DESIGNING EQUATOR-FACING WINDOW FOR DIRECT SOLAR GAINS OPTIMISATION IN BUILDINGS

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As solar gains play a vital role in influencing thermal environment in buildings, direct solar gains is the most influential of the three modes of transmission. So, optimising direct solar penetration through equator-facing window would aid in improving thermal performance of buildings during winter. This study seeks to investigate the effects of varying equator-facing window height on horizontal shading device size and the rate of change of radiation beam height (RBH). This study adopted the apparent sun-paths model described in Szokolay (2007) for this analysis. In varying the window height, calculated solar altitude was used to determine the shading device size and corresponding RBH while examining its rate of change. Results show that increase in window height increases the shading device size as well as corresponding RBH. However, the rate of increase of RBH diminishes with increase in window height indicating that optimising direct solar gains does not rely on largest window height. This study focuses on vertical aspect of the equator-facing window which requires only horizontal shading device for optimisation. However, it provides a basis for further research in modelling direct solar gains in buildings, and a useful means for architects to design equator-facing windows.

Keywords: direct solar gain, equator-facing window, façade, radiation beam, shading device.

INTRODUCTION

Since buildings are considered to contributor about 40% of global carbon emission (Edwards, 2015), research has been focused on passive control in buildings in order to maintain thermal comfort with minimal integration of active systems (Arif, Khan, and Alamgir, 2012). In architecture, thermal comfort is considered to be the most important factor in improving

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productivity in a work place – buildings (Arif et al., 2012; Athienitis, 2007; Mallawaarachchi, De Silva, and Rameezdeen, 2013). To achieve thermal comfort in buildings, the environment has to be regulated by controlling heat gain and loss to maintain thermal balance (Kim and Kim, 2009). In design, thermal control is approached in two ways – active and passive means (Olbina, 2005), with the passive approach being the first line of control. As the active control utilises mechanical systems for heating or cooling, designers rely on the passive control means to minimise energy use in buildings so as to reduce heating and cooling loads associated with these mechanical devices (Al-obaidi, Ismail, Malek, and Rahman, 2014; Olbina, 2005). As solar gains play a vital role in influencing thermal environment in buildings, direct solar gains is the most influential of the three modes of transmission; direct, indirect and isolated gains (Aelenei and Rodrigues, 2012; Kim and Kim, 2009; Lim and Gu, 2007; Torcellini and Pless, 2004; Zalewski, Lassue, Duthoit, and Butez, 2002). So, optimising direct solar penetration through equator-facing window would aid in improving thermal performance of buildings during winter (Kim and Kim, 2009; Lim and Gu, 2007; Torcellini and Pless, 2004).

It has been mentioned that in order to optimise direct solar gain, the total area of the equator-facing windows is required to be 30% of equator-facing façade (Athienitis, 2007; Olbina, 2005). However, nothing has been said on whether the window height or the width is the most important in optimising this radiation. How this 30% of the wall area as window opening can be shared between the window height and width has not been suggested. Varying the window width admits solar radiation in constant increment while varying the height admits this radiation in varying proportion, so it would be difficult to share the 30% without considering how varying the height affects horizontal shading device size which allows winter sun while blocking that of equinox and summer and corresponding radiation beam height (RBH) and its rate of change. Therefore, understanding the way the RBH increases with increase in window height with the intervention of shading device would aid in proportioning of the window opening for direct solar gains optimisation in buildings. This study seeks to investigate the effects of varying equator-facing window height on horizontal shading device size and the corresponding radiation beam height (RBH) and its rate of change with the view to determining how the window can be designed for direct solar gains optimisation in buildings.

The remaining sections of this paper indicate review of relevant literature to examine the parameters that can be considered in designing equator-facing window, and how they are interrelated to optimise direct solar gains in buildings. The approach adopted is presented to show how window height, shading device size and RBH are mathematically related. Thereafter, the results of the analysis of the effect of varying equator-facing window height on the shading device size and the corresponding RBH and its rate of change reported. These are then discussed to show the implication of the relationship of these parameters on direct solar gains optimisation in buildings. The final section then recounted on what has been presented and draws a conclusion on the topic.

