Journal of Scientific & Industrial Research
Vol. 81, October 2022, pp. 1098-1106
DOI: 10.56042/jsir.v81i10.63075

Effect of Overhang Shade on the Solar Heat Gain through Window in Composite Climatic in Mid-Western India

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Received 07 May 2022; revised 19 September 2022; accepted 20 September 2022

Solar heat gain (SHG) through fenestration (window) dominates towards cooling demands in buildings and eventually increases electricity consumption. Integration of fixed shading devices (i.e. overhang) can reduce the solar heat gain through and overall energy consumption. In this manuscript, solar heat gain factor (SHGF) has been assessed for different designs of overhang. ASHRAE method of fenestration design and heat balance has been used for the estimation of the SHGF and solar gain in the buildings of different designs of overhangs. Further, the SHGF and solar gain have been used to determine accurate heating and cooling loads.The values have been estimated for the peak winter and summer months of December and June for Indore city, India. Significant reduction in heating and cooling loads in the buildings having windows with overhangs has been estimated in winter and summer seasons. Integration of overhang lowers the energy demand by over 50% and 30% in rooms having windows in south and east/west walls respectively. The results of the this study would be extremely beneficial for designing the fixed type shading device in buildings in order to controlthe heating and cooling loads and in achieving the sustainable development goals (SDGs 11, 12 & 13).

Keywords: ASHRAE standard, Energy-efficient building, Fenestration shading, Sustainable building designs, Thermal load

Introduction

In the midst of accelerated global warming, economic insecurity, and finite resources, it is critical to identify measures, which better quantify territorial units' sustainable development. In the twenty-first century, the idea of sustainable development is important. As per the World Conservation Strategy, released in the year 1980[(1)], the process of modifying the biosphere and applying human, financial, and natural resource capital to meet or exceed human demands and improve the quality of life for all people. As stated in the document, Sustainable development takes into account the long-term and short-term benefits and drawbacks of different measures. Energy consumption in a building is governed by the local climatic conditions.[1] Buildings consume approx. 30−40% of the global total energy consumption, which significantly influenced by the thermal load due to solar gains through fenestration (window) components in buildings.[2] Different options for reducing cooling load and dependency on the fossil fuels are adopted in recent years.[3–8] Incorporation of energy efficient strategies for reduction in the overall energy consumption of the buildings have been highly appreciated.[9] However, the solar gains through windows has major contribution to these loads.[10] Solar gain through fenestration (windows), walls and skylight clerestory and roof has the potential to reduce the total heating/cooling energy requirements of a building. A number of strategies to minimize the solar heat gains through the fenestration components have been explored and adopted in different parts of the world. Recently, impact of different combinations of woven roller shade and glazing types on the energy and indoor visual performances have been explored for office buildings in cold climate.[11] Most recently, sensitivity analysis has been performed for dynamic roller shade integrated glazed façade for south façade in composite climate in India.[12] Recently, static and dynamic overhangs attached with smart glazings were explored to lower the heating/cooling loads in residential apartment buildings in U.S.[13] Use of static and dynamic overhang smart glazing system in the

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existing building yielded 7% and 22% reduction in annual energy consumptions respectively. Further, benefits of PV integrated sliding and rotating overhangs were assessed installing in residential apartment buildings. The performance of the similar overhangs without PV was also compared with the PV integrated overhangs. The apartments having large size of windows can be made net zero energy building by integrating PV sliding overhangs particularly located in mild climate zones of U.S.[14] One of the recent studies, indicated that the benefits using the smart glazing are not significant compared to static glazing for the south oriented windows in classroom of an educational building.[15] Previously, variation in lighting, heating and cooling energy consumption was estimated below 10% by applying different select controls for smart glazings in buildings.[16] Recently, the effect of overhang and fins integrated with smart glazings on the transmitted and lost solar energy through fenestration have been estimated for residential buildings in climate of Tehran.[17] Results of another study on the effect of externally integrated overhang with window highlights resulted in substantial reduction in cooling load in educational buildings.[18] Assessment of different shading types and their impacts on the performance of the buildings are taken from a few of the most relevant studies and summarized in the following Table 1.

During design stage of a building, SHGF is useful to estimate solar heat gain for comparative and optimization for different design schemes.

