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Analysis on thermal condition for a person sitting near a glass window

Somsak Chaiyapinunt[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: somsak.ch@chula.ac.th

Abstract. The effects of related parameters on thermal comfort condition for a person sitting near a glass window are investigated. The mean radiant temperature and PPD (predicted percentage of dissatisfied) are chosen to be the parameters for describing the human thermal comfort. The effects of the transmitted direct solar radiation, transmitted diffuse solar radiation, glass surface temperature and distance of a person from the glass window on the mean radiant temperature and PPD are studied. It is found that the intensity of the transmitted solar radiation and the value of glass surface temperature all have effect on the human thermal comfort. The mean radiant temperature and PPD are decreased when the distance of a seated person from the glass window is increased for the case of having transmitted diffuse solar radiation and having high glass surface temperature. The mean radiant temperature and PPD are increased when the distance of a person from the glass window is increased for the case of having transmitted direct solar radiation.

1. Introduction

Glass windows nowadays become a common type of building envelope for a commercial building especially for a high-rise building. Glass windows have a certain benefit in term of providing a visual connection for the tenants to the exterior. They also allow the natural light to admit into the interior space to reduce the use of the artificial light. But for building located in the tropical zone, the glass windows could also accept plenty of incident solar radiation into the interior space causing an unpleasant thermal condition for the tenants to live in. A large air conditioning system is usually required to get rid of the high solar cooling load. But in order to keep the thermal condition of the room pleasant for the tenants to live in, one also has to maintain the mean radiant temperature (the uniform temperature of an imaginary black enclosure which would result in the same heat loss by radiation from the person as the actual enclosure (ISO7730 [1]) of the space in the acceptable value rather than considering only the space inside temperature. To describe the thermal comfort condition, Fanger [2] has developed the thermal comfort indices as the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD). A considerable number of researches have been conducted on thermal performance of glass windows emphasized on the heat transmission and thermal comfort: Rizzo et al. [3], Athienitis and Haghighat [4]; Gan [5]; Chaiyapinunt et al. [6]; La Gennusa et al. [7]; La Gennusa et al. [8]; Singh et al. [9]; Chaiyapinunt and Khamporn [10]; Dong et al. [11]; Hwang and Shu [12] and Khamporn and Chaiyapinunt [13]. It was found that the thermal comfort of a person sitting near a glass window is dependent on the mean radiant temperature, the amount of solar radiation incident on the person and the glass surface temperature along with the other 5 parameters (air temperature, wind speed inside the room, vapor partial pressure, clothing surface temperature and metabolic rate).

Khamporn and Chaiyapinunt [13] have compared the predicted results from the developed mathematical model with the measured results from the experiment for verification purpose. It was found that the agreement of the predicted results and the measured data is good. The experiment was performed by setting the measurement transducers (simulate the person sitting near glass window) at the distance of 200 mm from the inside surface of the glass window. The thermal comfort condition analyzed from Khamporn and Chaiyapinunt [13] is based on the 200 mm distance from the glass window. The reason for chosen the distance was due to the small size of glass window (0.9x1.1 m) used in the experiment. It would be difficult to measure the proper value of the transmitted solar radiation if the sensor was moved away further into the room. The distance (200mm) was not so realistic for the people to sit near the glass window. Therefore, in this study, the effect of the related parameters (especially the distance of a seated person from the glass window) on the thermal comfort condition of a person sitting near the glass window are investigated.

2. Thermal comfort indices and related parameters

In this study, the indices that are chosen to describe the human thermal comfort condition are the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD). The expression for PMV and PPD can be written according to ISO 7730 [1] and Fanger [2] as

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

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

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

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

$$h_c = \begin{cases} 2.38\left(T_{cl} - T_a\right)^{0.25} & for\ \ 2.38\left(T_{cl} - T_a\right)^{0.25} \rangle\, 12.1\sqrt{v_{ar}} \\ 12.1\sqrt{v_{ar}} & for\ \ 2.38\left(T_{cl} - T_a\right)^{0.25} \langle\, 12.1\sqrt{v_{ar}} \end{cases} \tag{4}$$

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

where v_{ar} = relative air velocity (the air velocity relative to the occupant, including body movements), (m/s).
I_{cl} = clothing insulation, ((m^2-K)/W).

It is found that the mean radiant temperature of an enclosure is one of the important parameters in evaluating the value of the PMV. The mean radiant temperature of the enclosure can also be divided into the mean radiant temperature that is accounted only for the effect of the glass surface temperature and the mean radiant temperature that accounted for the effect of surface temperature and solar radiation [6]. The expression for both kinds of the mean radiant temperature can be written as

$$T_{tmrt} = [(t_{s1}+273)^4 \cdot F_{p-1} + (t_{s2}+273)^4 \cdot F_{p-2} + ...+ (t_{sn}+273)^4 \cdot F_{p-n}]^{0.25} - 273 \quad (6)$$

$$T_{smrt} = \left[(T_{tmrt}+273)^4 + \frac{a_p}{\varepsilon_p \sigma}\left(F_{p-win} I_{trdiff} + f_p I_{trdir} \right) \right]^{0.25} - 273 \quad (7)$$

where T_{tmrt} = mean radiant temperature due to surface temperature, ($°C$).

T_{smrt} = mean radiant temperature due to surface temperature and solar radiation, ($°C$).

t_{sj} = surface temperature of the enclosure wall number j, ($°C$).

F_{p-i} = angle factor between the person and surface i ($\sum_{i}^{n} F_{p-i} = 1$).

F_{p-win} = angle factor between the person and the glass window surface.

f_p = projected area factor.

a_p = absorptance of the outer surface of the person (standard value = 0.6).

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

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

I_{trdir} = transmitted direct solar radiation striking on the person, (W/m^2).

I_{trdiff} = transmitted diffuse solar radiation striking on the person, (W/m^2).

The expression for the mean radiant temperature due to surface temperature and solar radiation in equation (7) (in the part of solar radiation effect) has been adopted from the relation given by La Gennusa et al.[7].

In this study, we will emphasis on the thermal comfort condition for a person sitting turning sideway to the glass window. From equations (6) and (7), the mean radiant temperature is also dependent on the angle factor between the person and surfaces and the projected area factor besides the magnitude of the transmitted solar radiation. Rizzo et al. [3] have developed the algorithms for the calculation of mean projected area factors of seated person as a function of the azimuth angle, α , for selected values of the altitude angle, β (see figure 1 for angle definitions) as the following relation:

$$f_p(\alpha,\beta) = \sum_{i=0}^{4} A_i(\beta) \cdot \alpha^i \quad (8)$$

$$A_i(\beta) = \sum_{j=0}^{3} A_{ij} \cdot \beta^j \quad (9)$$

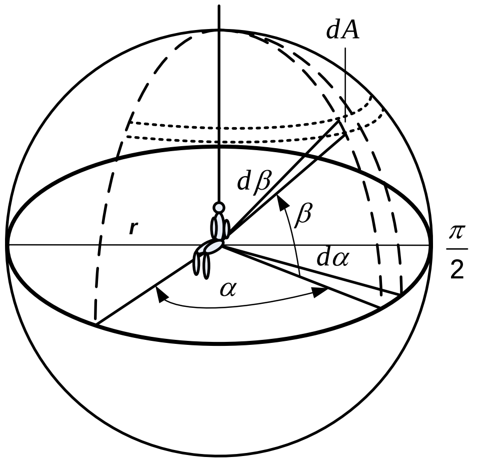

Figure 1. Definition of related angles for calculating the mean project area factor for a seated person.

