat absorptance is equal to 1. The slat reflectance is chosen to be the parameter to be studied. The slat reflectance of 0.2, 0.4, 0.6 and 0.8 (slat absorptance of 0.8, 0.6, 0.4 and 0.2) are chosen for this study. The predicted values of $SHGC_D$ and $ShW\ SHGC_D$ of the fenestration system at 0°, 45° and −45° slat angle are shown in Figs. 6–8. From Fig. 6, the $SHGC_D$ for the clear glass window and blind with slat reflectance of 0.2 at slat angle of 0° has the largest value compared to the blind of different slat reflectance throughout the range of considered solar profile angle (0–90°). The fenestration system with blind of slat reflectance of 0.8 has the smallest value of $SHGC_D$. The difference in the value of $SHGC_D$ from the blind with different value of slat reflectance is clearly seen in the range of solar profile angle around 30–75° (position that the blind blocks some part of the incident solar radiation). In other words, installing high slat reflectance blind yields the lower value of $SHGC_D$ especially when the blind is set in the position that it blocks some part of the incident solar radiation.

The effect of slat reflectance on the $ShW\ SHGC_D$ is also investigated from the curves with dotted line shown in Fig. 6. The fenestration system with blind of the highest slat reflectance (0.8) gives the smallest value of the $SHGC_D$ but it gives the highest value of the $ShW\ SHGC_D$. The fenestration system with blind of the smallest value of slat reflectance (0.2) gives the highest value of the $SHGC_D$ but it also gives the smallest value of the $ShW\ SHGC_D$. It means that the contribution of the $LoW\ SHGC_D$ to the $SHGC_D$ is large when using the blind with lower value of slat reflectance (or high slat absorptance). At 45° solar profile angle, the $LoW\ SHGC_D$ for the blind with low slat reflectance (0.2) is as high as 0.526 while the $LoW\ SHGC_D$ for the blind with high slat reflectance (0.8) is 0.231.

Fig. 7 shows the $SHGC_D$ for the clear glass window and blind when the slat angle of the blind is set at 45°. The variation of the $SHGC_D$ and the $ShW\ SHGC_D$ are similar to the ones shown in Fig. 6. When the slat angle of the blind is set at 45°, the blind in this position blocks a large portion of the incident radiation. The effect of the slat reflectance on the $SHGC_D$ is clearly seen throughout the considered solar profile angle. The fenestration system with blind of high slat reflectance (0.8) gives the smallest value of the $SHGC_D$. The difference between the $SHGC_D$ from the blind with high slat reflectance (0.8) and low slat reflectance (0.2) is as high as 0.2 for the solar profile angle around 35–65°. The reduction of the $SHGC_D$ between the plain clear glass window and the glass window and blind is as high as 0.5 for the system with blind of high slat reflectance.

The effect of the slat reflectance on the $ShW\ SHGC_D$ is similar to the effect of the slat reflectance on the ShW

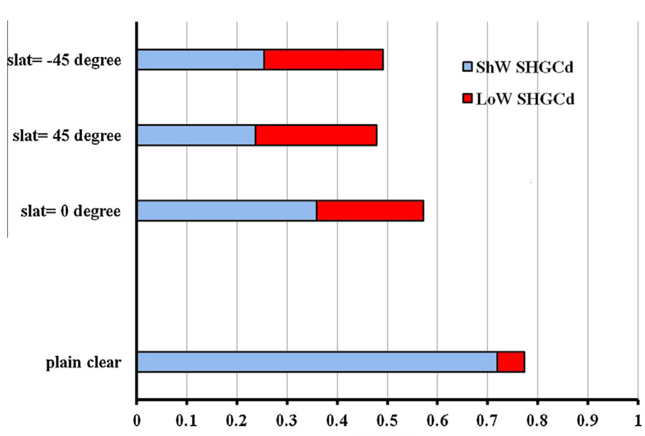

Fig. 5. $SHGC_d$, $ShW\ SHGC_d$ and $LoW\ SHGC_d$ of the plain clear glass window and clear glass window with blind when the slat angle is set at 0°, 45° and −45°.