Researchers[19–27] have used various methods to estimate heat analysis and applications. However, these methods require extensive computation time and complex in nature and difficult to use without having expertise in particular simulation tool used for building simulations. The American Society of Heating, Refrigerating and Air-Conditioning Engineers Handbook[20], provides a simpler method to calculate solar heat gain factors on cloudless days for daylight hours of the 21st day of each month for a given window orientation at a particular latitude and time of year. This data is used by the building designers for maximum load determination and heating/cooling machine sizing. It can be observed from the above comparative Table 1 that the effect of the overhang shading has hardly been explored in the composite climate. The objective of this paper is mainly to provide design guidelines and process for the overhang integrated glazed window particularly for buildings in composite climate. In this study, the assessments were performed for annual basis. However, solar gains are dependent on local conditions in addition to the expected variations due to latitude and season.[27] The seasonal variations eventually leads to significant variation in the heating

Table 1 — Comparative detail of the different shading strategies

Building types[Ref.]	Types of shading device	Major outcomes	Climate types	Location
Office[11]	Woven roller shade (Internal)	Irrespective of orientation of the window, upto 30% total energy can be achieved with dynamic roller shading for office of 30% window to wall ratio.	Cold	Shillong, India
Office[12]	Woven roller shade (External)	Values of the variation coefficients for HVAC, lighting consumptions, useful daylight illuminance and glare exceeded time fraction were estimated to be 33.75, 45.06, 58.25 and 87.92 respectively.	Composite	Amritser, India
Residential apartment[13]	Overhang	Energy consumption reduced by over 7% and 22% by static and dynamic overhangs respectively.	Dry	Boulder, CO, USA
Residential apartment[14]	Overhang without and PV integration	In Boulder, over 9% reduction was achieved by bare overhang. In Francisco, the energy demands of the housing units were completely met by PV-integrated overhang.	Mild	Boulder, CO, USA San Francisco, CA, USA
Residential[15]	Overhang and fins	Overhang reduced cooling demand most significantly for windows in NE and NW. Comparatively fins found to be less effective than overhangs.	Hot	Marrakech, Morocco
Educational[16]	Overhang	Introduction of overhang reduced cooling load by 50%.	Sub-tropical	Hong Kong

and cooling loads. The daily solar heat gain factors and solar gain have been estimated using the ASHRAE standard of fenestration heat balance for Indian climatic conditions. For the study a case of Indore city is selected, which is located (22.70°N, 75.90°E & 567 m ASL) in mid-western part of India. The climate of the city is classified as composite, which has three distinct seasons, summer, monsoon and winter. Further, the results of this study would help in achieving the sustainable goals e.g. sustainable cities and communities (SDG 11), climate action (SDG 13) and responsible consumption and production (SDG 12). The overall structure of the paper has been divided into four major sections that include introduction, methodology, results, discussion and conclusions.

Methodology

The heat entering in a room through a window during the day depends on area of the window and size of overhang on the window. For analyzing the effect of above factors on the heat entering the room, a room of fixed size 6 m long, 4.5 m wide and 3 m high was considered. The opening for heat admittance (i.e. the window) was assumed to be centrally placed in 4.5 m side. Solar heat gain, from the fenestration was estimated for every hour for the office period (8 am to 4 pm), using solar radiation and ambient temperature data from Mani and Rangarajan.[28] Flow diagram of the methodology discussed in the subsequent subsections is shown in the following Fig. 1.

Mathematical Modeling

The analysis was done in two parts. In the first part, effect of orientation and window area on the total heat gain (THG) and the total heat entering the room (Q) during the office hours from the window without overhang was analyzed. In the second part, the effect of orientation and overhang size on the solar heat gain (SHG′) for each hour of the day and the total heat entering the room during the office hours (Q′) from a fixed area (2.4 m^2) window was analyzed.

