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Effects of solar shading on thermal comfort in low-income tropical housing

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Abstract

This paper evaluates the effects of solar shading strategies on thermal comfort in low-income tropical housing in Uganda. Dynamic thermal simulations are conducted and the effects of various shading strategies including curtains, roof and window overhangs, veranda and tress on solar heat gain and thermal comfort are investigated. Adaptive approach for naturally ventilated buildings defined by CEN standard is used to assess the conditions in the case study buildings. According to the results, although shading significantly reduces solar heat gain, it is less effective in meeting thermal comfort requirements in low-income tropical houses. Solar shading is however considerably effective during the hottest periods of the year reducing the risk of extreme overheating by up to 52%. In this respect, a north-south building orientation with the main openings on the north elevation is recommended. Due to excessive solar heat gain, large openings on east- and west-facing walls should be avoided.

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Keywords: Solar Shading; Thermal Comfort; Low-income; Tropical; Housing; Uganda

1. Introduction

Uganda is one of the most economically deprived countries in the world. Around 33% of Uganda's population live in severe multidimensional poverty [1] and over 60% of its urban population living in slums [2,3]. Uganda has a moderate tropical climate [4] although global warming is expected to increase the average air temperature in East African countries by 3-4 °C during the next 70 years [5]. This situation along with inappropriate and defective

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construction methods and materials [6,7] may deteriorate thermal comfort conditions [8] affecting low-income populations the majority of whom live in single-roomed [9] overcrowded homes [10]. Considering the very low access to electricity in Uganda (18.2% [1]), natural ventilation is the major ventilation/cooling method in the majority of buildings. Natural ventilation can provide thermal comfort; however, to provide effective natural ventilation it is important to minimise internal and external heat gains [11].

Solar heat gain is identified as one of the main contributors to overheating in residential buildings. Therefore minimising solar heat gain can improve effectiveness of natural ventilation. Solar heat gain can be controlled by reducing solar transmittance through windows, improving construction details/types to minimise surfaces heat transfer [12], and introducing shading to minimise solar transmission and heat gains through glazed and opaque surfaces [13]. Solar transmittance which is usually measured by g-value and solar heat gain coefficient (SHGC) [14] is highly affected by glass types. Due to possible high costs and limited access to different glazing types for low-income people, changing the glazing may not be an appropriate strategy to control solar heat gain in low-income housing. Solar shading in contrast could be an appropriate strategy which could be considered to improve thermal comfort in low-income housing. Solar shading can be provided by means of internal and external shades. Generally, compared to internal shadings, external shadings are up to 30% more effective in minimising solar heat gain. For south and north facing windows it is generally recommended to use horizontal external shading while for east and west facing windows application of vertical shading is recommended [13]. Although more effective, external shading tend to be more expensive compared to internal shading [15]. This may arguably limit the applicability of external shades in low-income housing.

Fig. 1. Low-income housing.

This study evaluates the effects of solar shading strategies on the risk of overheating and thermal discomfort in low-income tropical houses in Uganda (Fig. 1). The effects of alternative construction methods and materials as well as refurbishment strategies on thermal comfort have been reported in other papers [8,16].

2. Methodology

Dynamic thermal simulations (DTS) were conducted in EnergyPlus to evaluate the effects various shading strategies on solar heat gain and thermal comfort in a typical low-income house in Uganda. The Test Reference Year (TRY) for Kisumu in Kenya was chosen as the closest available weather data to Kampala as there are no available weather data for thermal simulations in Uganda. Kampala and Kisumu are located on the northern shore of Lake Victoria with similar altitudes above the sea level.

Considering over 50% of Ugandan families live in single-roomed homes [9] with an average household size of 3.9 people in urban areas [17], a single-zone 3×3×3m house with 4 occupants was modelled. A south facing window

(1×1m) and door (2×1m) with an effective opening area of 80% were also considered. Permanent background ventilators were also introduced above the window and door as a common practice in Uganda (Fig. 2). “AirflowNetwork” in EnergyPlus was used to accurately simulate natural ventilation and air infiltration through the openings and cracks in the walls.

Fig. 2. Permanent ventilators on windows and doors.

According to available data, brick walls (57%) and iron sheet roofs (62%) are the prevailing walling and roofing methods/materials in Uganda. Cement/concert flooring (70%) is also the most common flooring material in urban areas of the country [9,17]. Simulations were therefore conducted for the most common construction method in urban areas of Uganda. Table 1 summarises the properties of the materials used.