Table 1 shows the coefficients of the polynomial algorithms (A_{ij}) used in equation (9) for the case of seated persons.

Table 1. Coefficients of the polynomial algorithms (A_{ij}) for the case of seated person.

j	*i*				
	0	1	2	3	4
Coefficients for seated person A_{ij}					
0	$+2.884\times10^{-1}$	$+2.225\times10^{-3}$	-9.292×10^{-5}	$+9.027\times10^{-7}$	-2.517×10^{-9}
1	$+2.225\times10^{-3}$	-7.653×10^{-5}	$+4.021\times10^{-6}$	-4.632×10^{-8}	$+1.380\times10^{-10}$
2	-5.472×10^{-5}	$+7.286\times10^{-7}$	-6.215×10^{-8}	$+7.690\times10^{-10}$	-2.341×10^{-12}
3	$+1.802\times10^{-7}$	-1.457×10^{-9}	$+3.152\times10^{-10}$	-4.015×10^{-12}	$+1.231\times10^{-14}$

Cannistraro et al. [14] have developed the algorithms for the calculation of the angle factors between human body and rectangular surfaces in parallelepiped environments as the following:

$$F_{p-n} = F_{\max}\cdot\left[1-\exp\left(\frac{-(a/c)}{\tau}\right)\right]\cdot\left[1-\exp\left(\frac{-(b/c)}{\gamma}\right)\right] \tag{10}$$

$$\tau = A + B\frac{a}{c} \tag{11}$$

$$\gamma = C + D\frac{b}{c} + E\frac{a}{c} \tag{12}$$

Figure 2 shows the definition of the related parameters used for calculating the angle factor in equation (10). Table 2 shows the value of the parameters to be used in equation (10) – (12).

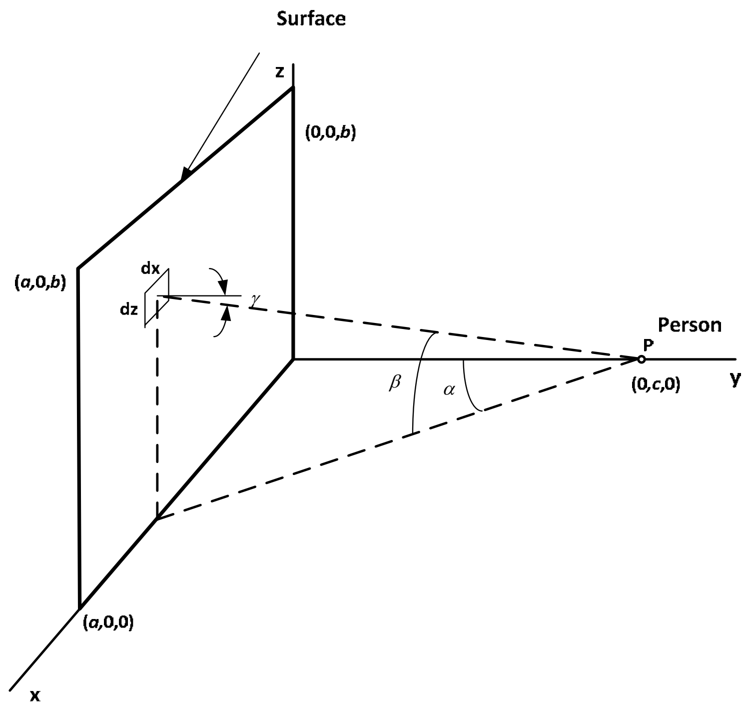

Figure 2. Definition of the related parameters used for calculating the angle factor in equation (10).

Table 2. Parameters to be used in equations (11) - (13) for the case of seated persons. [14]

Case	$F_{\max}$	A	B	C	D	E
Window Case 3	0.131	1.41607	0.09957	0.76196	0.07182	0.05578
Window Case 4	0.104	1.15253	0.13945	0.73371	0.09442	0.03688

3. Effect of related parameters on the thermal condition

To investigate the effects of related parameters on thermal comfort condition for a person sitting near a glass window, the room of size 4x8 m and height of 3 m with a glass window of 3x4 m as shown in figure 3 is used for this study. A person is assigned to sit turning sideway to the glass window. The position of a seated person is 0.6 m above the floor and lies in the middle of the room width. The glass window is divided into 4 subareas related to the occupant position (according to the work developed by Cannistraro et al. [14]). The sun is assumed in the position that the transmitted solar radiation always incident on the seated person with angle β as shown in figure 3. The distance of the seated person from the glass window, y_0, will be varied. The metabolic rate of the person is chosen to be 1.2 Met (M = 70 W/m^2)) corresponding to normal work when sitting in an office. The clothing insulation (I_{cl}) is chosen to be 0.0775 (m^2-K)/W (0.5clo). The mechanical efficiency of the person is set to be 0. The inside air temperature is kept around 25 ºC. The surface temperatures of the room except the glass window are assumed to be the same as the inside air temperature. Figure 4 shows the variation of the angle factor of a seated person and projected area factor between the seated person and the glass window surface with the distance from the glass window (from 0.5 m to 8 m). The value of angle factor is decreasing when the position of the seated person moved further away from the glass window. The value of the projected area factor is increasing when the position of the person moved further away from the glass window. The reason that the projected area factor is increasing is due to the assumption that the sun is always in the position that the transmitted solar radiation incident on the seated person with angle β as shown in figure 3. Therefore when the position of the seated person is moved further back in the room the angle β is decreasing causes the projected area of the seated person is increasing.

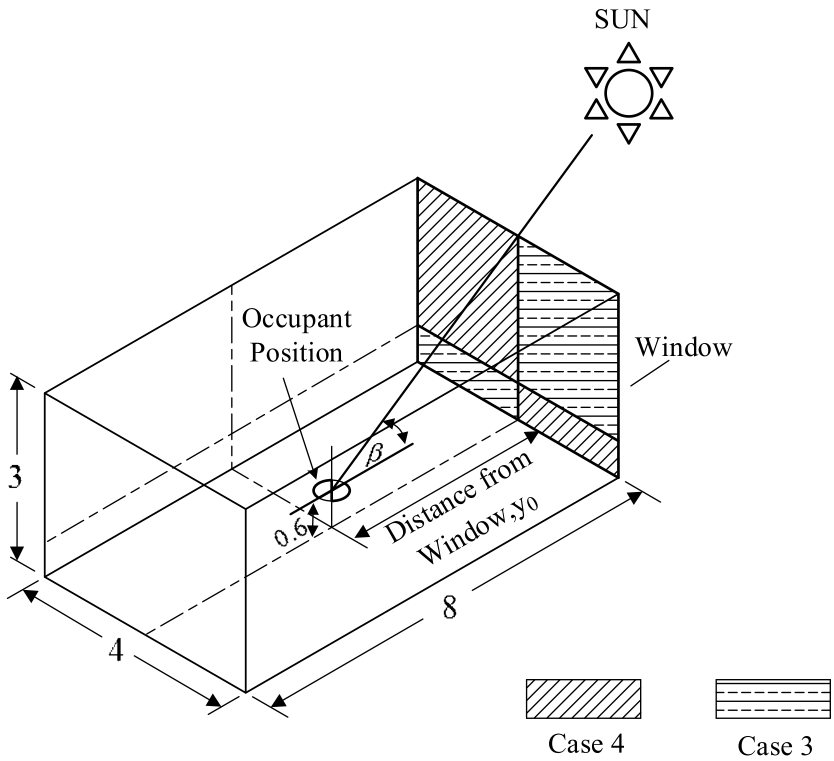

Figure 3. The room with glass window and related parameters used in the study.