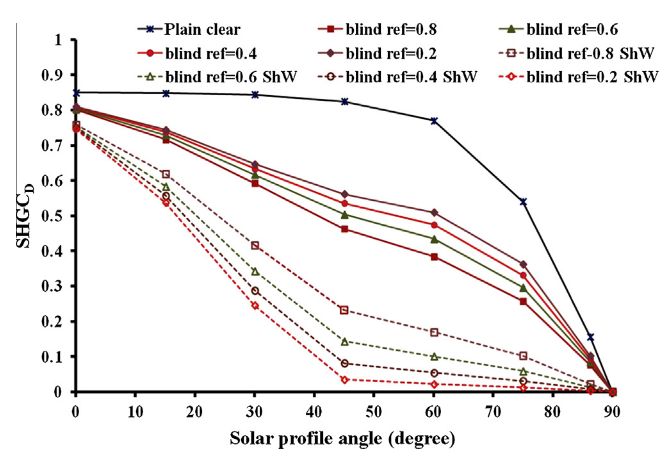

Fig. 6. $SHGC_D$ and $ShW\ SHGC_D$ of the clear glass window with blind when the slat angle is 0° and the slat reflectance is set at 0.2, 0.4, 0.6 and 0.8 compared with the $SHGC_D$ of plain clear glass window.

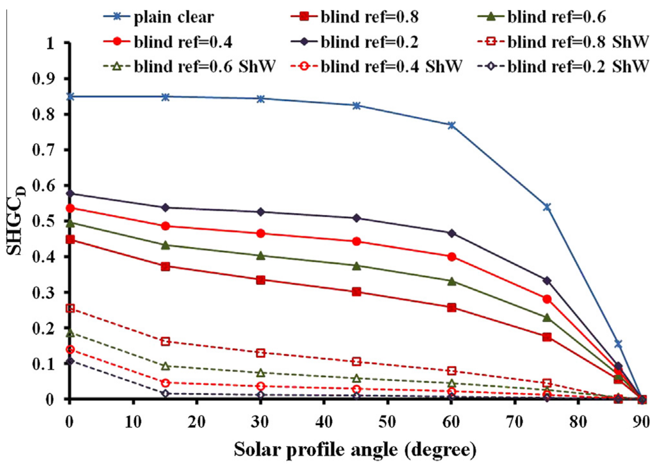

Fig. 7. $SHGC_D$ and $ShW\ SHGC_D$ of the clear glass window with blind when the slat angle is 45° and the slat reflectance is set at 0.2, 0.4, 0.6 and 0.8 compared with the $SHGC_D$ of plain clear glass window.

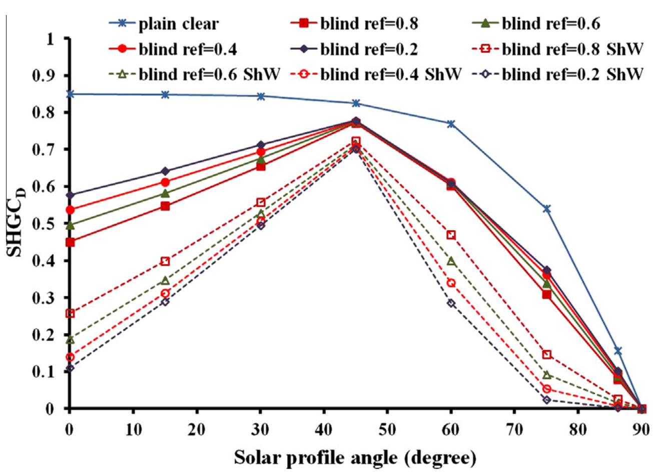

Fig. 8. $SHGC_D$ and $ShW\ SHGC_D$ of the clear glass window with blind when the slat angle is −45° and the slat reflectance is set at 0.2, 0.4, 0.6 and 0.8 compared with the $SHGC_D$ of plain clear glass window.

