Oral Presentation

The 7th TSME International Conference on Mechanical Engineering
13-16 December 2016

TSF0003

An experimental study on the thermal condition for a person sitting near a glass window with a vertical venetian blind installed

Somsak Chaiyapinunt[1,*], Rangsarid Patthanapanich[1], Benjamin Tenbuuren[1], Chayakorn Sitsumeth[1] and Nopparat Khamporn[2]

[1] Department of Mechanical Engineering, Faculty of Engineering, Chulalongkorn University, Phayathai, Bangkok 10330, Thailand.
[2] Department of Mechanical Engineering, Faculty of Engineering, Siam University, Petkasem, Bangkok 10160, Thailand
[*] Corresponding Author: E-mail. somsak.ch@chula.ac.th, Tel. 022186610, Fax. 022522889

Abstract

In this article, an experimental study on the thermal condition for a person sitting near a glass window with a vertical venetian blind installed is performed. The mean radiant temperature and PPD (predicted percentage of dissatisfied) are chosen to be the parameters for describing the human thermal comfort. Two types of glass windows, a clear and tinted glass, are chosen for the study. Three blind slat angles, 45°, 0° and -45°, are used to illustrate the effect of the blind slat angle on the human thermal comfort condition. From the study, it is found that the human thermal comfort condition for a person sitting near a glass window with a vertical blind installed is mainly dependent on the transmitted solar radiation incident on a person. In this study, it is found that the clear glass window with a blind installed at -45° slat angle gives the most thermal discomfort condition and the tinted glass window with a blind installed at 45° slat angle gives the least thermal discomfort condition.

***Keywords**:* Vertical venetian blind, Glass window, Thermal comfort, Mean radiant temperature, PPD.

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. The average typical energy consumption for air conditioning in office building for selected countries in a tropical zone (Malaysia, Indonesia, Thailand and Singapore) as the percentage of the total building's energy are as follow; 57%, 51%, 59% and 59%, respectively [1]. The high efficiency glass in term of heat reduction was preferably used as the glass window for building to reduce the energy usage in building from the air conditioning system. But when the building is actually in use, people tend to install an indoor shading device such as a horizontal venetian blind or a vertical venetian blind behind the glass window to control the light transmission and the condition of privacy. Therefore the understand of the thermal performance of the combined glass window and the venetian blind besides the understanding of the thermal performance of the plain glass window is necessary for designing a good energy-efficient building. Much work has been done about the heat transmission through the glass window with a venetain blind installed. But most of the works [2-11] are dealt with the flat slat horizontal blind. Chaiyapinunt and Worasinchai [12, 13] 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 [14] have performed a study on the effect of installing a curved horizontal venetian blind to the glass window on heat transmission to the space. Khamporn and Chaiyapinunt [15] have also performed a study on the effect of installing a curved horizontal venetian blind to the glass window on thermal comfort. All the works mentioned are specifically based on the horizontal venetian blind. Pipattadanukul and Chaiyapinunt [16] have done a study on the thermal performance of a curved vertical venetian blind. The work was based on the prediction from a developed mathematical model. In this article, an experimental study on the thermal condition for a person sitting near a glass window with a vertical venetian blind installed is performed. The effect of the glass window type and slat angle on the thermal performance is also investigated.

2. Theory

Thermal comfort is defined as the condition of mind that expresses satisfaction with the thermal environment (ISO 7730 [17] and ASHRAE Standard 55 [18]). The predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) are two indices that are commonly used to describe the thermal environmental condition. According to ISO 7730 [17] and Fanger [19] the expressions for PMV and PPD can be written as

TSF0003

$$PMV = \left(0.303e^{-0.036 \cdot M} + 0.028\right) \cdot [M(1-\eta) - 3.05\times10^{-3}\cdot(5733-6.99\cdot M(1-\eta)-P_a) - 0.42\cdot(M(1-\eta)-58.15) - 1.7\times10^{-5}\cdot M\cdot(5867-P_a) - 0.0014\cdot M\cdot(34-T_a) - 3.96\times10^{-8} f_{cl}\cdot((T_{cl}+273)^4 - (T_{mrt}+273)^4) - f_{cl}\cdot h_c(T_{cl}-T_a)] \quad (1)$$

$$PPD = 100 - 95\cdot e^{-(0.03353PMV^4 + 0.2179PMV^2)} \quad (2)$$

where

M = metabolic rate per unit body, (W/m^2).