Solar Heat Gain Factors, Total Heat Gain (THG) and Total Heat Entering the Room (Q) through Glass:

Solar heat gain factors and the total heat gain through single pane 3 mm glazing have been determined for Indore for summer (June) and winter (December) months using ASHRAE method of

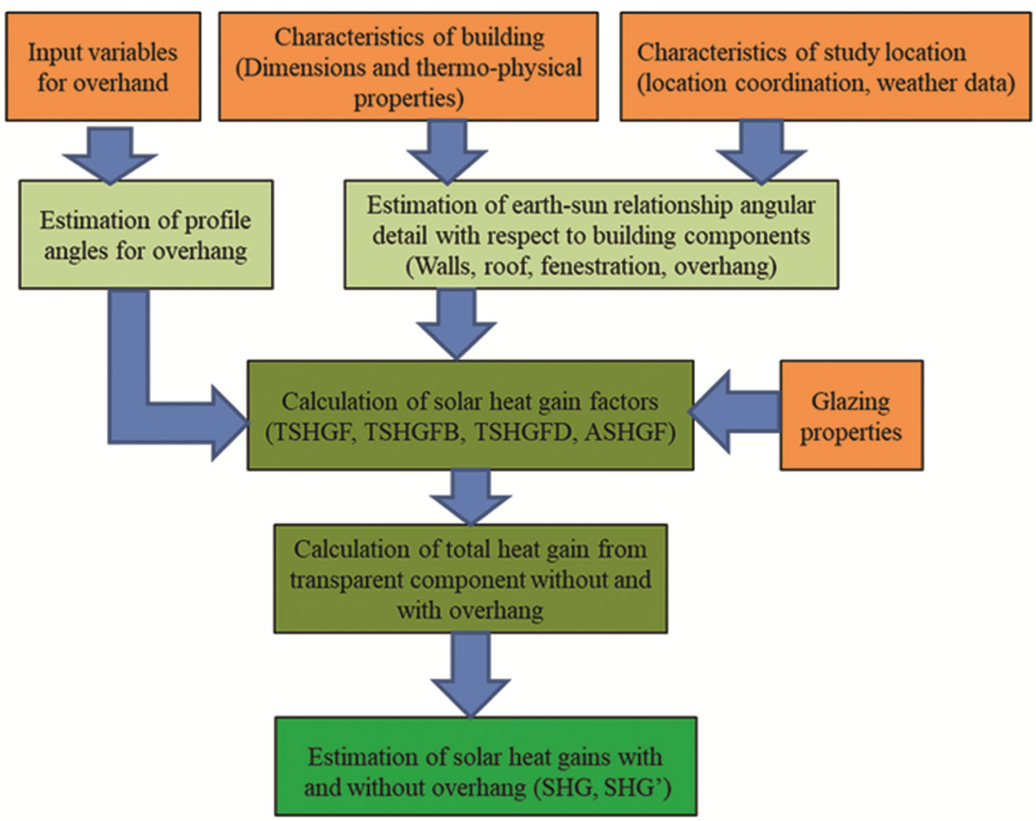

Fig. 1 — Flow diagram of the complete process used in this study

fenestration heat balance.[20] Solar heat gain factor due to transmitted component (TSHGF) of beam radiation, diffused radiation and ground reflected radiation is given by:

$$TSHGF = TSHGFB + TSHGFD$$

$$= G_{b,i}\tau_{b,i} + (G_{d,i} + G_{r,i})\,\tau_d \quad \text{... (1)}$$

$$= G_b R_{b,i}\tau_{b,i} + (G_d R_{d,i} + (G_b + G_d)\,R_{r,i})\tau_d \quad \text{... (2)}$$

$$R_{b,i} = \cos\theta_i / \sin\alpha_s \quad \text{... (3)}$$

$$R_{d,i} = (1 + \cos\beta)/2 \quad \text{... (4)}$$

$$R_{r,i} = \rho_g\,(1 - \cos\beta)/2 \quad \text{... (5)}$$

$\tau_{b,i}$ is the transmission coefficient of the glass for beam solar radiation incident at an angle θ_i and τ_d is the transmission coefficient of glass for diffuse solar radiation. Similarly solar heat gain factor due to the absorbed component (ASHGF) of beam radiation, diffused radiation and ground reflected radiation is given by:

$$ASHGF = ASHGFB + ASHGFD$$

$$= G_{b,i}\alpha_{b,i} + (G_{d,i} + G_{r,i})\,\alpha_d \quad \text{... (6)}$$

$\alpha_{b,i}$ is the absorption coefficient of the glass for beam solar radiation incident at an angle θ_i and α_d is the absorption coefficient of glass for diffuse solar radiation. The absorption and transmission coefficient of commonly used double strength sheet glass (DSA) for direct solar radiation incident at an angle θ_i and for diffuse solar radiation can be evaluated from the following expressions:[2]