$SHGC_D$ in the case of 0° slat angle. For the case of 45° slat angle, the contribution of the $LoW\ SHGC_D$ to the $SHGC_D$ is quite significant especially for the blind with low slat reflectance (0.2). At 15° solar profile angle, the $LoW\ SHGC_D$ for the blind with low slat reflectance (0.2) is as high as 0.521 while the $LoW\ SHGC_D$ for the blind with high slat reflectance (0.8) is 0.211.

When the blind is set at −45°, the $SHGC_D$ is increased as the solar profile angle is increased from 0° to 45° and it is decreased as the solar profile angle is increased from 45° to 90° as shown in Fig. 8. The explanation of the increasing of the $SHGC_D$ for the fenestration system is that when the solar profile angle is increased from 0 to 45°, more solar radiation can penetrate through the blind into the room. Once the solar profile angle is greater than 45° the slat starts to block the solar radiation beam from entering into the room causing the value of the $SHGC_D$ to decrease. The blind with high slat reflectance still gives a lower value of the $SHGC_D$ compared to the blind with a lower value of slat reflectance.

The blind with high slat reflectance still gives a higher value of the $ShW\ SHGC_D$ compared to the blind with a lower value of slat reflectance. The effect of the slat reflectance on the $SHGC_D$ and the $ShW\ SHGC_D$ is clearly seen when the blind is in the position that blocks some part of the incident radiation (solar profile angle of 0–40° and 50–80°). The behavior of the $LoW\ SHGC_D$ to the $SHGC_D$ is the same as previously described. At 0° solar profile angle, the $LoW\ SHGC_D$ for the blind with low slat reflectance (0.2) is as high as 0.46 while the $LoW\ SHGC_D$ for the blind with high slat reflectance (0.8) is 0.192.

Effect of the slat emittance on the $SHGC_D$ of the fenestration system is also investigated. From Figs. 6–8, it can be seen that the variation of the $SHGC_D$ and $ShW\ SHGC_D$ of the fenestration system on the investigated parameter has the same behavior for three slat positions chosen (0°, 45° and −45°). But among the three slat positions, the effect is more clearly seen in the case of the slat angle of 0°. Therefore in the following study, the results of the study on the investigated parameters will be shown only in the case of the slat angle of 0°. Therefore in order to study the effect of the slat emittance, the value of slat reflectance and slat angle are kept at 0.6 and 0°. The value of slat emittance is varied as 0.2, 0.4, 0.6 and 0.87. It is found from the predicted results from the simulation that the slat emittance does not have any effect on the $ShW\ SHGC_D$ and $ShW\ SHGC_d$ at all. The values of $SHGC_D$ and $SHGC_d$ from the simulation are shown in Table 5. The values of $SHGC_D$ and $SHGC_d$ change inversely with the value of slat emittance. It can be said that the slat emittance affects only the $LoW\ SHGC$. The effect of the slat emittance on the $SHGC_D$ and $SHGC_d$ is rather small (in the range of 0.05–4%). The slat with high emittance gives a lower value of $SHGC_D$ and $SHGC_d$ compared to the slat with low emittance.

4.3. Effect of the slat spacing

The next parameter to be investigated is the distance between the slats (slat spacing). The effect of the slat spacing (range from 10 to 25 mm) on the $SHGC_D$ and $ShW\ SHGC_D$ of the fenestration system with blind of 0.6 slat reflectance and 0° slat angle is shown in Fig. 9. From Fig. 9, it is found that decreasing the value of the slat spacing causes the value of $SHGC_D$ and $ShW\ SHGC_D$ to decrease. The fenestration system with the blind of 25 mm slat spacing gives the highest value of $SHGC_D$ and $ShW\ SHGC_D$. The fenestration system with the blind of 10 mm slat spacing gives the lowest value of $SHGC_D$ and $ShW\ SHGC_D$. The effect of the slat spacing on the $SHGC_D$ and $ShW\ SHGC_D$ is clearly seen for the solar profile angle of 10–40°. In those sun positions when the slat spacing is larger the solar radiation is more easily transmitted through the blind into the room.