P_a = vapor partial pressure, (Pa).

f_{cl} = clothing area factor.

T_{mrt} = mean radiant temperature, ($°C$).

T_a = air temperature, ($°C$).

T_{cl} = clothing surface temperature, ($°C$).

h_c = convective heat transfer coefficient, ($W/(m^2\text{-}K)$).

η = mechanical efficiency.

The clothing surface temperature can be evaluated by an iteration process from the following expressions

$$T_{cl} = 35.7 - 0.028M(1-\eta) - I_{cl}\left\{ \begin{array}{l} 3.96\times10^{-8}\cdot f_{cl}\cdot\left[\left(T_{cl}+273\right)^4 - \left(T_{mrt}+273\right)^4\right] \\ + f_{cl}\cdot h_c\cdot\left(T_{cl}-T_a\right) \end{array} \right\} \quad (3)$$

$$h_c = \begin{cases} 2.38\left(T_{cl}-T_a\right)^{0.25} & for\ \ 2.38\left(T_{cl}-T_a\right)^{0.25} > 12.1\sqrt{v_{ar}} \\ 12.1\sqrt{v_{ar}} & for\ \ 2.38\left(T_{cl}-T_a\right)^{0.25} < 12.1\sqrt{v_{ar}} \end{cases} \quad (4)$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 I_{cl} & for\ \ I_{cl} \le 0.078\ \ (m^2-K)/W \\ 1.05 + 0.645 I_{cl} & for\ \ I_{cl} > 0.078\ \ (m^2-K)/W \end{cases} \quad (5)$$

where

v_{ar} = relative air velocity (the air velocity relative to the occupant, including body movements), (m/s).

I_{cl} = clothing insulation, ($(m^2\text{-}K)/W$).

The mean radiant temperature, one of the important parameters required to calculate thermal comfort indices, can be obtained by converting the value of the measured operative temperature (temperature of an imaginary environment that transfers dry heat at the same rate as the actual environment) into the mean radiant temperature using the following equations [20]:

$$T_{smrto} = \left[(T_o + 273)^4 + \frac{h_{cg}}{\varepsilon_p \sigma}\left(T_o - T_a\right)\right]^{0.25} - 273 \quad (6)$$

$$h_{cg} = \max \text{ of } \begin{cases} 18\times v_a^{0.55} & \textit{Forced convection} \\ 3\times\left(\left|T_o - T_a\right|\right)^{0.25} & \textit{Free convection} \end{cases} \quad (7)$$

where

T_{smrto} = mean radiant temperature due to surface temperature and solar radiation evaluated from the value of operative temperature, ($°C$).

T_o = operative temperature, ($°C$).

T_a = air temperature, ($°C$).

v_a = air velocity, (m/s).

ε_p = emittance of exterior surface of person (standard value = 0.97).

σ = Stefan Boltzmann constant, ($W/(m^2\text{-}K^4)$).

3. Experimental set up

The experiment was performed to investigate the thermal comfort of a person sitting near a glass window with a vertical venetian blind installed.

3.1 Test room and instrumentation

The test room was located on the fourth floor of Hans Buntli building, Department of Mechanical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok (latitude 13.73°N, longtitude 100.57°E). The test room was constructed as a double-wall with a 50 mm (2-in.) fiber glass insulation placed in between. The west wall, which was exposed to the outside air, was constructed with aluminum cladding on the outside surface and a gypsum board as the inside surface with a 50 mm (2-in.) fiber glass insulation in between. The glass window of the size 0.9 x 1.1 m was installed as the test window on the west wall. The layout and dimension of the test room is shown in Fig. 1.