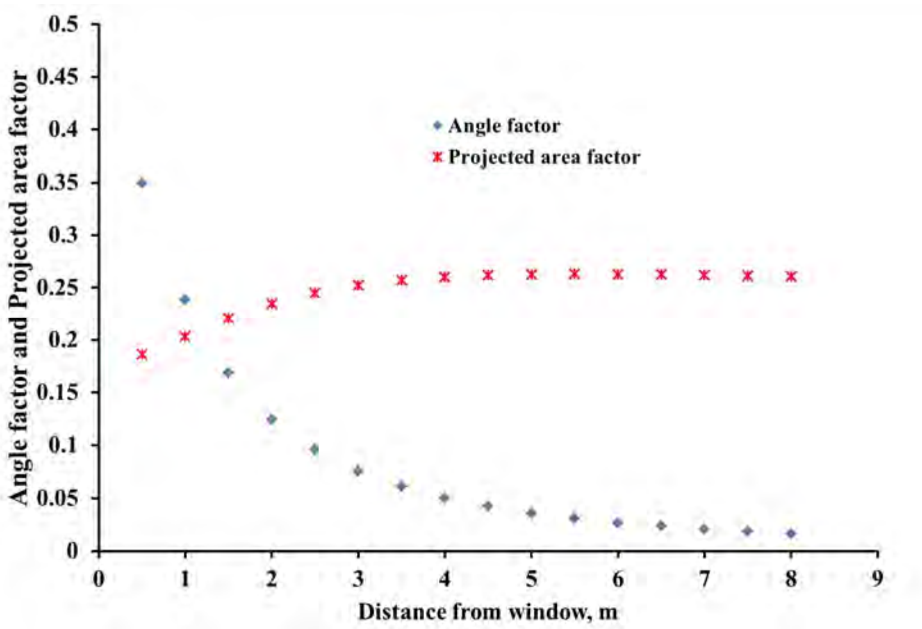

Figure 4. The variation of the angle factor and projected area factor with the distance of the seated person from the glass window.

3.1 *Effect of related parameters on the mean radiant temperature*

The effect of the related parameters (glass surface temperature, diffuse solar radiation and direct solar radiation) on the mean radiant temperature in the various positions along the room length is investigated. Figure 5 shows the variation of the mean radiant temperature along the distance from the glass window for the case of no transmitted solar radiation with different glass surface temperature. It can be seen that the glass surface temperature has direct effect on the mean radiant temperature. The value of the mean radiant temperature is always lower than the glass surface temperature. The mean radiant temperature is decreasing when the position of the seated person is moved further to the back of the room as shown in figure 5.

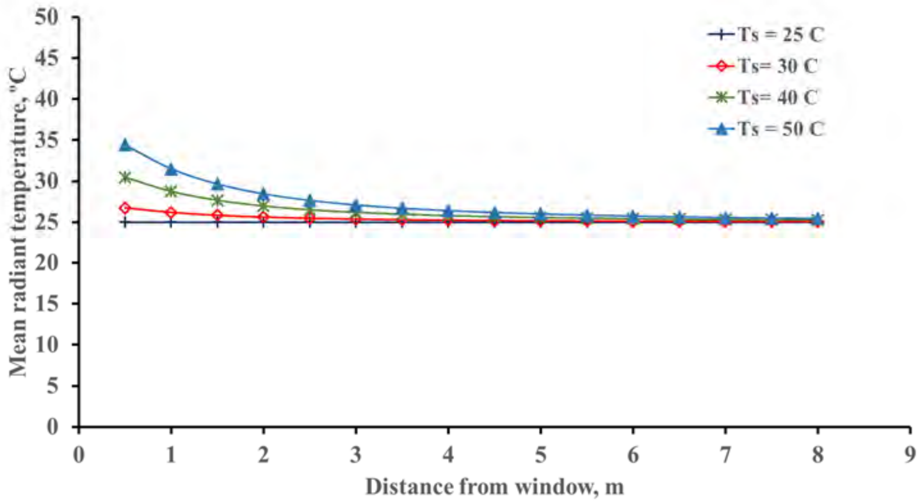

Figure 5. The variation of the mean radiant temperature with the distance of the seated person from the glass window for different value of glass surface temperature.

The effect of the transmitted diffuse solar radiation (no transmitted direct solar radiation) on the mean radiant temperature with different glass surface temperature is shown in figures 6 – 9. Figure 6 shows the variations of the mean radiant temperature along the distance of the room when the glass surface temperature is fixed at 25 °C and the transmitted diffuse solar radiation is varied from 0 to 500 W/m^2. The mean radiant temperature is directly dependent on the magnitude of the incident diffuse solar radiation. The value of the mean radiant temperature is decreasing with the distance of the seated person from the glass window. The decreasing pattern is in the exponential form. Figures 7 – 9 shows the variations of the mean radiant temperature along the distance of the room when the glass surface temperature is fixed at 30°C, 40°C, 50°C and the transmitted diffuse solar radiation is varied from 0 to 500 W/m^2. One can see clearly that the effect on the mean radiant temperature is the combination of the effect of the glass surface temperature and the effect of the transmitted diffuse solar radiation. The higher the glass surface temperature and the transmitted diffuse solar radiation, the higher the mean radiant temperature. The effect on the distance of the seated person on the mean radiant temperature for the case of the varying the glass surface temperature and the transmitted diffuse solar radiation is found to be dominant. The further away of the seated person from the glass window, the smaller value of the mean radiant temperature will the person feel.