LITERATURE REVIEW

Since designing equator-facing window is critical for direct solar gains optimisation in buildings, it is necessary to identify the design parameters that when appropriately estimated will improve this window. These parameters are identified and the most critical ones that influence direct solar penetration into building to optimise the gains are considered in the review of articles written by Arens et al. (2014); Arif et al. (2012); Athienitis (2007); Kim and Kim (2009); Szokolay (2007); Torcellini and Pless (2004); and Tsangrassoulis, Geros, and Bourdakis (2006).

The accounts by Arens et al. (2014); Athienitis (2007); Torcellini and Pless (2004); and Tsangrassoulis et al. (2006) altogether offer a full list of the design parameters considered for optimising direct solar radiation through windows. Arens et al. (2014) describe the use of solar calculator (SolCal) to estimate the effects of solar radiation on occupant's comfort. They estimated level of window shading needed to prevent unacceptable predicted mean thermal sensation vote (PMV) increases for occupants near windows. They state that an occupant's PMV increase caused by short-wave solar radiation can be used to determine the shading required of the glass and window shades, and suggested that "the transmission of glass plus shades together probably should not exceed 15% if the sun will be shining on an occupant indoors"(p 8). Athienitis (2007) describes a two-storey building considered to be zero-energy building with five major renewable energy features. One of these features is "direct gain passive solar design that emphasizes utilization of distributed thermal mass in the south-facing part of the ground floor". He described the design of the building and then presented the preliminary results of the first year of the building operation. Having integrated Trombe walls into the envelope of two selected buildings, Torcellini and Pless (2004) analyse the energy performance of the buildings. They analyse "measured electrical end uses, Trombe wall temperature profiles, and thermographic pictures" in order to establish the thermal performance of the walls. Tsangrassoulis et al. (2006) demonstrate how genetic algorithm combined with simplistic calculation can be applied at initial design of south (equator)-facing façade to estimate window size, glazing thermal and optical properties, and shading.

Similarly, Arif et al. (2012); Kim and Kim (2009); Szokolay (2007) present some parameters which were earlier identified. Arif et al. (2012) investigated the potential effects of orientation as a solar passive design strategy on indoor temperatures, and presented a model for predicting indoor temperatures in terms of the surrounding temperatures. They tested a single room module by measuring the indoor temperatures for eight different orientations, rotating the plan at 45° in each case. They establish that indoor temperatures vary with orientation for different seasons, the strategy can be employed to predict cooling and heating for thermal comfort in buildings, and that optimised orientation could aid in design for energy efficiency at national level. Kim and Kim (2009) developed an experimental external shading device to improve daylighting, thermal performance and view in buildings. The building in which the shading device is tested was simulated and measurements taken “to verify the differentiated advantages in illumination” of back space and building energy consumption while maintaining a clear view. They analysed results of the experiment to show the extent to which the shading device contributes in reducing lighting, heating and cooling loads. Szokolay (2007) describes sun-earth relationships thereby establishing “conceptual background” leading to the provision of “working tool for the assessment of overshadowing and sun penetration into buildings”. He focuses on the design of shading devices, which so much depends on the solar geometry.

In their paper, Aren et al. (2014) identify two window design parameters that can be determined by occupant’s PMV increase caused direct solar radiation. Although how they are related is not directly contextual to the paper, these parameters are glass transmittance property and window shading device which relate to amount of incident solar radiation, sun’s altitude and azimuth.

Citing Carpenter and Mc-Cowan (1998), Arif et al. (2012) mentioned that “the south orientation with a tendency for west was found to be the optimum for cold and temperate climates”. However, they did not explicitly mention in their discussion or conclusion the orientation that could provide optimum results for thermal comfort. It can be deduced that the south (equator-facing) orientation offers the benefit of achieving optimal performance.