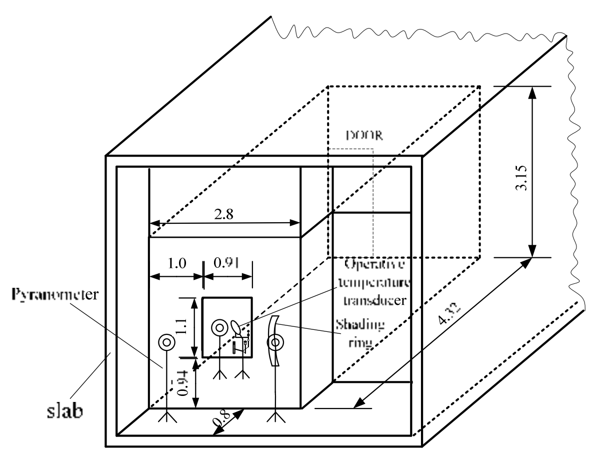

Fig. 1 The layout and dimension of the test room

A 6 mm clear glass and a 6 mm tinted (grey color) glass window were chosen as the test window for this study. A vertical venetian blind was installed behind the glass window with a distance of 120 mm from the inner glass surface to the center of the blind. The optical properties of the glass window and blind are shown in Table. 1. The blind chosen had slats of 90 mm in width and 0.3 mm in thickness. The slats had a radius of curvature of 143.4 mm. The slats were separated by a pitch of 80 mm. The conductivity of the slat was 120 W/(m-K). Two pyranometers ((Kipp & Zonen [21]) model CM 11 and CM6B) and a shadow ring [22] were used to measure the outside global solar radiation and diffuse solar radiation incident on the glass window. The third and fourth pyranometer ((Kipp & Zonen) model CM6B and CMP 6) were installed inside the test room to measure transmitted solar radiation. The operative temperature transducer (Innova MM0060) was installed 30 degrees to the vertical to simulate a person in the sitting position turned sideways to the glass window. The operative temperature sensor and pyranometers were installed 300 mm from the inner glass surface and 1300 mm above the floor. The inside air temperature was kept at 25°C by an air conditioning system. The inside room conditions: air velocity, air temperature, air humidity and operative temperature were measured using related transducers (Innova; MM0038, MM0034, MM0037 and MM0060 [23]). The data measured from the transducers were fed into the thermal comfort data logger (Innova 1221 [23]) and were processed using software to obtain the value of thermal comfort indices (i.e. mean radiant temperature, PMV and PPD). The value of thermal comfort indices will be used to represent the thermal condition for a person sitting near a glass window with a vertical venetian blind installed. In the experiment, the metabolic rate of the person is chosen to be 1.2 Met corresponding to normal work when sitting in an office. The cloth insulation is chosen to be 0.5 clo. The mechanical efficiency of the person is set to be 0.

Some specifications of experimental devices are listed in Table. 2. Figs. 2, 3 and 4 show the installation of the pyranometers and transducers. Fig. 5 shows the installation plate used for set the blind in 3 slat positions; 0°, 45° and -45° and the defined slat positions.

Fig. 2 The pyranometers and a shadow ring

Fig. 3 The vertical blind and the experimental devices

Fig. 4 Operative temperature sensor

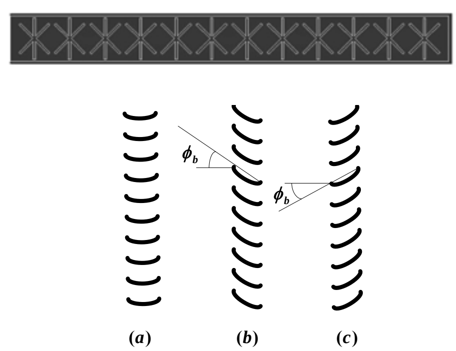

Fig. 5 The installation plate used for set the blind into the specified position and the defined slat position; (a) 0° (b) 45° (c) -45°

Table. 1 Glass and blind optical properties

Description	Solar Energy			Emissivity	
	Trn	Ref	Ab	Ef	Eb
clear	0.801	0.069	0.13	0.84	0.84
grey	0.419	0.051	0.531	0.84	0.84
slat	-	0.33	0.67	0.82	0.82

Note: Trn = Transmittance, Ref = Reflectance, Ab = Absorptance, Ef = Front emittance, Eb = Back emittance.

Table. 2 Some specifications of experimental devices

Item	Qty	Model	Accuracy
Pyranometer	2	CM6B	5 to 20 µV/ W/m^2
Pyranometer	1	CMP6	5 to 20 µV/ W/m^2
Pyranometer	1	CMP 11	7 to 14 µV/ W/m^2
Operative temperature transducer	1	MM0060	-20 to 50°C range: ±0.5°C
Air velocity transducer	1	MM0038	1<v_a<10m/s :typically better than ±0.1v_a m/s
Air temperature transducer	1	MM0034	-20 to 50°C range: ±0.5°C
Air humidity transducer	1	MM0037	10K< t_a-t_d <25K : ±0.1 kPa
Thermal comfort data logger	1	1221	Resolution ±0.1°C
Data logger	1	NI9211	ADC resolution 24 bit