$$\alpha_{b,i} = \sum_{j=0}^{5} a_j \cos^j \theta_i \quad \text{... (7)}$$

$$\tau_{b,i} = \sum_{j=0}^{5} t_j \cos^j \theta_i \quad \text{... (8)}$$

$$\alpha_d = 2\sum_{j=0}^{5} a_j /(j+2) \quad \text{... (9)}$$

$$\tau_d = 2\sum_{j=0}^{5} t_j /(j+2) \quad \text{... (10)}$$

where, a_j and t_j are given in Table 2

From these coefficients, it can be shown that for normal incidence the value of $\tau_b = 0.870$ and $\alpha_b = 0.051$ while for diffuse radiation $\tau_d = 0.40$ and $\alpha_d = 0.03$ are obtained.

Table 2 — Coefficients of Double Strength sheet (DSA) glass for transmittance and absorptance calculations[22]

j	0	1	2	3	4	5
aj	0.01154	0.77674	−3.94657	8.57881	−8.38135	3.01188
tj	−0.00885	2.71235	−0.62062	−7.07329	9.75995	−3.89922

The incident angle θ_i of the beam radiation is calculated through the relation (represented in Fig. 2)[21]:

$$\cos\theta_i = \cos\alpha_s \cos\gamma_p \sin\beta + \sin\alpha_s \cos\beta \quad \text{... (11)}$$

where, β is the tilt of fenestration, (90° for fenestration in walls) Surface-solar azimuth angle γ_p of the fenestration is calculated through:

$$\gamma_p = \gamma_s - \gamma_i \quad \text{... (12)}$$

γ_i is the surface azimuth angle of fenestration and γ_s the solar azimuth angle determined by:

$$\gamma_s = \cos^{-1}((\sin\alpha_s \sin\varphi_L - \sin\delta)/(\cos\alpha_s \cos\varphi_L)) \quad \text{... (13)}$$

α_s is the Solar altitude angle that can be determined from the relation:

$$\alpha_s = \sin^{-1}(\cos\varphi_L \cos\delta \cos\omega + \sin\varphi_L \sin\delta) \quad \text{... (14)}$$

φ_L is the latitude of place and δ is the declination angle:

$$\delta = 23.45 \sin(360/365(284 + J)) \quad \text{... (15)}$$

where, J is the Julian day starting from January 1st and ω the hour angle:

$$\omega = (ST - 12) \times 15 \quad \text{... (16)}$$

Solar heat gain factor, SHGF can be calculated from the above calculated Transmitted Solar Heat Gain Component and Absorbed Solar Heat Gain Component using the relation:[20]

$$SHGF = TSHGF + (h_i/(h_i + h_o)) \times ASHGF \quad \text{... (17)}$$

where, h_i and h_o are the inside and outside heat transfer coefficients and are taken to be 8.29 W/m^2 °C and 23 W/m^2°C. The values of coefficients taken in this study are normally used for design purposes.

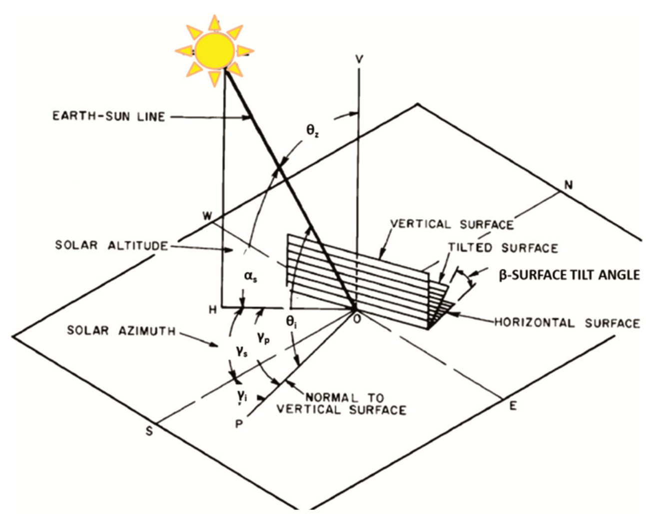

Fig. 2— Representation of the different sun-earth relationship angles w.r.t. building surface

However, the speed of the wind/air movement and surface orientation (in case of outdoor) has significant effect in determining the heat transfer coefficients. For calculating the coefficients more accurately, readers can be adopt relationships given in Ref.[22] The total heat gain (THG) admitted through area A of the fenestration due to transmitted radiation ,absorbed radiation and conducted through glass can then be calculated from:

$$THG = A \times (SHGF + U_g (T_a - T_i)) \qquad \dots (18)$$

where, A is the area of the window, U_g is the overall coefficient of heat transfer through window, T_a is theambient temperature, T_i is the inside design temperature taken to be 25°C.