Table 5
$SHGC_D$ and $SHGC_d$ of the fenestration system with different values of slat emittance.

Solar profile angle (°)	$SHGC_D$ for $e = 0.2$	$SHGC_D$ for $e = 0.4$	$SHGC_D$ for $e = 0.6$	$SHGC_D$ for $e = 0.87$
0	0.8051	0.8046	0.8045	0.8044
15	0.7350	0.7319	0.7301	0.7288
30	0.6252	0.6208	0.6184	0.6166
45	0.5152	0.5094	0.5063	0.504
60	0.446	0.4401	0.4368	0.4341
75	0.3085	0.3018	0.2987	0.2965
90	0	0	0	0
$SHGC_d$	0.5795	0.5755	0.5735	0.572

Note: e = emittance.

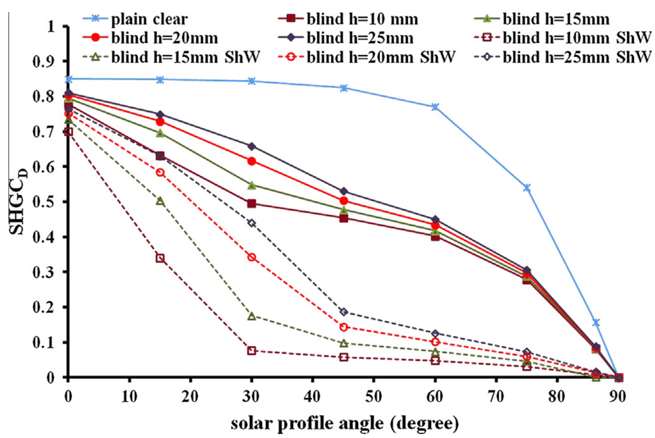

Fig. 9. $SHGC_D$ and $ShW\ SHGC_D$ of the clear glass window with blind when the slat angle is 0° and the slat spacing is set at 10, 15, 20 and 25 mm compared with the $SHGC_D$ of plain clear glass window.

4.4. Effect of the slat radius of curvature

The effect of the slat curvature on the $SHGC_D$ and $ShW\ SHGC_D$ is also investigated. The radius of curvature of the slat is varied from 25 mm to 200 mm. The results of the simulation are shown in Fig. 10. The effect of slat curvature on the $SHGC_D$ and $ShW\ SHGC_D$ is not as pronounced as the effect of other parameters investigated. The glass window with blind of smaller value of radius of curvature (slat has more curvature) gives a smaller value of $SHGC_D$ and $ShW\ SHGC_D$. The effect of the radius of curvature is clearly seen in the range of solar profile angle from 0° to 15° and from 45° to 75°. The $SHGC_D$ and $ShW\ SHGC_D$ of the glass system with blind of smaller value of radius of curvature is smaller than the $SHGC_D$ and $ShW\ SHGC_D$ of the glass system with blind of higher value of radius of curvature due to the blockage of the solar radiation from the projected area of the curved slat.