Table 1. Material properties used in the simulations.

Material	Thermal Conductivity W/(mK)	Thickness (m)	Density (Kg/m3)	Solar Transmitance	Solar Absorptance
Brick	1.0	0.200	1900	-	0.70
Iron sheet roof	37.0	0.003	7800	-	0.70
Concrete	1.31	0.100	2240	-	0.70
Glass	0.90	0.006	-	0.775	-

The occupancy profile in the case study building has been specified as fully occupied between 6pm- 8am and one occupant between 8am and 6pm. Window and door were assumed to be open between 6:30am- 6:30pm and7am- 8pm respectively [18]. For the purpose of this study, thirty different combination scenarios were simulated. The effects of various internal and external shading strategies including curtains, roof and window overhangs, veranda and tress on solar heat gain and thermal comfort were investigated (Table 2).

Table 2. Tested scenarios.

Shading Option	Conditions

Curtains	None	Always On	On if beam plus diffuse solar radiation incident on the window exceeds 50 W/m2
Roof overhangs	None	0.5 both sides	Veranda: 2m shade on south and 0.5m roof shade on north
External horizontal shade on windows (window overhang)	None	0.5m	-
Trees	None	2 triangular trees, one on south and one on north (12m high, 6m wide, 6m away from the building)	

The performance of proposed options have been studied by reporting solar heat gain and risk of overheating. Adaptive approach has been used to assess thermal comfort conditions. Thermal comfort in adaptive approach is affected by occupants' behaviours and expectations in naturally ventilated buildings [19]. Based on this method of evaluation it is proposed that occupants' perception regarding thermal comfort is affected by their past thermal history [20]. For typical occupants, CEN standard BS EN 15251 [21] suggests the following equation to estimate comfortable temperature in naturally ventilated buildings (Equations 1):

$$T_{comf} = 0.33\ T_{rm} + 18.8 + 3 \ (where\ T_{rm} > 10\ °C) \quad (1)$$

Where:
T_{comf} = the maximum comfortable temperature (ºC)
T_{rm} = the running mean temperature for today weighted with higher influence of recent days [22] (ºC).

T_{rm} can be calculated using Equation 2 below:

$$T_{rm} = (1-\alpha).\ \{T_{ed-1} + \alpha.\ T_{ed-2} + \alpha^2.\ T_{ed-3} \ldots.\} \quad (2)$$

Where:
T_{ed-1} = the daily mean external temperature for the previous day (ºC)
T_{ed-2} = the daily mean external temperature for the day before (ºC) and so on
α = constant; Tuohy *et al.* [23] suggest to use 0.8 for α.

In adaptive method risk of overheating is assessed based on frequency and severity of overheating. The risk of overheating in a room is evaluated by using three different criteria. A building is assumed to be overheated if it fails any two of the three adaptive assessment criteria. All three criteria are defined in terms of ΔT, which is the difference between the operative temperature and the maximum acceptable temperature (Table 3). Operative temperature articulates the joint effect of air temperature and mean radiant temperature along with the internal air movement as a single figure. For indoor air speed less than 0.1m/s, operative temperature could be calculated from the following equation [24]:

$$T_{op} = (T_a + T_r)/2 \quad (3)$$

Where:
T_a= air temperature (ºC)
T_r= mean radiant temperature (ºC)

Table 3. Assessment criteria to study risk of overheating in naturally ventilated buildings.

Assessment Criteria	Acceptable deviation

Criterion 1	Frequency of occupied hours when operative temperature is greater than maximum comfortable temperature	Up to 3% of occupied hours
Criterion 2	severity of thermal discomfort by calculation of Number of day degree hours of warm period >6 °hrs a day	0 day
Criterion 3	severity of thermal discomfort by reporting Number of hours in which ΔT > 4 K	0 hour

2. Results

Table 4 summarises the results of simulations for all 30 combination scenarios. The results have been divided into five geometry categories and six schedule categories as follows. The effects of including/excluding trees and curtains have been evaluated for each geometry condition.