Note: v_a = air velocity
t_a = air temperature, t_d = dew-point temperature
ADC = analog-to-digital converter

3.2 Uncertainty analysis

In this study, uncertainty analysis was performed on measured data and evaluated data using the value of measured data. The sources of uncertainty include sensor accuracy and error due to the sensor set up. Sensor accuracy can be obtained from the manufacturers [21], [23] as shown in Table. 1. Total uncertainty of the data can be estimated from the root mean square of all bias uncertainties associated with the measurements as follows:

$$U_R = \sqrt{\left(\frac{\partial R}{\partial x_1}U_1\right)^2 + \left(\frac{\partial R}{\partial x_2}U_2\right)^2 + \ldots\ldots\ldots\ldots\ldots\ldots \left(\frac{\partial R}{\partial x_n}U_n\right)^2} \quad (8)$$

where R = data which is the function of the independent variables $x_1, x_2, x_3, \ldots . x_n$.
x_i = independent variable of the data R (for i = 1 to n).
U_R = total uncertainty of the data R.
Ui = total uncertainty of the independent variable (x_i) of the data R.

The uncertainties associated with measured solar radiation (i.e. sensor errors, error from shadow ring and error related to slat angle adjustment, etc.) are estimated to be as follows: ±8.12% for incident global solar radiation, ±8.20% for diffuse solar radiation and ±9.23% for transmitted solar radiation (Chaiyapinunt and Khamporn [24]). The uncertainty of the measured outside air temperature, inside glass surface temperature, blind temperature and operative temperature is about ±0.5°C for each. For neglecting errors due to angle factor and shading fraction, Khamporn and Chaiyapinunt [25] estimated the uncertainties for the mean radiant temperature evaluated from the measured operative temperature to be ±3.5 %. The average estimated uncertainty of total PPD evaluated from the value of mean radiant temperature evaluated using the measured operative temperature is approximately ±2% (during the times 5:00-14:00 and 18:00-19:00 hours) and approximately ±13% (during the time 14:00-18:00 hours).

4. Thermal performance

Figs. 6 and 8 show the time variation of incident global solar radiation, incident diffuse solar radiation and transmitted solar radiation for a clear and a tinted glass window. Figs. 7 and 9 show the time variation of the mean radiant temperature, operative temperature and predicted percentage of dissatisfied (PPD) for a clear and a tinted glass window.

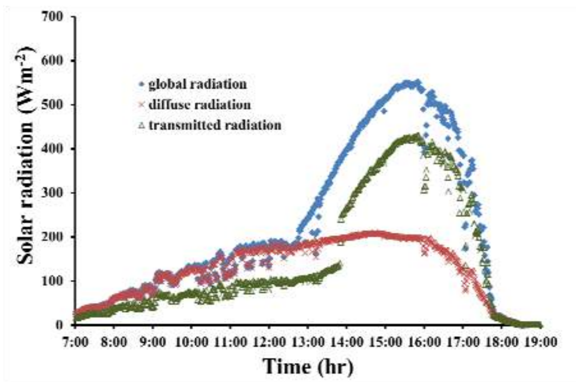

Fig. 6 Incident solar radiation and transmitted solar radiation on a clear glass window (April 1, 2016)

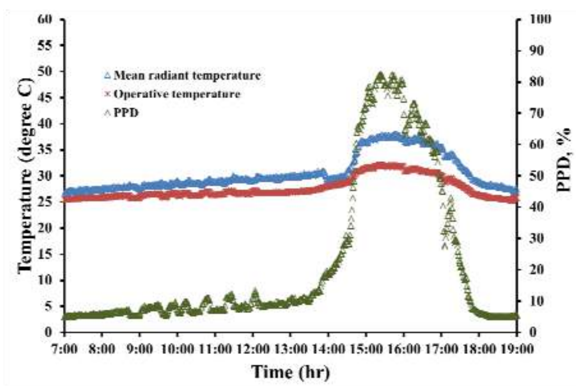

Fig. 7 Mean radiant temperature, operative temperature and PPD for a clear glass window (April 1, 2016)