The total heat entering the room, Q, through the fenestration during the office hour will be the sum of the THG for each of the office hour and can be calculated from:

$$Q = \sum_{Officehours} THG \qquad \dots (19)$$

Solar Heat Gain Factors with Overhang Width of the Window:

The shadow height S_H (Fig. 3), produced by a horizontal projection P_V can be calculated using the solar surface azimuth γ_p, solar altitude α_s and the vertical profile angle α_p.

$$S_H = P_v \tan \alpha_p \qquad \dots (20)$$

where,

$\tan \alpha_p = \tan \alpha_s / \cos\gamma_p$

The sunlit area A_{SL} and shaded area A_{SH} of the fenestration through an overhang is variable during the day and is calculated for each hour using the following relations:

$$A_{SL} = W (H - S_H) \qquad \dots (21)$$

$$A_{SH} = A - A_{SL} \qquad \dots (22)$$

The solar heat gain factors through a partially shaded fenestration product (SHGF′) can then be estimated using the following relation.

$$SHGF' = (A_{SL}/A)\ SHGF + (TSHGFD + (hi/(ho + hi)) \times ASHGFD) \times A_{SL}/A \qquad \dots (23)$$

The solar heat gain (SHG′) for the fenestration is then given by:

$$SHG' = A \times SHGF' \qquad \dots (24)$$

For analyzing the effect of width of overhang on the heat entering the room through the window, due to transmitted component and absorbed component of solar radiation have been considered. The heat conducted through the window, term $[U_g (Ta - Ti)]$ being unaffected by the overhang size has not been included for analyzing the effect of overhang.

The total heat entering the room, Q′, through the fenestration with an overhang during the office hour will be the sum of the SHG′ for each of the office hour and can be calculated from

$$Q' = \sum_{Officehours} SHG' \qquad \dots (25)$$

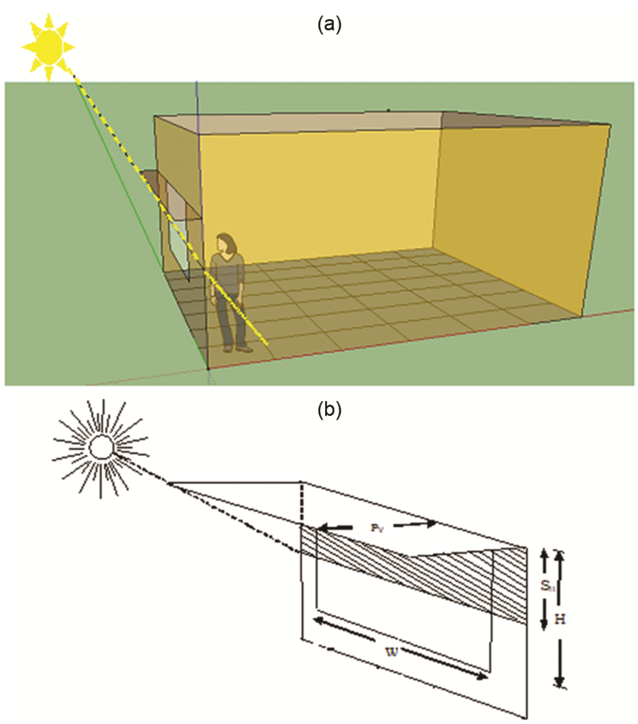

Fig. 3a) — Schematic diagram of overhang shading a) 3D representation of schematic of shading and direct solar radiation interaction, b) Schematic for projection of overhang shading on the fenestration

Results and Discussion

For a typical window of dimensions 2.0 × 1.2 m, area 2.4 m^2 the daily sum of total heat gain from 8 hrs to 16 hrs (Q in kWh) was estimated for June and December for representative days respectively. The contribution of THG can be seen, in Table 3. for June and December months, which are representative months for summer and winter season respectively.