A. Geometry categories:
1. Base Case
2. Window Shade/Overhang
3. Roof Shade/Overhang
4. Roof + Window Shade/Overhang
5. Veranda

B. Schedule categories:
6. Curtain Off- No Trees
7. Curtain Off - Trees on North and South
8. Curtain On - No Trees
9. Curtain On - Trees on North and South
10. Curtain on if beam plus diffuse solar radiation incident on the window exceeds 50 W/m2 - No Trees
11. Curtain on if beam plus diffuse solar radiation incident on the window exceeds 50 W/m2 - Trees on North and South

According to the results, none of the tested scenarios passed thermal comfort criteria. However, compared to the base case, thermal comfort conditions improved when solar shading was introduced. The best conditions were achieved when Veranda with a 2 meter projected roof was considered. Shading strategies seemed to be most effective during the hottest periods of the year when Criterion 3 (times ΔT over 4 K) was more likely to fail. Indeed, geometry shading strategies (Category A/Schedule 1) had very marginal effects on Criterion 1 and Criterion 2 of TM52 thermal comfort criteria.

For Schedule 1 (Curtain Off- No Trees), compared to base case, risk of extreme overheating for Criterion 3 reduced by 47.6% when Veranda was considered. The risk of overheating also reduced considerably for other methods. A similar performance to Veranda was achieved when roof and window overhangs were jointly considered. For Schedule 2, when trees were introduced, compared to the base case, all shading strategies achieved a similar performance reducing risk of extreme overheating by more than 40%. Including Curtains in Schedule 3 also slightly improved thermal comfort conditions. Comparing schedule 2 with schedule 3, it is evident that curtains have been more effective in achieving better conditions during extremely hot days (Criterion 3) while trees performed slightly better than curtains for Criterion 2. Moreover, the results reveal that schedules 3 and 5, and schedules 4 and 6 has almost identical performances meaning that the beam plus diffuse solar radiation incident on the window always exceeded 50 W/m^2 (which means that the curtains were always on). Overall, as expected, best thermal comfort conditions were achieved when threes and curtains were considered together (schedules 4 and 6).

Table 4. Thermal comfort criteria for simulated scenarios.

Geometry	Criterion 1 (%)	Criterion 2 (Daily degree-hours over 6)	Criterion 3 (ΔT over 4 K)
		Schedule 1: Curtain Off- No Trees	
Base Case	13.40%	134	21
Window Shade/Overhang	13.03%	132	15
Roof Shade/Overhang	12.76%	128	14
Roof + Window Shade/Overhang	12.47%	123	12
Veranda	12.38%	124	11
		Schedule 2: Curtain Off - Trees on North and South	
Base Case	13.07%	130	20
Window Shade/Overhang	12.64%	124	12
Roof Shade/Overhang	12.35%	120	12
Roof + Window Shade/Overhang	12.13%	118	11
Veranda	12.15%	121	11
		Schedule 3: Curtain On - No Trees	
Base Case	13.10%	132	18
Window Shade/Overhang	12.94%	129	13
Roof Shade/Overhang	12.51%	125	13
Roof + Window Shade/Overhang	12.39%	123	11
Veranda	12.23%	122	11
		Schedule 4: Curtain On - Trees on North and South	
Base Case	12.81%	126	13
Window Shade/Overhang	12.52%	123	12
Roof Shade/Overhang	12.20%	118	11
Roof + Window Shade/Overhang	11.98%	117	11
Veranda	12.08%	118	10
		Schedule 5: Curtain on if beam plus diffuse solar radiation incident on the window exceeds 50 W/m2 - No Trees	
Base Case	13.09%	132	18
Window Shade/Overhang	12.93%	129	13
Roof Shade/Overhang	12.50%	125	13
Roof + Window Shade/Overhang	12.37%	122	11
Veranda	12.22%	122	11
		Schedule 6: Curtain on if beam plus diffuse solar radiation incident on the window exceeds 50 W/m2 - Trees on North and South	
Base Case	12.79%	126	13
Window Shade/Overhang	12.52%	123	12
Roof Shade/Overhang	12.19%	118	11
Roof + Window Shade/Overhang	11.95%	117	11
Veranda	12.04%	117	10

2. Discussion

According to the results of this study, although solar shading improves thermal comfort conditions, shading strategies are less effective in achieving thermal comfort requirements in low-income tropical housing. Therefore, solar shading should be used in conjunction with other strategies in order to meet thermal comfort criteria. Nevertheless, excessive solar heat gain has been identified as one of the major contributors to overheating in buildings. Solar gain can be controlled by introducing shading to minimise solar transmission and heat gains through glazed and opaque surfaces [13]. Further studies were therefore carried out to evaluate the performance of building elements and shading strategies in terms of solar heat gain and transmittance.