In describing the design of a two-storey single family zero-energy building, Athienitis (2007) mentions south (equator-facing) façade, aspect ratio and solar roof as the main feature for optimising form. He further states that “the direct gain system is the major solar energy capture and utilization system of the house”. This system can be optimised, while adequately sizing all windows, in relation to “distributed thermal mass”. This is relevant to this review because it identifies window size as a key parameter for optimising direct solar gains in building.

Kim and Kim, (2009) state that advanced numerical studies were carried out in which optimised shading device design criteria to reduce loads for lighting, heating and cooling were established. Also, they state that size (projection depth) is the most important parameter for the design of shading device in daylighting performance, and that optimisation of this size had been established by considering solar altitude and incidence angles in critical seasons. They lay emphasis on the equator-facing window which shows promising features in terms of direct solar radiation optimisation in buildings.

Szokolay (2007) identifies façade orientation and vertical shadow angle (VSA) as critical parameters for the design of shading device, and the VSA which is equal to the solar altitude determines the shading performance of the device. He establishes three steps to consider in designing a shading device; identification of overheated period, establishment of shadow angle (horizontal or vertical) and design of the device to satisfy these conditions. The VSA helps to establish equator-facing external shading device size which is also related to window height.

Torcellini and Pless (2004) mentioned that Trombe wall could be integrated along with windows, eaves and other elements to control solar gains. Window position and orientation and eave projection (also shading device size) are parameters that function together to regulate the amount of solar radiation that penetrates directly into the building. The direct solar radiation is allowed during winter and blocked during summer when the window faces the South or North (equator) when in the Northern or Southern hemisphere respectively.

Tsangrassoulis et al. (2006) suggest that passive solar techniques (design) should consider shading device or window size to avoid overheating during summer period so as to increase direct solar gains in winter while maintaining adequate daylight. They identify window length and height, glazing solar transmittance and U-value, and overhang (shading device) width as the design parameters to be estimated to optimise direct solar gains in buildings.

Although different approaches were considered, Arens et al. (2014); Arif, et al. (2012); Athienitis (2007); Kim and Kim (2009); Szokolay (2007); Torcellini and Pless (2004); Tsangrassoulis, et al. (2006) attempt to show the relationships among the window design parameters in order to optimise direct solar gains to reduce heating, cooling and lighting loads thereby improving thermal and daylighting performance.

However, it is imperative to examine the robustness of these literatures in order to buttress their strength to this critical review. Aren et al. (2014) show convincingly the limit transmission of window glass and shading of direct solar radiation should not exceed to avoid occupant’s thermal discomfort. But they do not contextualise to indicate instances when direct solar radiation may be required (for example, in winter). Also, Arif et al. (2012) suggest that orientation as a passive solar design strategy can play prominent role in energy efficient building design thereby achieving sustainable development. Consequently, their results do not suggest which orientation is optimum. In the same way, Athienitis (2007) shows convincingly how the basic principle of sizing equator-facing window area is reflected in a “two-storey single family detached solar home located in Montreal”. It is indicated in the design that the equator-facing window as proportion of the equator-facing façade is 30%. Kim and Kim (2009) show that the experimental external equator-facing shading device has shown promising results by providing 50% illumination performance than the conventional device, and 20% and 12% reduction in cooling and heating loads respectively, although, these are just in the context of South Korea, but the results may look different for other locations. In addition, Szokolay

(2007) presents how the sun relates to the earth, and how this relationship is used to establish solar altitude and orientation that is useful in optimising sun's penetration into buildings. Torcellini and Pless (2004) state that a Trombe wall provides passive solar heating in building while excluding light and glare, and that shading is required to minimise heat gains in summer. Tsangrassoulis et al. (2006) show convincingly that in complex situations window size, glazing transmittance and U-value, and shading device size can only be adequately estimated using a more general method like genetic algorithm.