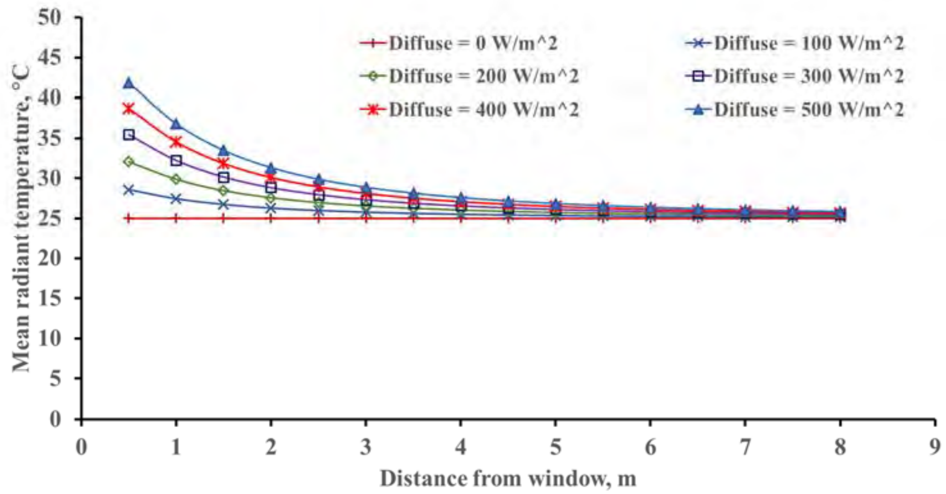

Figure 6. The variation of the mean radiant temperature with the distance of the seated person from the glass window for different value of the diffuse solar radiation when the glass surface temperature is fixed at 25°C.

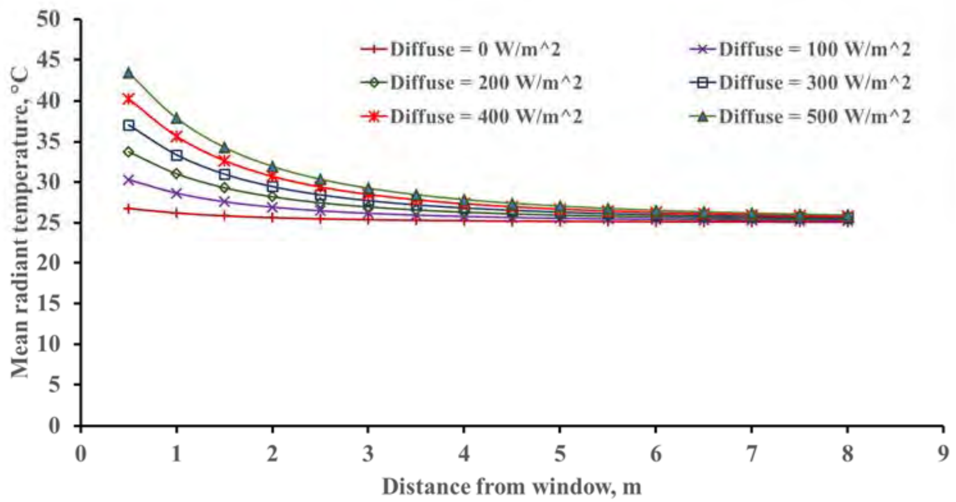

Figure 7. The variation of the mean radiant temperature with the distance of the seated person from the glass window for different value of the diffuse solar radiation when the glass surface temperature is fixed at 30°C.

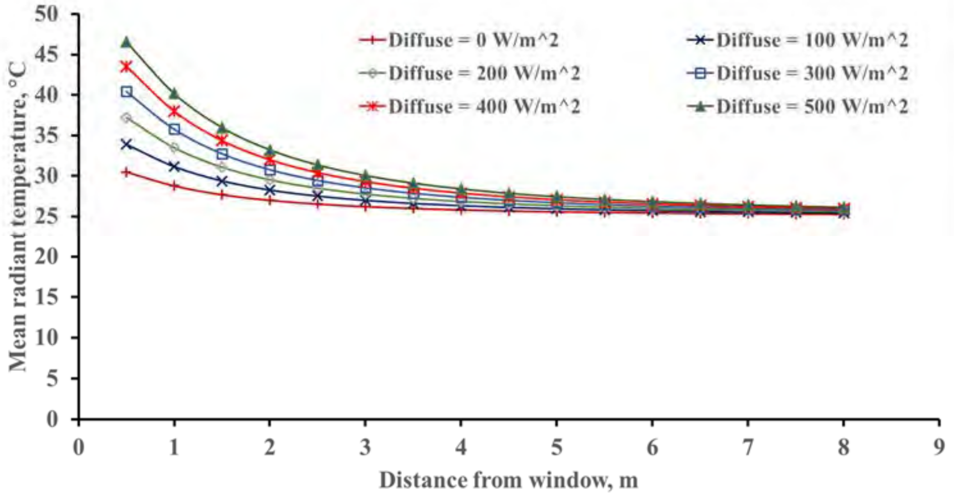

Figure 8. The variation of the mean radiant temperature with the distance of the seated person from the glass window for different value of the diffuse solar radiation when the glass surface temperature is fixed at 40°C.

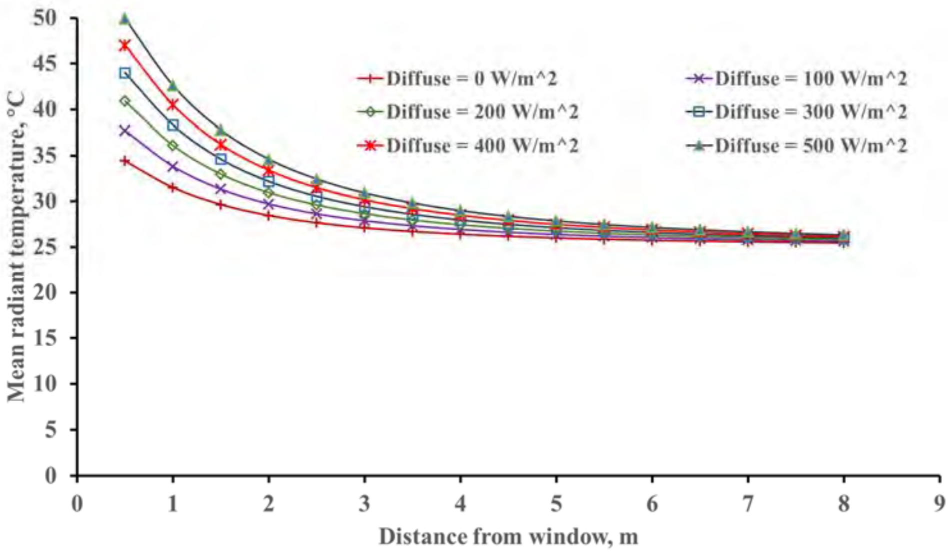

Figure 9. The variation of the mean radiant temperature with the distance of the seated person from the glass window for different value of the diffuse solar radiation when the glass surface temperature is fixed at 50°C.

The effect of the transmitted direct solar radiation (no transmitted diffuse solar radiation) on the mean radiant temperature with different glass surface temperature is shown in figures 10 – 13. Figure 10 shows the variations of the mean radiant temperature along the distance of the room when the glass surface temperature is fixed at 25 °C and the transmitted direct solar radiation is varied from 0 to 500 W/m^2. The mean radiant temperature is directly dependent on the magnitude of the transmitted direct solar radiation incident on a person. The value of the mean radiant temperature is slowly increasing with the distance of the seated person from the glass window. The increasing of the mean radiant temperature is almost diminished when the distance of the seated person from the glass window exceeded 4 m. Figures 11 – 13 shows the variations of the mean radiant temperature along the distance of the room when the glass surface temperature is fixed at 30°C, 40°C, 50°C and the transmitted direct solar radiation is varied from 0 to 500 W/m^2. One can see clearly that the effect on the mean radiant temperature is the combination of the effect of the glass surface temperature and the effect of the transmitted direct solar radiation. The mean radiant temperature is directly dependent on the glass surface temperature and transmitted direct solar radiation. It is interesting to find that, with the assumption that the transmitted direct solar radiation is always incident on the seated person, the further away of the seated person from the glass window, the higher value of the mean radiant temperature will the person feel.