4.5. Effect of the distance between the blind and glass window

The effect of the distance between the blind and the inside surface of the glass window is also investigated. The distance from the blind center to the inside glass window surface of 20, 30, 40, 50, 60 and 80 mm are used in the simulation to see the effect of the distance from the blind to the glass window surface on the $SHGC_D$ and $ShW\ SHGC_D$. It is found from the prediction results that there is no effect of such distance on the $ShW\ SHGC_D$ and $ShW\ SHGC_d$ at all. Therefore it can be said that the distance between the blind and the inside surface of the glass window affects only the $LoW\ SHGC$. The value of $SHGC_D$ and $SHGC_d$ for the fenestration system with different values of distance between the blind and the inside surface of the glass window are shown in Table 6. The effect of such distance on the $SHGC_D$ and $SHGC_d$ for the fenestration system is quite small. Table 7 shows the variation of $LoW\ SHGC_D$ and $LoW\ SHGC_d$ with the solar profile angle. It is found that the effect of the distance between the blind and glass window on the $LoW\ SHGC_D$ is also dependent on the solar profile angle. At 0° solar profile angle, the $LoW\ SHGC_D$ is high when the distance between the blind and glass window is small (distance = 20 mm). Increasing the distance causes the value of $LoW\ SHGC_D$ getting smaller until it reaches the minimum value when the distance is around 40–50 mm. Further increasing the distance between the blind and glass window, the $LoW\ SHGC_D$ is increasing in a very small magnitude. At 15° solar profile angle, the value of $LoW\ SHGC_D$ is increasing when the distance of the blind and glass window is increasing. For the solar profile angle of 30–45°, the value of the $LoW\ SHGC_D$ is

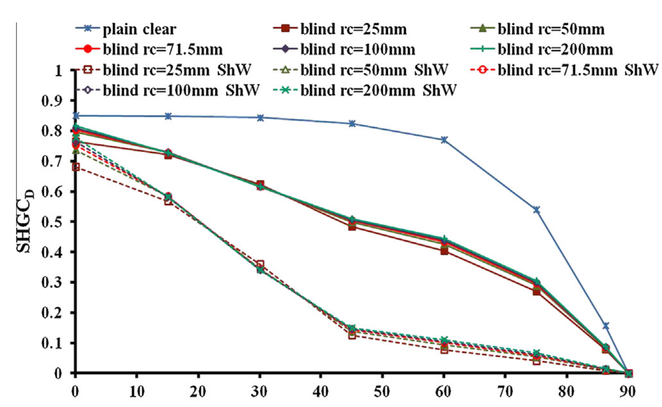

Fig. 10. $SHGC_D$ and $ShW\ SHGC_D$ of the clear glass window with blind when the slat angle is 0° and the slat radius of curvature is set at 25, 50, 71.5, 100 and 200 mm compared with the $SHGC_D$ of plain clear glass window.

Table 6
$SHGC_D$ and $SHGC_d$ of the fenestration system with different value of distance between the blind and the inside surface of the glass window.

Solar profile angle (°)	$SHGC_D$ for $d = 20$ mm	$SHGC_D$ for $d = 30$ mm	$SHGC_D$ for $d = 40$ mm	$SHGC_D$ for $d = 50$ mm	$SHGC_D$ for $d = 60$ mm	$SHGC_D$ for $d = 80$ mm
0	0.8057	0.8047	0.8044	0.8044	0.8045	0.8045
15	0.7214	0.7269	0.7288	0.7298	0.7303	0.7304
30	0.5992	0.6134	0.6166	0.6161	0.6156	0.6148
45	0.4807	0.5004	0.504	0.5032	0.5024	0.5013
60	0.4107	0.4286	0.4341	0.4343	0.4337	0.4329
75	0.2808	0.2925	0.2965	0.2982	0.2982	0.2978
90	0	0	0	0	0	0
$SHGC_d$	0.5595	0.569	0.572	0.5725	0.572	0.572

Note: d = distance between the blind and the inside surface of the glass window.

increasing when the distance is increasing until it reaches the maximum value at the distance of 40 mm. Further increasing the distance causes the value of the LoW $SHGC_D$ starting to decrease. For solar profile angle of 60–75°, the value of the LoW $SHGC_D$ is still increasing when the distance is increasing. But the maximum value is shifted from the distance of 40 mm to the distance of 50 mm. For the LoW $SHGC_d$, the value of LoW $SHGC_d$ is increasing with the distance between the blind and glass window until it reaches the maximum value around the distance of 50 mm. Further increasing the distance causes the value of LoW $SHGC_d$ to decrease in a very small amount. By carefully considering the results shown in Table 7, one can conclude that installing blind (in the position that the slat intercept some part of the solar radiation (solar profile angle of 15–75°)) closer to the glass window causes smaller value of LoW $SHGC_D$ and LoW $SHGC_d$ compared to installing the blind further from the glass window. But this effect is reversed when the distance is larger than the nominal value (in this case, it is found that the nominal value of the distance should be around 40–50 mm). When the blind is in the position that most of the solar radiation can pass through the blind without touching the slat (solar profile angle of 0°), installing the blind close to the glass window will get higher value of LoW $SHGC_D$. When the distance between the blind and glass window is increased the value of LoW $SHGC_D$ is decreased until it gets the minimum value around the nominal distance (40–50 mm).