As expected, in the summer period higher total heat gains were estimated due to higher altitude angles of

Table 3 — Daily sum of total heat gain for the month of June & December

	Q (kWh)			
	East	North	South	West
June	6.15	4.97	4.80	6.15
December	4.35	1.81	10.38	4.35

the Sun for all studied façade orientations except south facade. The highest daily heat gain for east and the west windows is mainly a result of direct solar gain in the morning or evening hours. The north window mainly receives the diffuse component and the THG is about 19% lower compared to the east and west windows. The south window receives about 22% less heat than east and west windows. For winterseason, the south window receives highest heat received because sun remains in the south at lower altitude most of time. Further, the east and west windows receive about 58% less heat than the south window while least heat (about 83% lower than south) is received by the north window. For an aspect ratio of 2.5 the area was increased and the kWh contribution of THG was estimated for the months of June and December and the results are presented in Figs 4 & 5 respectively. It is obvious that without overhangs the THG is directly proportional to the area of the window as is evident from Figs 4 & 5.

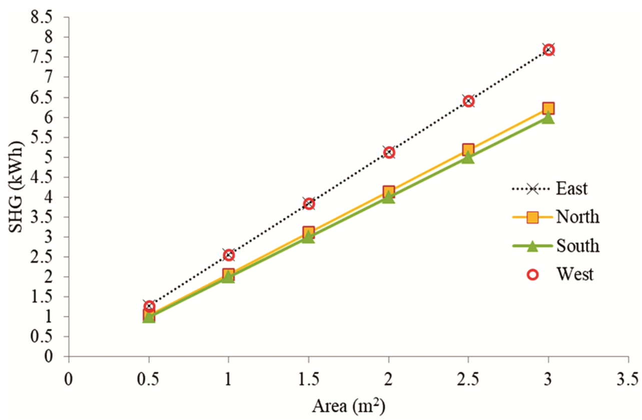

Fig. 4 — Variation of daily total heat gain with change in window area (without overhang) in the month of June

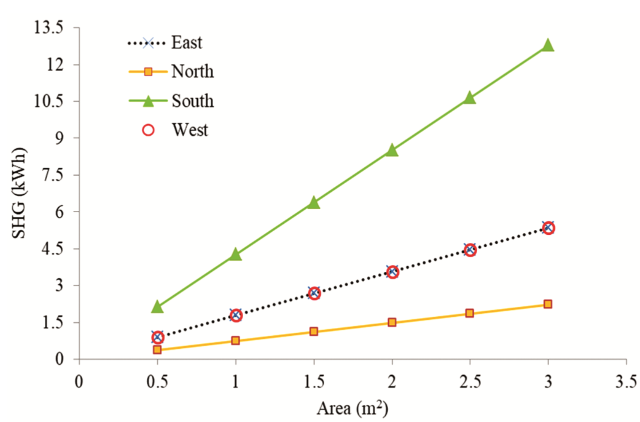

Fig. 5 — Variation of daily total heat gain with change in window area (without overhang) in the month of December

To appreciate the effect of variation of width of overhang on the heat gained through the window, it is desirable to study variation of the SHG′ of the window instead of total heat admission through glass as the contribution by the term [$A \times U_g \times (Ta - Ti)$] in equation 18 will not change with overhang size. Hourly variation in the solar heat gain for four principal window orientations (S, W, N and E) with the overhang width was estimated and depicted in Figs 6 & 7 for the months of June and December respectively. It can be observed from the Fig. 6 that low solar altitudes and small angle of incidence in the month of June lead higher SHG′ for east window in the morning hours and the west window in afternoon hours. Secondly the SHG′ decreases with increase in overhang width for east-west and north windows but no effect of overhang width on south window is observed during the month of June. It is also seen from Fig. 4 that in the month of June, there is no effect of variation of an overhang width for the