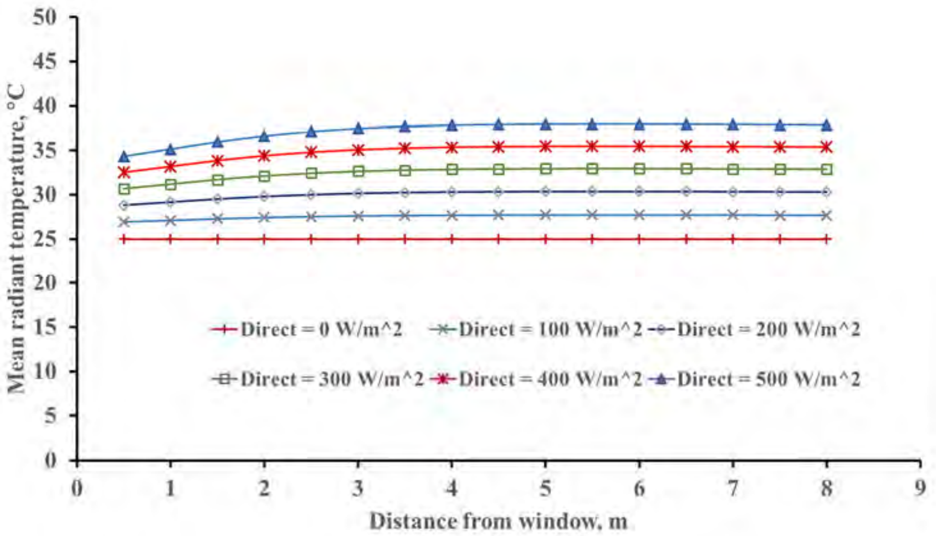

Figure 10. The variation of the mean radiant temperature with the distance of the seated person from the glass window for different value of the direct solar radiation when the glass surface temperature is fixed at 25°C.

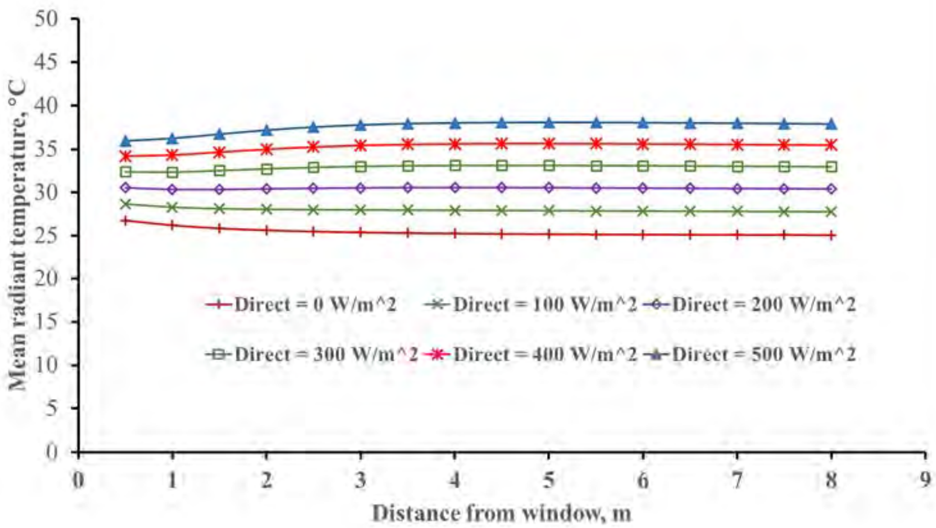

Figure 11. The variation of the mean radiant temperature with the distance of the seated person from the glass window for different value of the direct solar radiation when the glass surface temperature is fixed at 30°C.

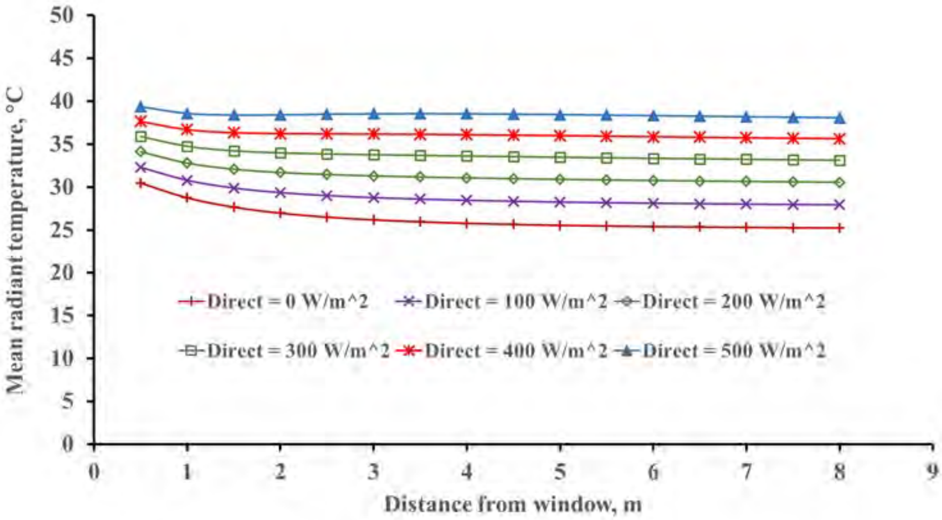

Figure 12. The variation of the mean radiant temperature with the distance of the seated person from the glass window for different value of the direct solar radiation when the glass surface temperature is fixed at 40°C.

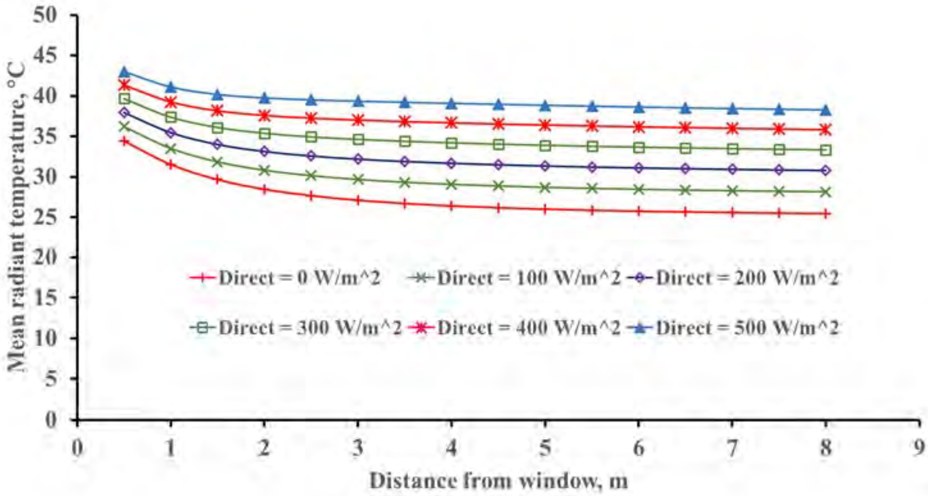

Figure 13. The variation of the mean radiant temperature with the distance of the seated person from the glass window for different value of the direct solar radiation when the glass surface temperature is fixed at 50°C.