The effects of the investigated parameters on the $SHGC_d$, are also studied. Fig. 11 shows the comparison between the value of $SHGC_d$ of the plain clear glass window and the fenestration system (clear glass window with blind) in different values of slat reflectance, different values of slat spacing and different values of slat curvature. The effects of the investigated parameters on the $SHGC_d$ are similar to the effects of the same investigated parameters on the $SHGC_D$ except for the case of the slat curvature. The glass window with blind of higher slat reflectance will give the lower value of $SHGC_d$. The glass window with blind of higher slat spacing will give the higher value of $SHGC_d$. The glass window with blind of the lower value of slat radius of curvature will give a greater value of $SHGC_d$ (which is opposite to the results for the variations of the slat curvature to the $SHGC_D$). But the difference in the value of $SHGC_d$ between the maximum and minimum slat curvature considered is less than 1.6%. So it can be concluded that the effect of the slat curvature on the $SHGC_d$ can be considered as negligible.

The variations of the ShW $SHGC$ and LoW $SHGC$ with the related parameters of the fenestration (glass window with blind) may not be very important when the total heat transmission is the main concern. But they become very important when the local thermal discomfort of a person who sits near the fenestration is of interest. Since the ratio of the ShW $SHGC$ to LoW $SHGC$ does not directly correspond to the ratio of the discomfort index (i.e. PPD

Table 7
LoW $SHGC_D$ and LoW $SHGC_d$ of the fenestration system with different value of distance between the blind and the inside surface of the glass window.

Solar profile angle (°)	LoW $SHGC_D$ for $d = 20$ mm	LoW $SHGC_D$ for $d = 30$ mm	LoW $SHGC_D$ for $d = 40$ mm	LoW $SHGC_D$ for $d = 50$ mm	LoW $SHGC_D$ for $d = 60$ mm	LoW $SHGC_D$ for $d = 80$ mm
0	0.0527	0.0517	0.0514	0.0514	0.0515	0.0515
15	0.1374	0.1429	0.1448	0.1458	0.1463	0.1464
30	0.2562	0.2704	0.2736	0.2731	0.2726	0.2718
45	0.3367	0.3564	0.36	0.3592	0.3584	0.3573
60	0.3097	0.3276	0.3331	0.3333	0.3327	0.3319
75	0.2218	0.2335	0.2375	0.2392	0.2392	0.2388
90	0	0	0	0	0	0
$SHGC_d$	0.2005	0.21	0.213	0.2135	0.213	0.213

Note: d = distance between the blind and the inside surface of the glass window.

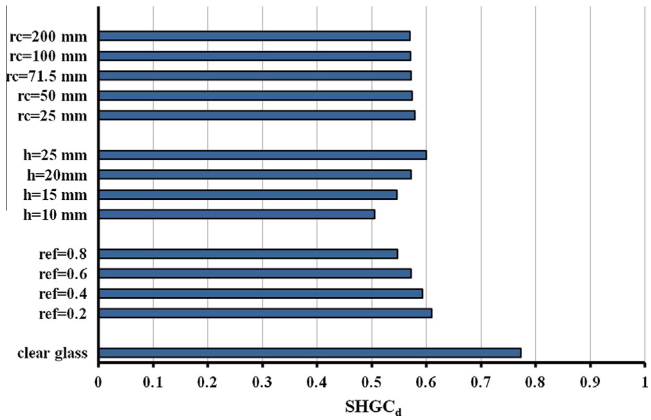

Fig. 11. $SHGC_d$ of the plain clear glass window and clear glass window with blind when varied the slat reflectance, slat spacing and slat radius of curvature.