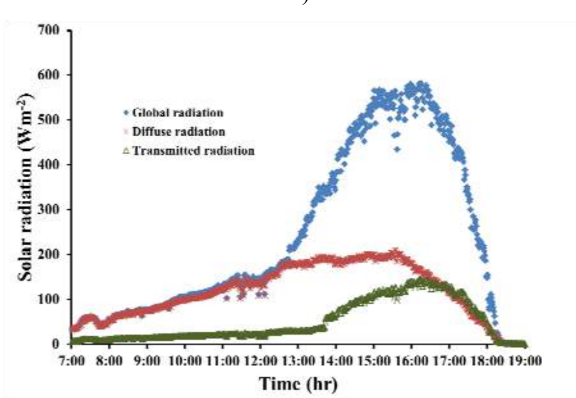

Fig. 8 Incident solar radiation and transmitted solar radiation on the 6 mm tinted glass window (April 2, 2016)

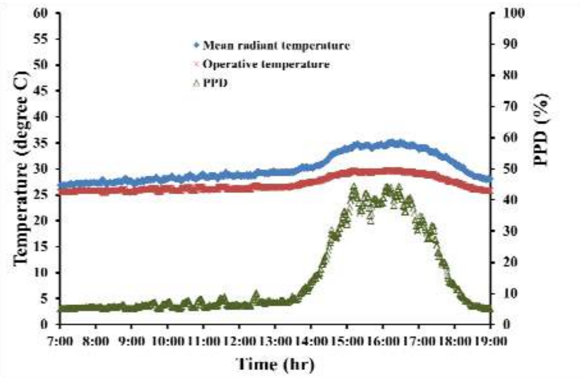

Fig. 9 Mean radiant temperature, operative temperature and PPD for a tinted glass window (April 2, 2016)

It can be seen from Figs. 6 and 8 that the magnitude of the incident global solar radiation and incident diffuse solar radiation in the morning are similar as the building faces west. Thus, only diffuse solar radiation can be measured in the morning. The direct solar radiation is incident on the glass window starting at around 13:00 hours. Maximum global solar radiation occurs at around 15:00 to 16:30 hours. The time variation of the transmitted solar radiation has a similar pattern to the incident global solar radiation, but of a smaller magnitude dependent on the optical properties (i.e. transmittance, etc.) of the glass window. It can be clearly seen that the transmitted solar radiation for the tinted glass window is remarkably less than the transmitted solar radiation for the clear glass window. The reason is that the transmittance of the tinted glass window is lower than the transmittance of the clear glass window (Table. 1). The operative temperature, shown in Figs 7 and 9, is increased when there is a high value of transmitted solar radiation entering into the room during the time of 14:00 to 17:00. The mean radiant temperature is also increased with the operative temperature. It was found that for a clear glass window the mean radiant temperature reaches the maximum value of 38°C at the time around 15:45. The PPD also has the maximum value of 82% at the time around 15:45. It was found that for a tinted glass window the mean radiant temperature reaches the maximum value of 34.5°C at the time around 16:00. The PPD also has the maximum value of 44% at the time around 16:00. The difference between the PPD for a clear glass window and a tinted glass window can be directly related to the amount of the transmitted solar radiation through the glass window. People who sit near the clear glass window with high incident solar radiation will feel more discomfort compared to the case of people sitting near the tinted glass window.

Figs. 10, 12 and 14 show the time variation of incident global solar radiation, incident diffuse solar radiation and transmitted solar radiation for a clear glass window with a vertical venetian blind installed at 45°, 0° and -45° slat angle. Figs. 11, 13 and 15 show the time variation of the mean radiant temperature, operative temperature and predicted percentage of dissatisfied (PPD) for a clear glass window with a vertical venetian blind installed at 45°, 0° and -45° slat angle.

When the blind is set at 45° slat angle, the blind will block most of the solar radiation from entering into the room. Fig. 10 shows the transmitted solar radiation is significantly reduced compared to the case of a plain clear glass window (Fig. 6). The transmitted solar radiation reaches its maximum value at time around 17:20. The mean radiant temperature and PPD are also reduced compared to the case of the plain clear glass window (Fig. 7). Fig. 11 shows that the mean radiant temperature is reduced from 38°C for a clear glass window to 33°C for a clear glass window with a vertical blind installed at 45° slat angle. The PPD is reduced from 82% for a plain clear glass window to 31% for a clear glass window with a vertical blind installed at 45° slat angle.