3.2 *Effect of related parameters on the predicted percentage of dissatisfied*

With the effect of the related parameters (glass surface temperature, diffuse solar radiation and direct solar radiation) on the mean radiant temperature in the various positions along the room length as shown in figures 5 – 13, the effect of the related parameters on the predicted percentage of dissatisfied (PPD) is then investigated. Figure 14 shows the variation of the PPD of the seated person along the distance from the glass window for different values of the glass surface temperature. The pattern of the variation of the PPD with the distance of the seated person from the glass window is similar to the pattern of the variation of the mean radiant temperature with the distance of the seated person from the glass window. The value of PPD is about 40% for the case of glass surface temperature of 50°C at the distance of 0.5 m from the glass window. The value of PPD is decreasing rapidly with the distance from the glass window. The value of PPD is rapidly reduced to around 12% when the distance from the glass window is 1.5 m. The PPD for the case of glass surface temperature 25°C and 30°C are around 5% which indicates the pleasant thermal condition for people to live in.

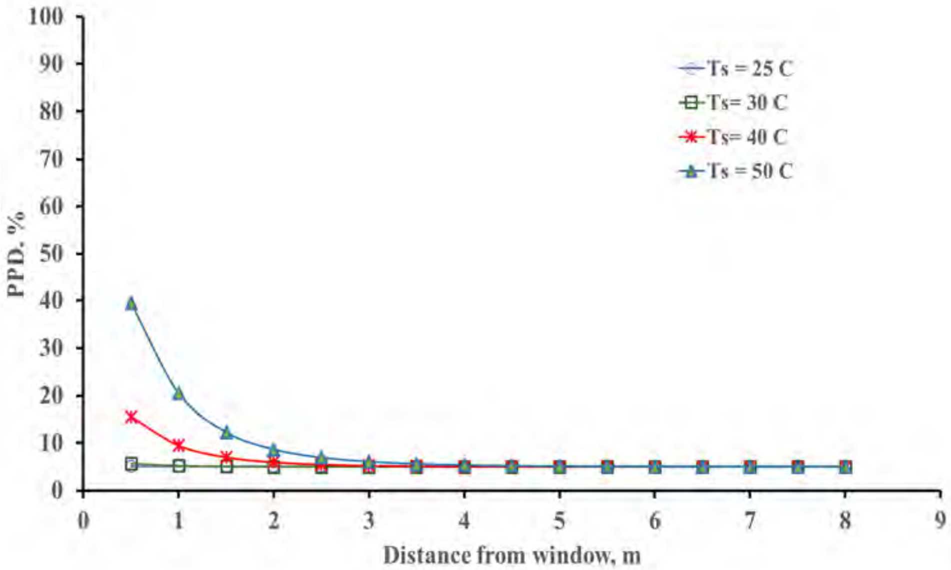

Figure 14. The variation of the predicted percentage of dissatisfied with the distance of the seated person from the glass window for different value of glass surface temperature.

Figures 15 - 18 show the variation of the PPD of the seated person along the distance from the glass window for different value of the diffuse solar radiation when the glass surface temperature is varied from 25°C - 50°C. The pattern of the variation of the PPD with the distance of the seated person from the glass window is similar to the pattern of the variation of the mean radiant temperature with the distance of the seated person from the glass window. The value of PPD reaches more than 90% for the seated person at 0.5 m from the glass window for the case of diffuse solar radiation is 500 W/m^2 with different values of glass surface temperature. The effect of discomfort (PPD) is reduced when a person sit further away from the glass window. The higher the value of the diffuse solar radiation and glass surface temperature, the higher discomfort condition the seated person will feel. The effect of discomfort condition is decreasing as the distance of the seated person from the glass window is increasing.

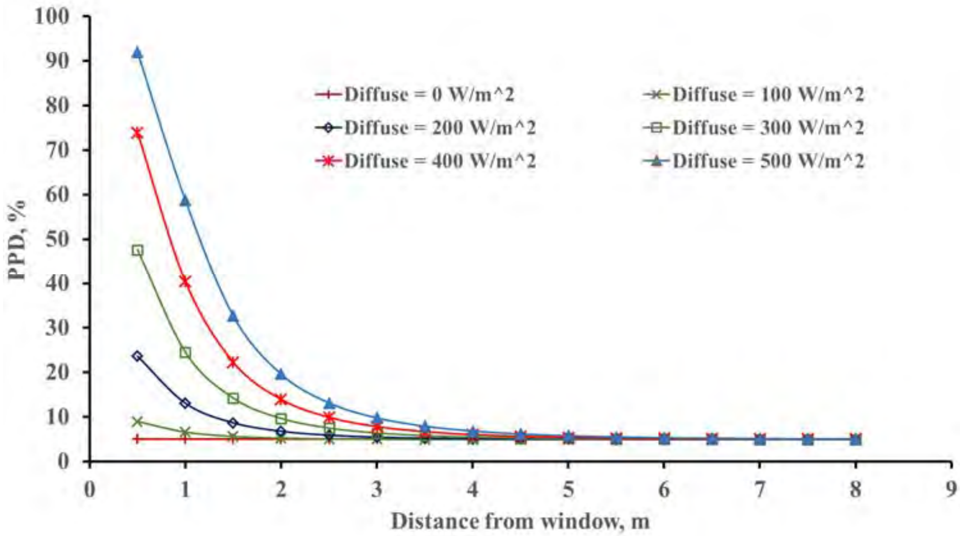

Figure 15. The variation of the predicted percentage of dissatisfied with the distance of the seated person from the glass window for different value of the diffuse solar radiation when the glass surface temperature is fixed at 25°C.

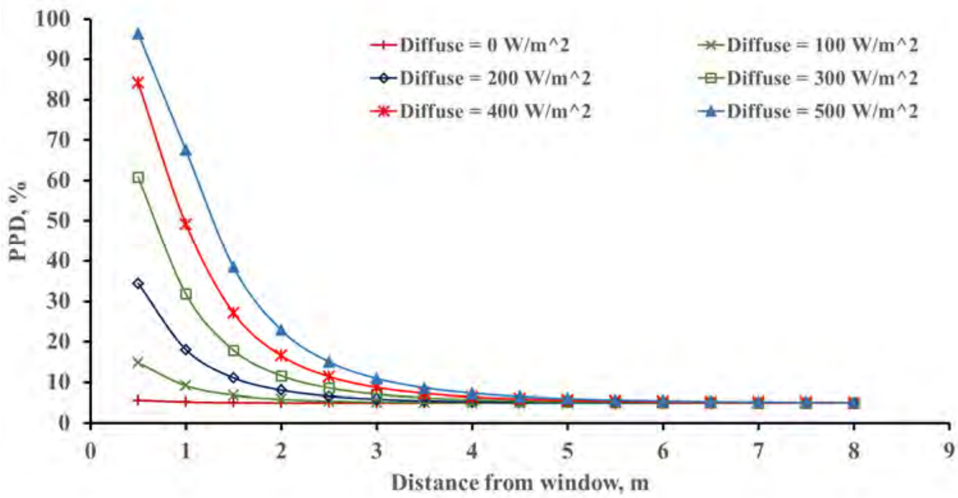

Figure 16. The variation of the predicted percentage of dissatisfied with the distance of the seated person from the glass window for different value of the diffuse solar radiation when the glass surface temperature is fixed at 30°C.