In reviewing the question of what design parameters that when appropriately estimated can improve equator-facing window for direct solar gains optimisation to improve thermal performance in buildings, seven literatures were critically reviewed. These literatures help in identifying four window design parameters. Window size, glazing thermal and optical properties, and shading device size are design parameters that can relate to one another in order to optimise direct solar gains in buildings during winter (Arens et al., 2014; Athienitis, 2007; Kim and Kim, 2009; Szokolay, 2007; Torcellini and Pless, 2004; Tsangrassoulis et al., 2006). When these parameters are adequately estimated for the equator-facing façade, they can optimise direct solar gain thereby reducing cooling load in summer and heating load in winter. Orientation is one of the parameters considered in window design with much emphasis on equator-facing window (Arif et al., 2012; Athienitis, 2007; Torcellini and Pless, 2004; Tsangrassoulis et al., 2006).

Although the reviewed literature identify four essential window design parameters and mention their relevance in reducing cooling, heating and lighting loads, they however fail to show how window height and shading device size relate, and subsequently determine the amount of solar radiation that could penetrate through the equator-facing window into the building. Therefore, this research focuses on equator-facing orientation with much consideration to window height and its effects on shading device size, and radiation beam height (RBH) and its rate of change.

RESEARCH DESIGN AND METHOD

This study adopted the apparent sun-paths model described in Szokolay (2007) for this analysis. The apparent sun paths are routes the sun follows during sun-rise and sun-set periods. The major sun paths have been identified to be those of equinoxes, mid-summer and mid-winter (Szokolay, 1999, 2007). The earth-sun relationship in terms of heliocentric and lococentric views formed the basis of the description of the apparent sun-paths model. While lococentric view represents the idea in which a location is considered to be the centre of a celestial dome with sun rising from the east and setting at the west, and the sun's apparent position is given by altitude and azimuth.

Heliocentric view shows the seasonal variations in apparent sun paths presenting different solar altitudes at mid-summer, equinox and mid-winter (see figures 1 and 2). On the equinox days, the sun rises from east at exactly 6:00 hr and sets in the west at 18:00 hr, and it reaches an altitude (ALT) of 90º – │LAT│at 12:00 noon, when zenith angle is the same as latitude (LAT) (Szokolay, 2007). From this position the sun's altitude increases by 23.5° at mid-summer and decreases by 23.5° at mid-winter (Szokolay, 1999). This altitude was considered for the design of shading device of the equator-facing window to give automatic seasonal adjustment that would allow winter solar radiation beam and block equinox and summer sun (Szokolay, 1999). "…at equinox the noon altitude line coincides with the sectional view of the sun-path, indicating that the vertical shadow angle (VSA, for an equator-facing window) will be constant for the whole day" (Szokolay, 1999:50).

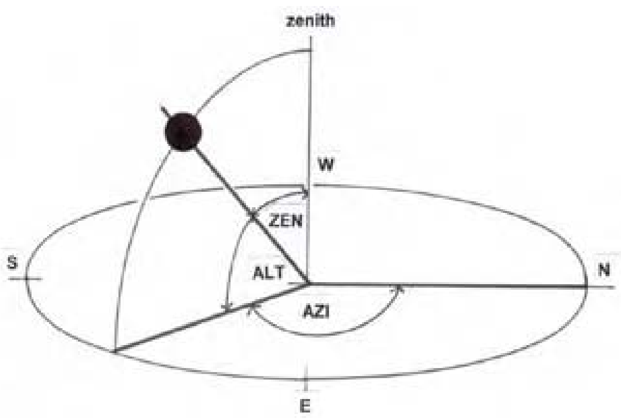
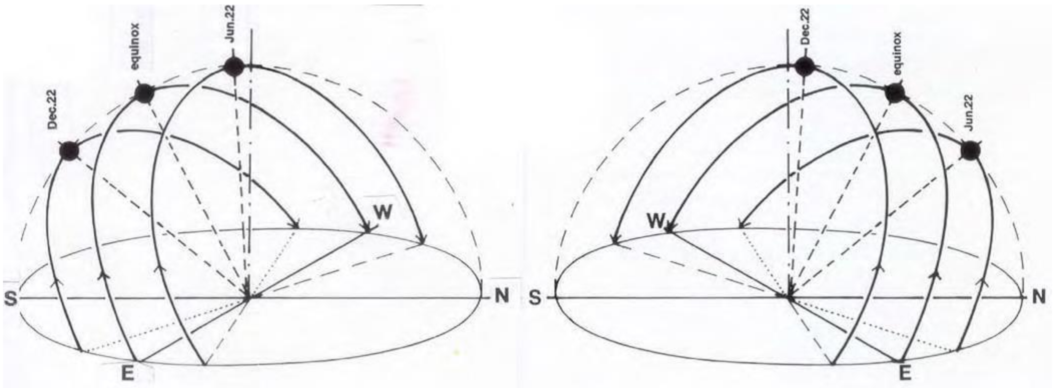