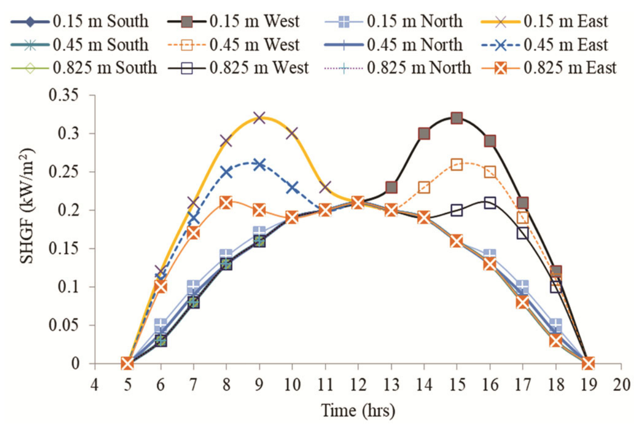

Fig. 6 — Effect of overhang width on the SHGF in the month of June

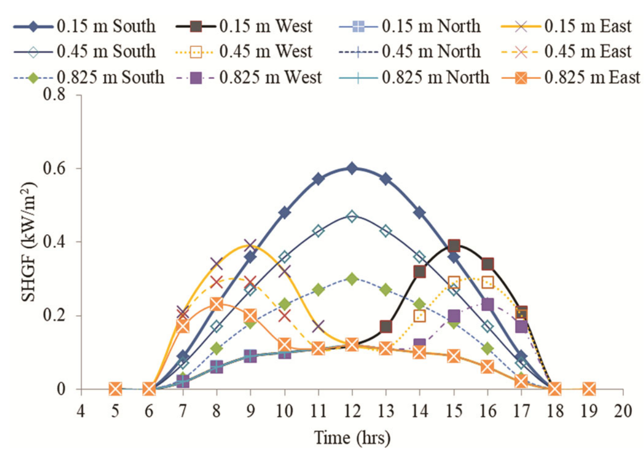

Fig. 7 — Effect of overhang width on the SHGF in the month of December

windows in all the four cardinal orientations at 12:00 noon and the SHG′ value for all the orientations is the same (0.20 kW/m^2) because at 12:00 noon, no direct radiation is entering through the windows from all the cardinal orientations. Further, the SHG′ values in the south window during morning hours in the month of June are observed to be equal to the corresponding values in west window, while, the values for the south window during the evening hours are equal to the corresponding values in east window.

During the month of December, it can be seen from Fig. 7 that for a given size of overhang SHG′ is the highest for the south window and are least for the north window. For east and west, the values of SHG′ are the same and their value is in between the SHG′ for south and north window. It is also seen that the SHG′ through north window is independent of overhang size as no direct radiation is received through this window during the winter. The values of SHG′ in south window decrease continuously with increase in size of the overhang. For east window in the morning hours and west window in the afternoon hours, SHG′ decreases continuously with increase in overhang size. While, for east window in the afternoon hours and west window in the morning hours, the SHG′ values are independent of overhang size. In the month of December, no effect of the variation of overhang width on SHG′ values can be observed at 12:00 noon in east, west and north windows, which was estimated 0.10 kW/m^2. However, a sharp decrease in SHG′ values from the south window at this hour with increase in the width of the overhang is observed.

As can be seen in Fig. 8 the net heat entered in the room during the office hours, Q′ in kWh through the windows in the four cardinal directions during the month of June.The results for the month of December are presented in Fig. 9. It is evident from the Figs 8 & 9 that the kWh contribution of Q′ from north window decreases with increasing the overhang width in the month of June. However, the thermal gain for south window remains the same as the sun mostly resides towards the north. The kWh contribution of Q′ from the east and the west windows is excessive indicating the contribution of direct component. The north window receives about 7% to 21% less heat than that received from the east and west windows while, from the south window, it is about 22% less than it is from the east and the west windows. For a normal size overhang (width 0.45 m) east/west window receives 14% more heat than the south window while, north window receives only 0.1% heat as received from the south window. The decrease in Q′ value when the overhang size is increased from 0.15 m to 0.825 m is observed to be about 16% for east/west window and only 1% for north and south window.

In the month of December, the kWh contribution of Q′ is the highest from the south window and a sharp decrease in its value can be seen with the increase in overhang width, indicating that excess direct gain can be cut off by an overhang when the direct gain is not desired. The north window receives about 55 to 78% less heat than it is from the south window and there is no effect of overhang width on the heat received. The east and west window receive about 40–56% less heat than that of the south window and a certain amount of direct solar heat can be seen entering through the east and the west windows. For a normal overhang size (width 0.45 m); the heat received from south window is about 248% higher than that received from the north window, while, it is about 53% higher than that received from the east/west window. The decrease in the heat received through the window when the