Fig. 3 shows the sun path diagram during winter and summer in Kampala. It is evident that the sun falls on the south elevation during the hottest summer periods during December and February. Therefore, it could be argued that significant solar transmittance may occur during the hottest period of year from windows and other openings on the south elevation.

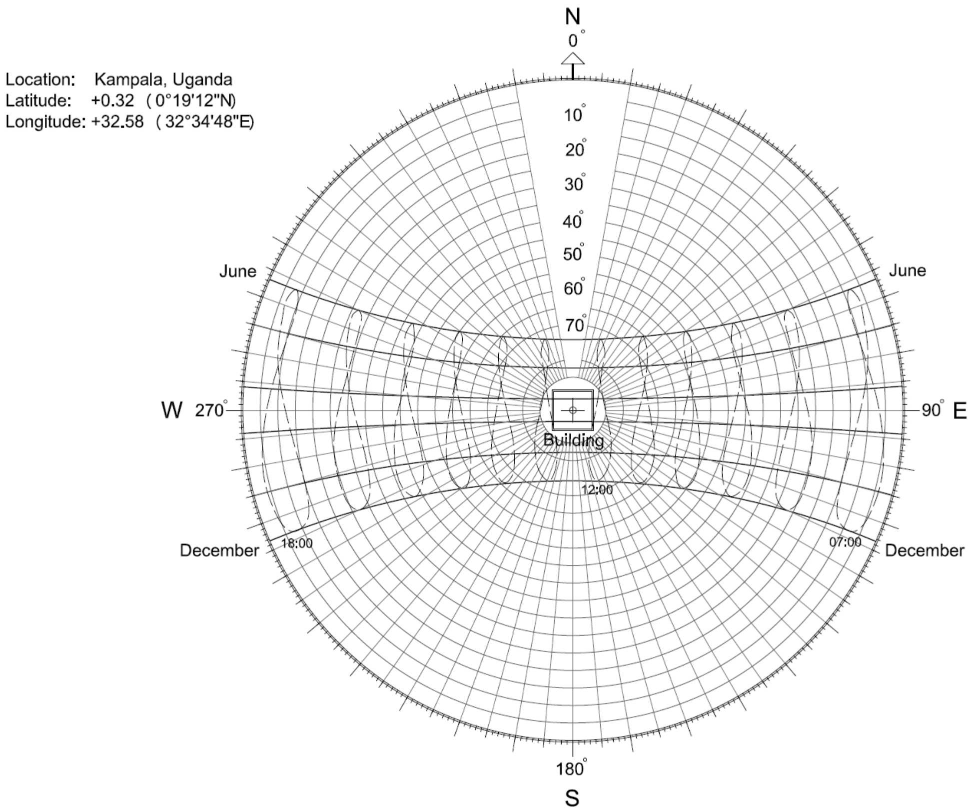

Fig. 3. Sun path diagram - Kampala, Uganda.

Additional simulations were conducted to assess the performance of shading strategies in terms of controlling solar transmittance through the windows. Table 5 summarises the average transmitted solar radiation rate for the window over the entire year (total transmitted solar radiation rate/365) for all 30 different tested scenarios. The transmitted solar radiation rate, according to EnergyPlus, is the sum of transmitted “Beam Solar Radiation Rate” and “Diffuse

Solar Radiation Rate" through the window [25]. The average diffuse and direct solar radiation rates per area for the site are also reported in Table 5. According to the results, apart from trees, the rest of the shading strategies have considerably reduced the transmitted solar radiation through the window. A possible explanation for this is that unlike "attached shadings surfaces", such as overhangs, trees have not been able to provide effective shading over the windows. The most effective condition has been achieved when curtains were combined with window and roof overhangs. In this condition, transmitted solar radiation has decreased from 57.06 W (the base case without any shading) to 13.42 W which means a reduction of around 76%.

Overall, the findings reveal that solar shading is very effective in reducing solar heat gain through windows; however, due to the relatively small size of the windows in the case study buildings and considerably higher solar heat gain through other building elements, such as the roof, window shading/overhang did not make a meaningful difference in terms of total solar heat gain and thermal comfort. Shading could however significantly improve the conditions by reducing excessive solar heat gain through large openings on the walls.

It should be noted that, according to Fig. 3, the sun has a very high altitude in Kampala during the entire year. This indicates that the roof is receiving the highest solar heat gain compared to other building elements, implying the importance of rood as a major contributor to risk of overheating in tropical climates. The high sun altitude also indicates that, unless planted very close to the building, trees may be less effective in providing effective shading over the buildings; however, the microclimatic effects of plants and trees may improve the conditions. Such effects of trees and plants on thermal comfort in tropical climates were not the focus of this study and should be investigate in more detail.