Figure 1: Apparent Sun's Position Source: Szokolay (1999:39, 2007:6)



NORTHERN HEMISPHERE SOUTHERN HEMISPHERE

Figure 2: Annual Variation of the Apparent Sun Paths Source: Szokolay (2007:8)

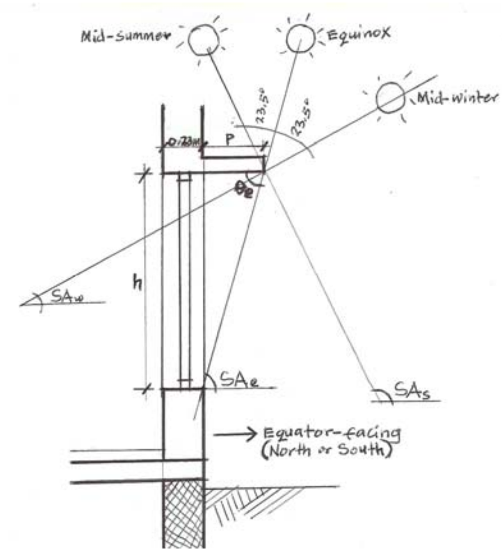


Figure 3: Equator-facing Window with Auto Seasonal Adjustment

Adopting this model for this study, the window height was varied to see the effects on shading device size (projection) and corresponding radiation beam height. As the solar altitude at equinox (SA_e) coincides with VSA of the shading device, the equator- facing window height (h) together with SA_e alternate angle to θ_e were used to calculate the shading device size (P) (figure 3). Similarly, the shading device size, the window height and the solar altitude at mid-winter (SA_w) alternate angle to θ_w were used in calculating the RBH (figure 4), and subsequently its rate of change.

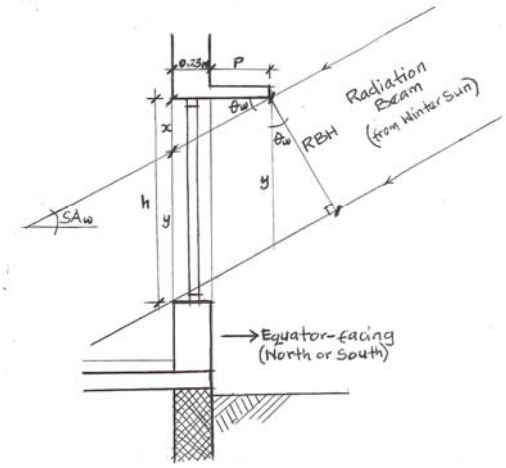


Figure 4: Winter Solar Radiation Beam

For a location of given latitude (LAT),

Solar altitude at equinox (SA_e) = $90^\circ - |LAT|$ -----------------------------------1

From figure 3, $P = h \div \tan\theta_e$ --2

Where h = window height, $\theta_e = SA_e$.