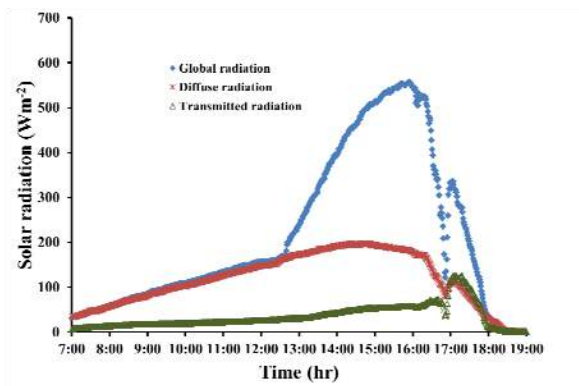

Fig. 10 Incident solar radiation and transmitted solar radiation on a clear glass window with blind at 45° degree slat angle (April 13, 2016)

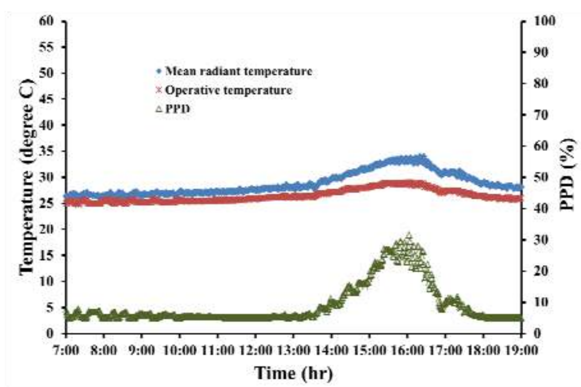

Fig. 11 Mean radiant temperature, operative temperature and PPD for a clear glass window with blind at 45° degree slat angle (April 13, 2016)

When the blind is set at 0° slat angle, the effect of the blind on reducing the transmitted solar radiation is not so profound compared to the case of 45° slat angle. Fig. 12 shows the transmitted solar radiation reaches its maximum value at time around 16:00. Fig. 13 shows that the mean radiant temperature is reduced from 38°C for a clear glass window to 34.4°C for a clear glass window with a vertical blind installed at 0° slat angle. The PPD is reduced from 82% for a plain clear glass window to 58% for a clear glass window with a vertical blind installed at 0° slat angle.

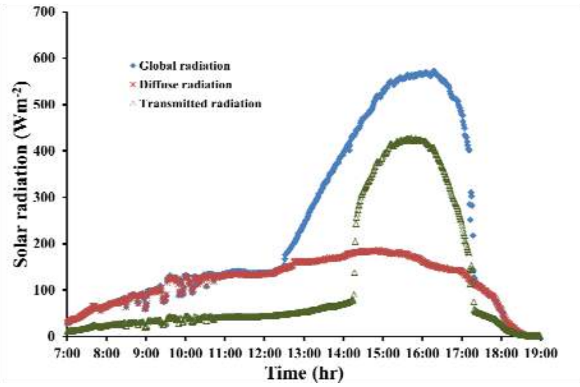

Fig. 12 Incident solar radiation and transmitted solar radiation on a clear glass window with blind at 0° degree slat angle (May 13, 2016)

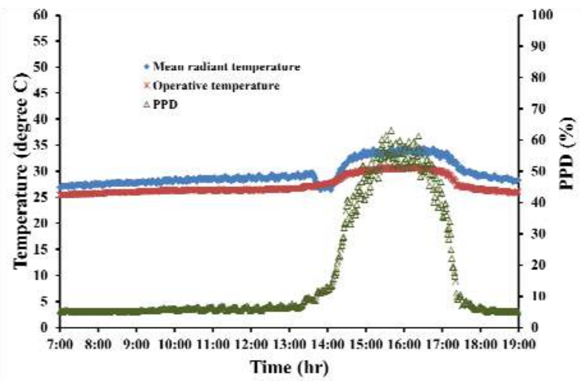

Fig. 13 Mean radiant temperature, operative temperature and PPD for a clear glass window with blind at 0° degree slat angle (May 13, 2016)

When the blind is set at -45° slat angle, the effect of the blind on reducing the transmitted solar radiation is not so profound compared to the case of 45° slat angle. Fig. 14 shows the transmitted solar radiation reaches its maximum value at time around 16:00. Fig. 15 shows that the mean radiant temperature is reduced from 38°C for a clear glass window to 36.7°C for a clear glass window with a vertical blind installed at -45° slat angle. The PPD is reduced from 82% for a plain clear glass window to 80% for a clear glass window with a vertical blind installed at -45° slat angle.