Table 5. The average transmitted solar radiation rate through the window (W).

	Base Case	**Window Shade/Overhang**	**Roof Shade/Overhang**	**Roof + Window Shade/Overhang**	**Veranda**
Curtain Off- No Trees	57.06	41.24	52.89	40.88	42.29
Curtain Off - Trees on North and South	54.08	38.84	49.75	38.48	39.84
Curtain On - No Trees	18.3	13.22	16.96	13.11	13.56
Curtain On - Trees on North and South	17.34	12.45	15.95	12.34	12.77
Curtain on if beam plus diffuse solar radiation incident on the window exceeds 50 W/m2 - No Trees	19.1	14.18	17.77	14.06	14.48
Curtain on if beam plus diffuse solar radiation incident on the window exceeds 50 W/m2 - Trees on North and South	18.23	13.54	16.9	13.42	13.79
Average site diffuse solar radiation rate per area: 178.56 W/m2					
Average site direct solar radiation rate per area: 103.34 W/m2					

Fig. 4 shows the average annual solar radiation heat gain rate per area (W/m^2) for the building envelope in the base case where no shading is considered. The results reveal that solar heat gain of the roof is nearly three times higher than north and south facing walls. This confirms the previous findings which highlighted the roof as a major contributor to solar heat gain. The roof construction should therefore be considered as a major issue in thermal comfort evaluations in tropical climates. Other studies also support this finding identifying the roof as a key factor in reducing or increasing the risk of overheating and thermal discomfort in low-income tropical housing [8,16].

The results also reveal that the average solar heat gain from east and west facing walls and windows is up to 1.4 times higher than from walls and windows facing north and south. Building layout and orientation are therefore critical when assessing overheating and thermal comfort in Kampala. In this respect a North-South orientation with main openings on the north elevation is recommended. Due to the rather very high solar heat gain, large openings on east and west elevations should also be avoided.

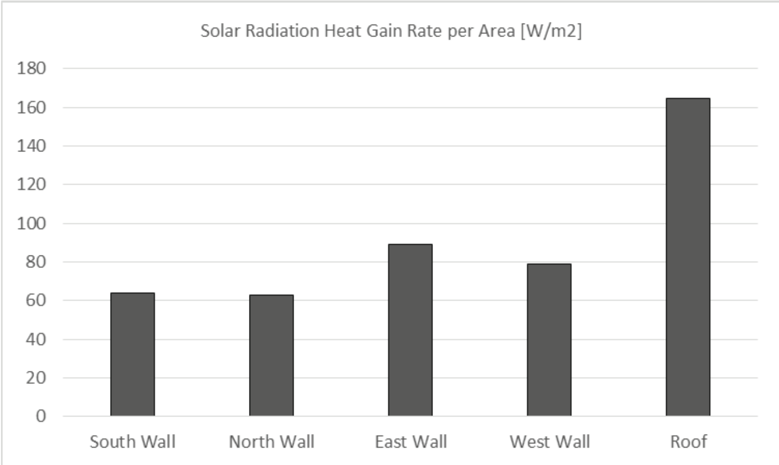

Fig. 4. Solar radiation heat gain for the base case without shading (W/m^2).

2. Conclusion

This paper investigated the effects of shading strategies including curtains, roof and window overhangs, veranda and tress on solar heat gain and thermal comfort in low-income tropical houses in Uganda. Dynamic thermal simulations were conducted for buildings with brick walls and iron sheet roof as the most common construction method in Uganda. According to the results, although introducing solar shading improved thermal comfort conditions, none of the tested scenarios were effective enough to meet thermal comfort criteria. The results reveal that shading strategies are most effective during the hottest periods of the year reducing the risk of extreme overheating by up to 52%. According to the results, when it comes to solar heat gain, a north-south building orientation with the main openings on the north side is recommended as the most appropriate building layout/orientation to reduce the risk of overheating and thermal discomfort in tropical climate of Kampala. Moreover, large openings on east- and west-facing walls should be avoided to minimise excessive solar heat gain.

This study concentrated on the effects of solar shading on thermal comfort. Further research is required to evaluate the effects of other types of shading as well as issues such as natural ventilations strategies, occupancy behaviors and microclimatic effects of trees/plants on thermal comfort in low-income tropical housing.

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