From figure 4,

RBH = $h\cos\theta_w - (P+W)\cos\theta_w\tan\theta_w$ ---3

Solar altitude at mid-winter (SA_w) = $\theta_e - 23.5^o$ ---------------------------------4

Where P = shading device size (projection), W = wall thickness, and θ_w = SA_w.

Therefore, these formulae were applied to calculate the shading device size and corresponding RBH by varying the equator-facing window height from 0.6 to 3.0 m at 0.3 m intervals. The rate of change of RBH for each change in the window height was then calculated. The results were presented for the different values of window height while considering latitudes 10°, 20°, 30°, 40° and 50° N or S.

RESULTS

To investigate the effect of varying equator-facing window height on horizontal shading device size, and corresponding RBH and its rate of change, the RBH was calculated for each value of P, and the rate of change of RBH was determined as the ratio of increase in RBH and the RBH as h increases.

Table 1 shows the calculated values of shading device size and corresponding radiation beam height with its rate of change for varying equator-facing window for latitude 10^0. Using calculated solar altitude at equinox (SA_e) which is 80^0, the value of optimal shading device size (P) was determined for each window height (h). As the sun moves down 23.5^0 at mid-winter, solar altitude decreases to 56.5^0 forming the basis for the calculation of the RBH at mid-winter for the same location. These results show that as the window height was varied from 600 mm to 3000 mm at 300 mm interval, the shading device size increased along with the corresponding RBH while its rate of change diminished.

Table 1: Window Height, Shading Device Size and RBH for Latitude 10^0

	Window height, h (mm)								
Shading and RBH Elements	600	900	1200	1500	1800	2100	2400	2700	3000
Shading size, P (mm)	105	158	211	264	317	370	423	476	528
Radiation beam height, RBH (mm)	56	177	299	420	542	663	784	906	1028
Rate of change of RBH		2.17	0.68	0.41	0.29	0.22	0.18	0.15	0.13

Table 2 shows the results of the shading device size in millimetres as determined for various latitudes as indicated. The calculations were done in the same way (using formula 2) as applied in table 1, and the solar altitudes at mid-winter for these latitudes were 56.5^0, 46.5^0, 36.5^0, 26.5^0 and 16.5^0 respectively. As the window height was varied and with increasing latitude, the horizontal shading device became excessively large.

Table 2: Shading device size (mm)

	Window height (mm)								
Latitude	600	900	1200	1500	1800	2100	2400	2700	3000
10^0	105	158	211	264	317	370	423	476	528
20^0	218	327	436	545	655	764	873	982	1091
30^0	346	519	692	866	1039	1212	1385	1558	1732
40^0	503	755	1006	1258	1510	1762	2013	2265	2517
50^0	715	1072	1430	1787	2145	2502	2860	3217	3575

Also for the same locations, table 3 shows the results of calculated RBH in millimetres corresponding to the shading device size in table 2 for varying window height. Formula 3 was applied in this case. This indicates that the RBH increased as the window height was increased and the latitude as well.

Table 3: Radiation Beam Height, RBH (mm)

	Window height (mm)								
Latitude	600	900	1200	1500	1800	2100	2400	2700	3000
10^0	56	177	299	420	542	663	784	906	1028
20^0	92	219	347	474	601	728	856	983	1110
30^0	143	281	419	557	695	833	972	1110	1248
40^0	212	368	525	681	837	993	1149	1305	1461
50^0	308	495	681	867	1053	1239	1425	1611	1797

Table 4: Rate of Change of Radiation Beam Height

	Window height (mm)								
Latitude	600	900	1200	1500	1800	2100	2400	2700	3000
10^0	-	2.17	0.68	0.41	0.29	0.22	0.18	0.15	0.13
20^0	-	1.39	0.58	0.37	0.27	0.21	0.18	0.15	0.13
30^0	-	0.97	0.49	0.33	0.25	0.20	0.17	0.14	0.12
40^0	-	0.74	0.43	0.30	0.23	0.19	0.16	0.14	0.12
50^0	-	0.60	0.38	0.27	0.21	0.18	0.15	0.13	0.12

In addition, Table 4 presents the values of the rate of change of the RBH for all 0.3 m increase in window height. This rate of change of RBH is expressed as the ratio of the increase in corresponding RBH to the RBH (see table 3). This shows that with varying window height and increasing latitude, the rate of change of the RBH diminished becoming minimal with larger windows.