It can conclude that installing a vertical venetian blind behind a clear glass window will improve the thermal condition for a person sitting near the glass window. Among the three slat angles (45°, 0° and -45°), the blind setting at 45° slat angle gives the least thermal discomfort condition and the blind setting at -45° slat angle gives the most thermal discomfort condition. The operative temperature is dependent on the transmitted solar radiation. The PPD and mean radiant temperature are also directly dependent on the amount of the transmitted solar radiation incident on a person sitting near the glass window.

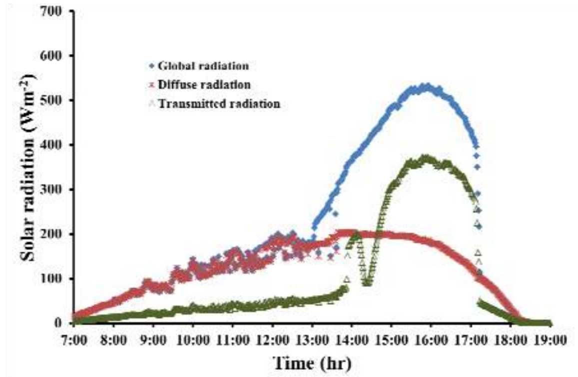

Fig. 14 Incident solar radiation and transmitted solar radiation on a clear glass window with blind at -45° degree slat angle (March 6, 2016)

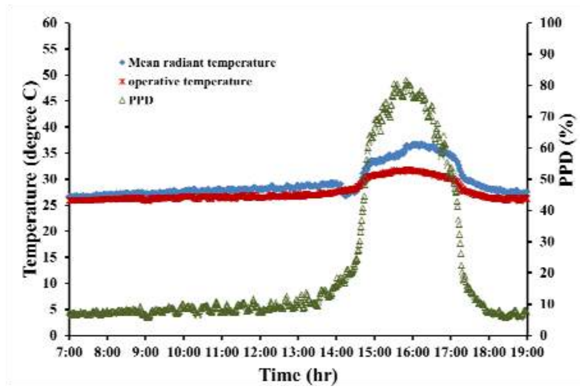

Fig. 15 Mean radiant temperature, operative temperature and PPD for a clear glass window with blind at -45° degree slat angle (March 6, 2016)

Figs 16 to 21 show the time variation of incident global solar radiation, incident diffuse solar radiation, transmitted solar radiation, mean radiant temperature, operative temperature and PPD for a tinted glass window with a vertical venetian blind installed at 45°, 0° and -45° slat angle.

The effect of installing a vertical venetian blind to the tinted glass window is the similar to the case of installing a vertical venetian blind to the clear glass window. The time variation of the transmitted solar radiation, mean radiant temperature and PPD have similar pattern to the ones for a clear glass window with a vertical blind installed, but of a smaller magnitude. The reason is that the transmittance of the tinted glass window is lower than the transmittance of the clear glass window. Among the three slat angles (45°, 0° and -45°), the blind setting at 45° slat angle gives the least thermal discomfort condition and the blind setting at -45° slat angle gives the most thermal discomfort condition.

From the experimental study, it can be said that the thermal performance of the glass window with a vertical blind installed is quite similar to the thermal performance of the glass window with a horizontal blind installed [15]. Since the vertical blind is typically larger than the horizontal blind in term of slat width and slat pitch (spacing between the slats), the effect of the blind on thermal condition for a vertical blind will be less than for a horizontal blind. One can see from Figs. 12 and 14 (a clear glass window with a vertical blind installed at 0° and -45° slat angle) that the reduction in transmitted solar radiation compared to the case of a plain clear glass window is not significant. Therefore, the slat position of the blind (slat angle) of the vertical blind has more effect on the thermal condition in a room than the horizontal blind.

Fig. 16 Incident solar radiation and transmitted solar radiation on a tinted glass window with blind at 45° degree slat angle (April 9, 2016)

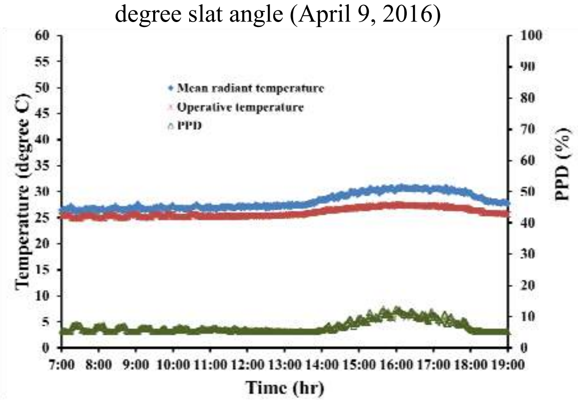

Fig. 17 Mean radiant temperature, operative temperature and PPD for a tinted glass window with blind at 45° degree slat angle (April 9, 2016)