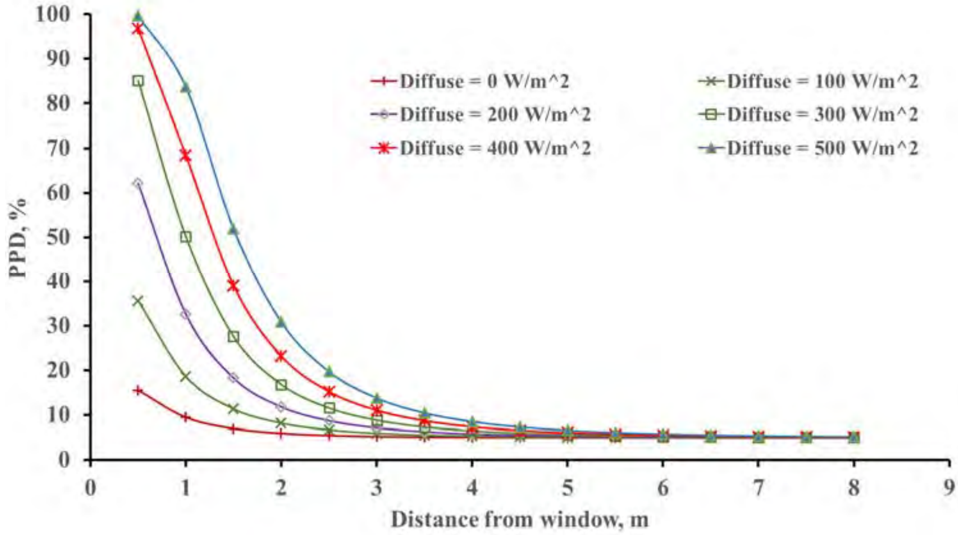

Figure 17. The variation of the predicted percentage of dissatisfied with the distance of the seated person from the glass window for different value of the diffuse solar radiation when the glass surface temperature is fixed at 40°C.

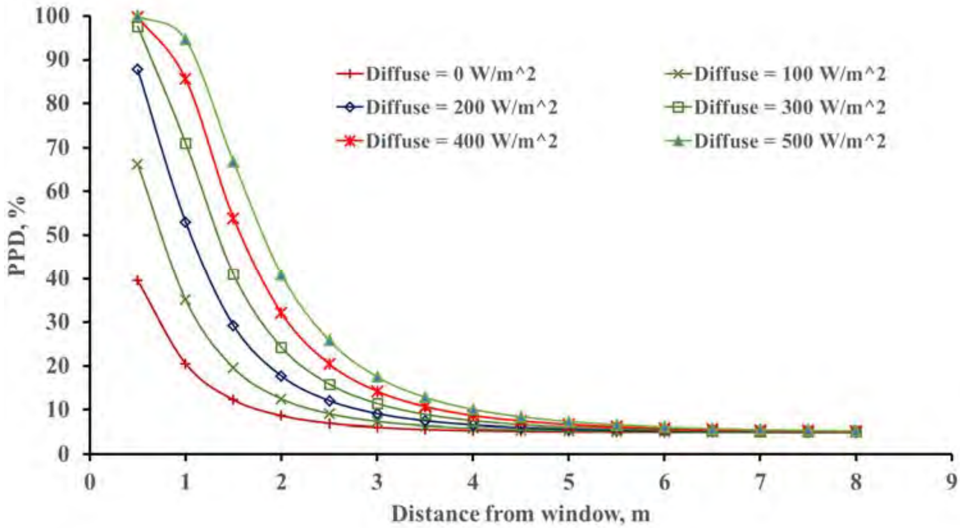

Figure 18. The variation of the predicted percentage of dissatisfied with the distance of the seated person from the glass window for different value of the diffuse solar radiation when the glass surface temperature is fixed at 50°C.

Figures 19 - 22 show the variation of the PPD of the seated person along the distance from the glass window for different value of the direct solar radiation when the glass surface temperature is varied from 25°C - 50°C. The PPD is directly dependent on the magnitude of the transmitted direct solar radiation incident on a person. The value of the PPD is increasing with the distance of the seated person from the glass window. The increasing of the PPD is almost diminished when the distance of the seated person from the glass window exceeded 4 m. Figures 20 – 22 shows the variations of the PPD along the distance of the room when the glass surface temperature is fixed at 30°C. 40°C, 50°C and the transmitted direct solar radiation is varied from 0 to 500 W/m^2. One can see clearly that the effect on the PPD is the combination of the effect of the glass surface temperature and the effect of the transmitted direct solar radiation. The PPD is directly dependent on the glass surface temperature and the transmitted direct solar radiation.

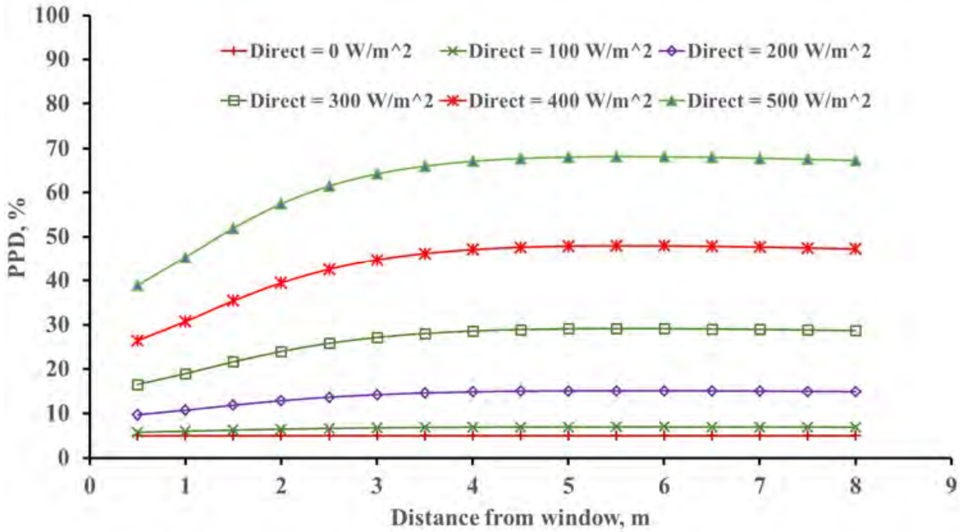

Figure 19. The variation of the predicted percentage of dissatisfied with the distance of the seated person from the glass window for different value of the direct solar radiation when the glass surface temperature is fixed at 25°C.