As a unit, the equator-facing window was designed while considering it height and horizontal shading device size, and the height of radiation beam that penetrates the window at mid-winter determined. Comparing these results, the implications of the relationship among the window height, shading device size and RBH as well as its rate of change on direct solar gains optimisation in buildings were discussed.

DISCUSSION

Having considered some critical window design parameters in reviewing the literature, no data clearly indicates how the equator-facing window height relates to horizontal shading device size and direct solar radiation beam height. Therefore, this study was designed to investigate the effect of varying equator-facing window height on shading device size and corresponding radiation beam height (RBH) along with its rate of change in order to determine if direct solar gains optimization depends solely on the largest window height.

The shading device size and corresponding RBH increased as window height was varied indicating that the direct solar gains in building can increase. For different latitudes and as the location is further from the equator, the shading device size increased becoming excessively large which indicates its impracticability as a single unit unless split. From 30^0 to 50^0 latitudes, the shading device sizes ranged between 1000 and 3600 mm which as cantilever may be impracticable. However, the rates of change of RBH diminished as window height was varied for different latitudes and as these locations were further from the equator indicating that optimising direct solar gains does not depend on the largest window height. By these results, the optimum window height falls between 2400 mm and 2700 mm as further increase indicates almost constant rate of change of RBH – between 0.12 and 0.13.

This combination of findings provides some support for architects and building designers in the industry to conceptualise design of equator-facing window in which the height plays prominent role in determining the size of horizontal shading device as well as the amount of solar radiation penetrating through the window into the building in winter. Also, the implication for policy is that building regulation authorities could consider the results as bases to draw out guidelines for assessing equator-facing window size for optimum solar gains and daylighting in buildings. In addition, the findings provide researchers in the built environment the grounds to hypothesise in order to undertake further research in determining the exact equator-facing window height and width in relation to the wall area for optimum direct solar gains in winter. In future investigations, it might be possible to also consider climatic factor in this analysis in order to determine the amount of solar radiation gained for each situation.

CONCLUSION

This paper has explained the central importance of varying window height in designing equator-facing window for direct solar gains optimization in buildings. Optimum window area (width x height) was considered to be 30% of the area of the equator-facing façade, but it was not clear how these could be split between the width and the height. Relevant literatures were reviewed to identify design parameters that were considered to be important in designing windows. Equator-facing orientation, window height and shading device size were considered to be the most influential for direct passive solar design. This research was designed and the method explained while the results were presented and discussed.

The purpose of this study was to investigate the effect of varying equator-facing window height on shading device size, and corresponding radiation beam height and its rate of change in order to determine if direct solar gains optimisation in buildings depends on largest window height. Findings show that in general the shading device size and corresponding RBH increase as equator-facing window height varies. However, the corresponding rate of change of RBH diminishes with such increase in window height. These results suggest that in the design of equator-facing window optimising direct solar gains in buildings does not rely on the largest window height. Therefore, the findings contribute to how the 30% of the equator-facing façade area can be used to apportion the window width and height by considering the optimum height – not the largest height.

This study focuses on vertical aspect of the equator-facing window which gives automatic seasonal adjustment as well as requires only horizontal shading device for optimisation. Moreover, further research is necessary to model the amount of direct solar radiation (while considering climatic condition) that passes through the equator-facing window into the building. However, the study provides a basis for further research in modelling direct solar gains in buildings, and a useful means for architects to design equator-facing windows.

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