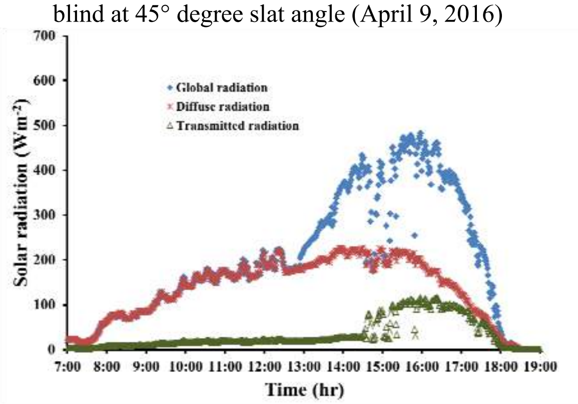

Fig. 18 Incident solar radiation and transmitted solar radiation on a tinted glass window with blind at 0° degree slat angle (March 26, 2016)

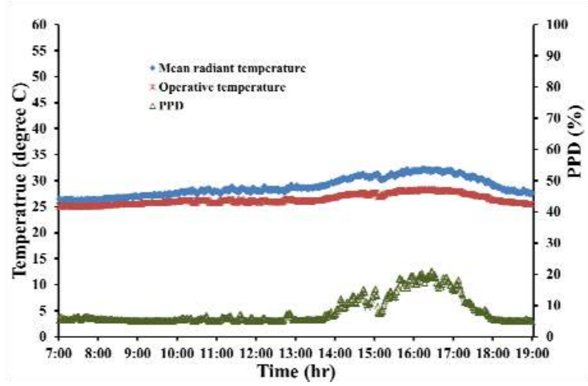

Fig. 19 Mean radiant temperature, operative temperature and PPD for a tinted glass window with blind at 0° degree slat angle (March 26, 2016)

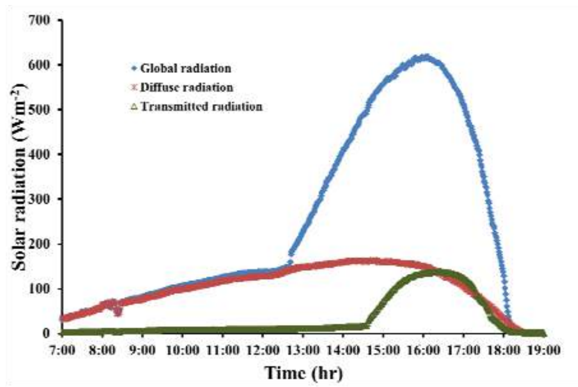

Fig. 20 Incident solar radiation and transmitted solar radiation on a tinted glass window with blind at -45° degree slat angle (April 11, 2016)

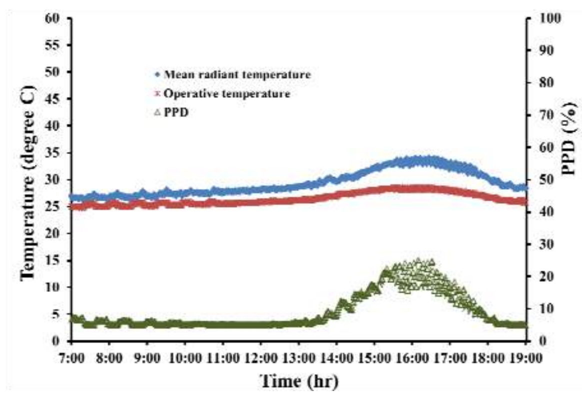

Fig. 21 Mean radiant temperature, operative temperature and PPD for a tinted glass window with blind at -45° degree slat angle (April 11, 2016)

5. Conclusion

An experimental study on the thermal condition for a person sitting near a glass window with a vertical venetian blind installed is performed. The mean radiant temperature and PPD, which can be evaluated from the measured operative temperature, are chosen to be the parameters for describing the human thermal comfort. Two types of glass windows; a clear and a tinted glass, are chosen for the study. Three blind slat