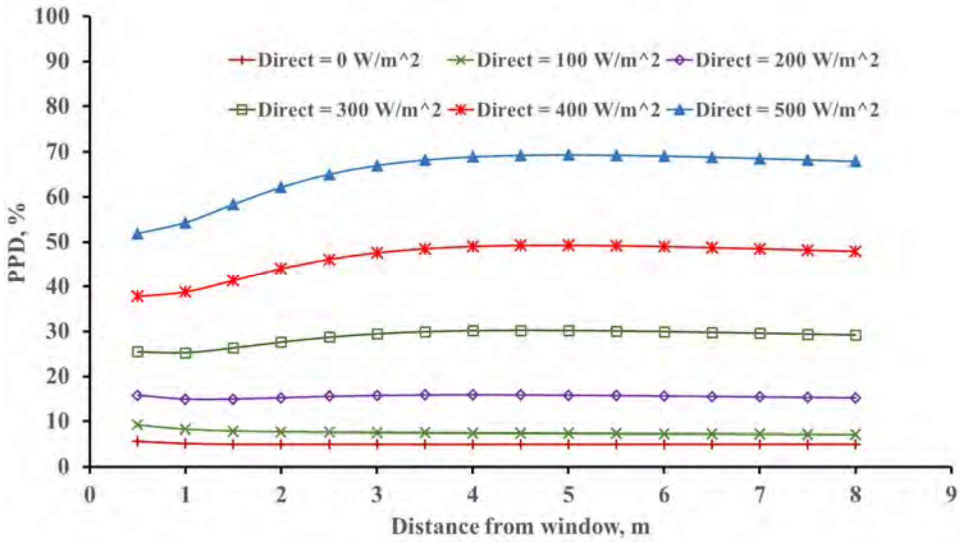

Figure 20. The variation of the predicted percentage of dissatisfied with the distance of the seated person from the glass window for different value of the direct solar radiation when the glass surface temperature is fixed at 30°C.

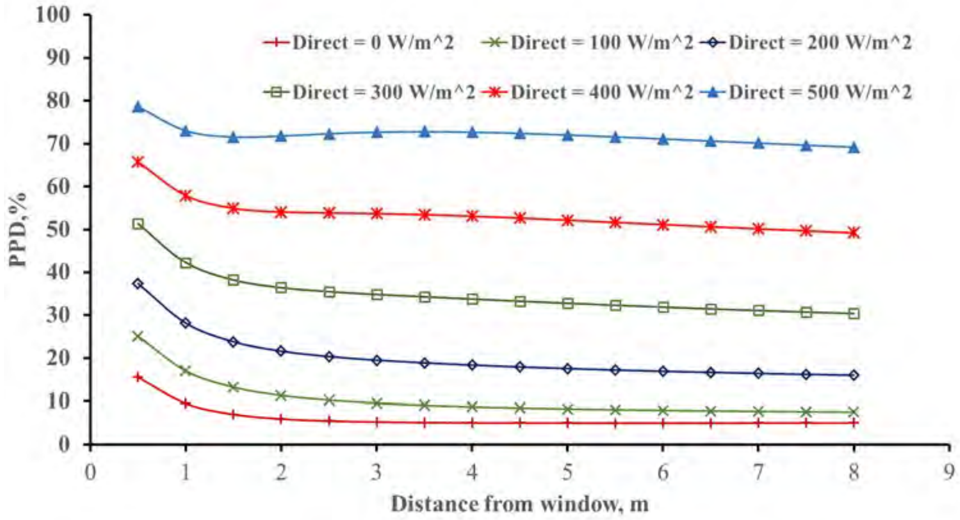

Figure 21. The variation of the predicted percentage of dissatisfied with the distance of the seated person from the glass window for different value of the direct solar radiation when the glass surface temperature is fixed at 40°C.

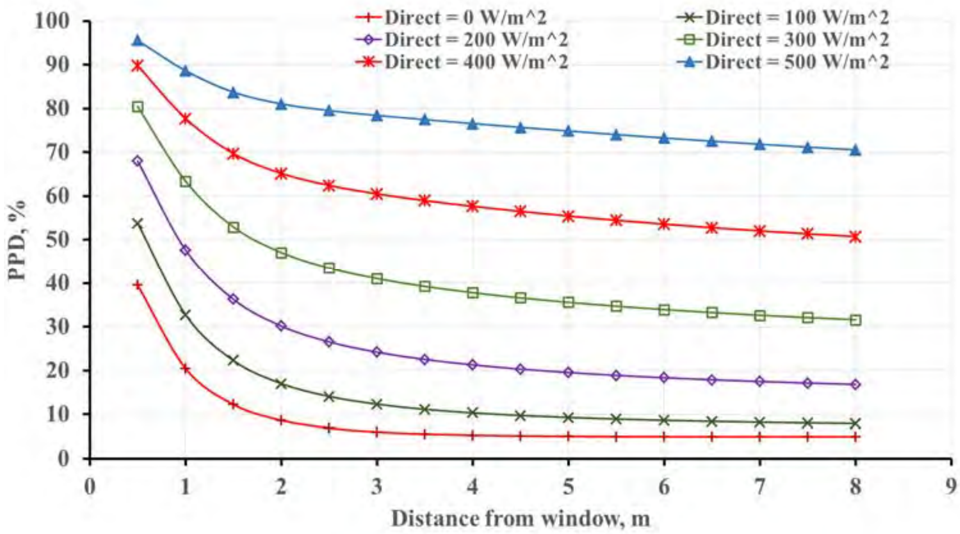

Figure 22. The variation of the predicted percentage of dissatisfied with the distance of the seated person from the glass window for different value of the direct solar radiation when the glass surface temperature is fixed at 50°C.

4. Conclusion

The effects of related parameters on thermal comfort condition for a person sitting near a glass window are investigated. The effects of the transmitted direct solar radiation, transmitted diffuse solar radiation, glass surface temperature and distance of a person from the glass window on the mean radian temperature and PPD are studied. It is found that the intensity of the transmitted solar radiation and the value of the glass surface temperature all have effect on the human thermal comfort condition. The effect of the distance of the seated person from the glass window on the thermal condition for the seated person can be classified into two cases. For the first case, the thermal discomfort is decreased when the distance of the seated person from the glass window is increased for the case of having transmitted diffuse solar radiation and having high glass surface temperature. For the second case, the thermal discomfort is increased when the distance of the seated person from the glass window is increased for the case of having transmitted direct solar radiation.

In this study, the effect of the transmitted direct solar radiation and transmitted diffuse solar radiation on the thermal condition is separately analysed. The case of having only transmitted diffuse solar radiation could be the case of glass window facing north and facing west in the morning. In actual condition, the glass window will usually receive the incident solar radiation in both components; direct solar radiation and diffuse solar radiation. The type of the glass window (optical properties) will dictate the magnitude of the transmitted solar radiation and the glass surface temperature. Therefore, understanding the effect of each related parameter on thermal comfort condition could help the architects and engineers to choose the proper glass window as the building envelope in respect of the heat transmission and thermal comfort. It also helps the architects to design the layout for people in the room regarding the position of seated person to achieve an acceptable level of thermal comfort.

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