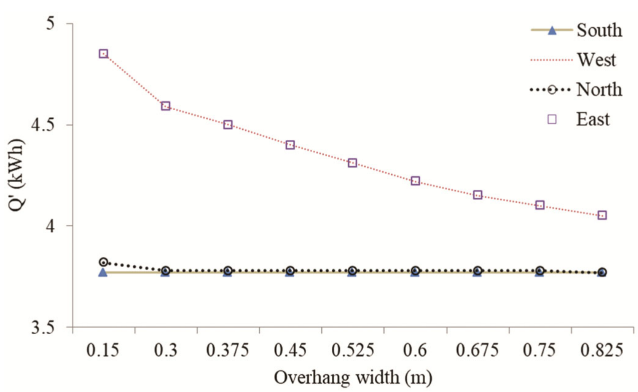

Fig. 8 — Variation of daily sum of heat gain for the months of June

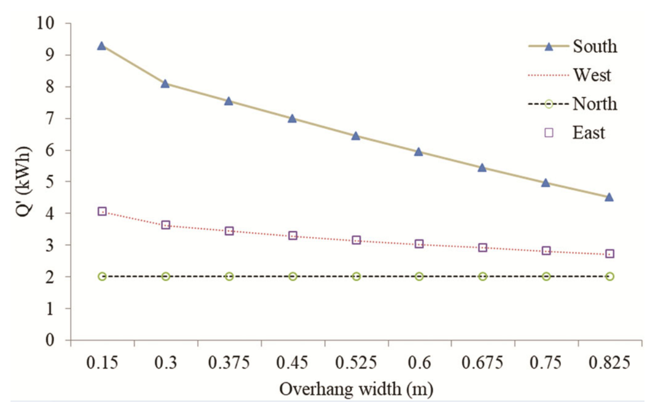

Fig. 9 — Variation of daily sum of heat gain for the month December

overhang size is increased from 0.15 m to 0.825 m is observed to be 51% for south window and about 33% for east/west window.

It is also seen from Figs 8 and 9 that the net heat gained through east, west and north windows in the month of June for all sizes of overhang is more than in the month of December for the corresponding overhang size, while, the net heat gain from the south window for all overhang sizes in the month of December is greater than the net heat gain received for the corresponding overhang size in the month of June.

Conclusions

There is a marked effect of an overhang in reducing the SHG on the South façade in December and to some extent in the North façade in June indicating that in Northern hemisphere placement of windows in these orientations is effective. In East and West facades the overhang width does not reduce the radiant flux significantly indicating that the window placement should not be adhered to or the placement should be minimal. In the month of June, for a normal size overhang (width 0.45 m) east/west window receives 14% more heat than the south window while, north window receives only 0.1% heat as received from the south window. The decrease in Q′ value when the overhang size is increased from 0.15 m to 0.825 m is observed to be about 16% for east/west window and only 1% for north and south window. In the month of December, for a normal overhang size (width 0.45 m); the heat received from south window is about 248% higher than that received from the north window, while, it is about 53% higher than that received from the east/west window. The decrease in the heat received through the window when the overhang size is increased from 0.15 m to 0.825 m is observed to be 51% for south window and about 33% for east/west window. Results of this study are limited to the overhang shading types and may vary for other shading types and climatic conditions. Further, variation in the glass types may change the transmittance and absorption coefficients and eventually change the total heat gain and solar heat gain factors. The variation in the glass types, climate types and other designs of the overhangs can be scope for further studies in future.

Nomenclature

G	Global radiation
SHG	Solar heat gain
THG	Total heat gain
TSHGF	Total solar heat gain factor
TSHGFB	Total heat gain factor due to beam radiation
TSHGFD	Total heat gain factor due to diffuse and ground reflected radiations
ASHGF	Solar heat gain factor due to absorption component
ASHGFB	Solar heat gain factor due to absorption component of beam radiation
ASHGFD	Solar heat gain factor due to absorption component of diffuse and ground reflected radiation
τ	Transmittance
θ_i	Incidence angle
θ_z	Zenith angle
α_s	Solar altitude
$\alpha_{b,i}$	Absorption coefficient of glass for bean radiation
α_d	Absorption coefficient of glass for diffuse radiation
α_p	Vertical profile angle
$\tau_{b,i}$	Transmission coefficient of glass for beam radiation
β	Surface tilt angle
ρ_g	Reflectance of glass
γ_p	Surface solar azimuth angle
γ_s	Solar azimuth angle
γ_i	Surface azimuth angle
δ	Declination angle
ω	Hour angle
φ_L	Latitude angle of the location

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