(Predicted People of Dissatisfied)) from the solar radiation (shortwave effect) and the discomfort index (i.e. PPD) from the surface temperature (longwave effect). It is also found from Khamporn (2012) that when the solar radiation is allowed to pass through the blind striking on a person who sits nearby, the discomfort from the solar radiation (shortwave effect) will be dominated over the discomfort from the surface temperature (longwave effect). Though it is found from the study that installing a high reflectance blind to a glass window may give the smallest *SHGC* but it also gives the largest *ShW SHGC*. Therefore installing a high reflective blind to a glass window may result in the local discomfort for the person who sits near the fenestration than installing a low reflective blind. The knowledge about the *ShW SHGC* and *LoW SHGC* becomes very important for designing an energy efficient building envelope with a preferred thermal environment in the space using a curved venetian blind installed to a clear glass window.

5. Conclusion

The effect of installing a curved venetian blind to the glass windows in terms of solar heat transmission to the space is investigated in this study. The *SHGC* is chosen to be a heat transmission index for this study. The *SHGC* is further divided into *SHGC* for the direct solar radiation ($SHGC_D$) and *SHGC* for the diffuse solar radiation ($SHGC_d$). The study is based on the predicted results calculated by the developed mathematical model. The effect of the parameters of the fenestration on the *SHGC* are studied to gain more understanding about the thermal performance of the glass window with a curved venetian blind installed. Besides the understanding of the solar heat gain through the fenestration in the overall picture, one also needs to maintain the thermal comfort condition for the occupants in the space. The understanding about the solar heat gain through the fenestration in the part of the shortwave and the longwave is needed. The *SHGC* is further classified as the *ShW SHGC* and *LoW SHGC*. Then, the effect of the related parameters on the *ShW SHGC* and *LoW SHGC* are investigated. Installing a curved venetian blind to the plain glass window causes the decrease in solar heat gain. It is found that the amount of reduction in solar heat gain is mainly dependent on the slat optical properties, slat angle and solar profile angle. It is also found that installing blind with a higher value of slat reflectance will yield a smaller value of $SHGC_D$ and $SHGC_d$. When considering the effect of slat reflectance on the *ShW* $SHGC_D$ and *LoW* $SHGC_D$, though the higher value of the slat reflectance gives higher value of the *ShW* $SHGC_D$, it gives a lower value of the *LoW* $SHGC_D$. It is also found that installing the blind with a lower value of slat reflectance gives a much higher value of $SHGC_D$ though the value of the *ShW* $SHGC_D$ is much lower. The slat emittance does not have any effect on the *ShW* $SHGC_D$ and *ShW* $SHGC_d$ at all. There is only small effect from the variation of the slat emittance on the *LoW* $SHGC_D$. The slat spacing also affects the $SHGC_D$ and *ShW* $SHGC_D$. The glass window with blind of a lower value of slat spacing gives a lower value of $SHGC_D$ and *ShW* $SHGC_D$. The effect of the slat curvature on the $SHGC_D$ and *ShW* $SHGC_D$ is small when compared to the effect of other parameters. The effect of the distance between the glass window and blind appears only on the *LoW* $SHGC_D$. But the effects are not pronounced. The effects of the investigated parameters on the $SHGC_d$ are similar to the effect on the $SHGC_D$ except for the case of the effect of the radius curvature.

The type (direct radiation and diffuse radiation) and magnitude of the incident solar radiation on the building envelope during the day are mainly dependent on the building location (respect to the sun path) and building orientation. The incident solar radiation on the specific side of the building envelope is as the following: east; direct and diffuse radiation in the morning and only diffuse radiation in the afternoon, west; only diffuse radiation in the morning and direct and diffuse radiation in the afternoon, south; direct and diffuse radiation in the morning and afternoon, north; only diffuse radiation in the morning and afternoon. The variation of the $SHGC_D$ and $SHGC_d$ with the related parameters from this study will provide the necessary knowledge for the designer to design or select the proper type of the venetian blind to install behind the glass window for specific side of the building more effectively. The understanding about the variation of $SHGC_D$ and $SHGC_d$ in the part of shortwave and longwave with the related parameters from this study will provide more information about the characteristic of solar heat gain into the space which will directly related to the thermal comfort condition in the space. In conclusion, in order to reduce solar heat gain one should install the high reflectance curved venetian blind with a small slat distance and a small radius of curvature. The blind should be set in the position that blocks the direct solar radiation.

Acknowledgements

The authors are grateful for the financial support from the National Metal and Materials Technology Center, National Science and Technology Development Agency and the Thailand Research Fund.

References

Chaiyapinunt, S., Khamporn, N., 2013. Shortwave thermal performance for a glass window with a curved venetian blind. Sol. Energy 91, 174–185.

Chaiyapinunt, S., Worasinchai, S., 2009a. Development of a mathematical model for a curved venetian blind with thickness. Sol. Energy 83 (7), 1093–1113.

Chaiyapinunt, S., Worasinchai, S., 2009b. Development of a model for calculating the longwave optical properties and surface temperature of a curved venetian blind. Sol. Energy 83 (6), 817–831.

Chaiyapinunt, S., Phueakpongsuriya, B., Mongkornsaksit, K., Khomporn, N., 2005. Performance rating of glass windows and glass windows with films in aspect of thermal comfort and heat transmission. Energy Build. 37, 725–738.

Chantrasrisalai, C., Fisher, D.E., 2004. Comparative analysis of one-dimensional slat-type blind models, Simbuild 2004, IBPSA-USA National Conference, Boulder, CO, August 4–6.

Collins, M.R., Harrison, S.J., 2004. Estimating the solar heat and thermal gain from a window with an interior venetian blind. ASHRAE Trans. 110 (1), 486–500.

EnergyPlus, 2005. EnergyPlus Engineering Reference: The Reference to EnergyPlus Calculation, April.

Khamporn, N., 2012. Development of a mathematical model to predict thermal comfort performance of a glass window installed with interior venetian blind. PhD. Dissertation, Faculty of Engineering, Chulalongkorn University.

Khamporn, N., Chaiyapinunt, S., 2014. An investigation on the human thermal comfort from a glass window. Eng. J. 18, 25–43.

Klems, J.H., 1994a. A new method for predicting the solar heat gain of complex fenestration systems: 1. Overview and derivation of the matrix layer calculation. ASHRAE Trans. 100 (1), 1065–1072.

Klems, J.H., 1994b. A new method for predicting the solar heat gain of complex fenestration systems: 2. Detailed description of the matrix layer calculation. ASHRAE Trans. 100 (1), 1073–1086.

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

Klems, J.H., Warner, J.L., Kelley, G.O., 1996. A comparison between calculated and measured SHGC for complex glazing systems. ASHRAE Trans. 102 (1), 931–939.

Kuhn, T.E., 2006a. Solar control: a general evaluation method for facades with venetian blinds or other solar control systems. Energy Build. 38, 648–660.

Kuhn, T.E., 2006b. Comparison of two new systems with the state of art on the basis of a new general evaluation method for facades with venetian blinds or other solar control systems. Energy Build. 38, 661–672.

Pfrommer, P., Lomas, K.J., Kupke, C.H.R., 1996. Solar radiation transport through slat-type blinds: a new model and its application for thermal simulation of buildings. Sol. Energy 57 (2), 77–91.

Wright, J.L., Huang, N.Y.T., Collins, M.R., 2008. Thermal resistance of a window with an enclosed venetian blind: a simplified model. ASHRAE Trans. 114 (1), 471–4782.

Yahoda, D.S., Wright, J.L., 2004. Methods for calculating the effective longwave radiative properties of a venetian blind layer. ASHRAE Trans. 110 (1), 463–473.