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Effects of Natural Ventilation on Thermal Comfort in Low-income Tropical Housing

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Abstract: This paper evaluates the effects of natural ventilation on thermal comfort and risk of overheating in low-income tropical housing in Uganda. Dynamic simulations are conducted in EnergyPlus to assess various strategies including single sided and cross ventilation, roof vents and night ventilation in case study dwellings. The Chartered Institution of Building Services Engineers Technical Memoranda 52 (CIBSE TM52) is used to assess thermal comfort conditions within the case study dwellings. The results indicate that natural ventilation strategies marginally reduce the risk of overheating. Overall, compared to other strategies, such as roof insulation, natural ventilation is less effective in terms of improving indoor comfort conditions. This paper is a part of a series of publications on the effects of climate change on thermal comfort in low-income tropical housing.

Keywords: Thermal Comfort; Climate Change; Resilience; Refurbishment; Low-income; Tropical; Housing; Uganda; Africa.

Nomenclature:

Top is the operative temperature
Tmax is the maximum comfortable temperature
Tupp is Tmax+4
ΔT is the difference between the operative temperature and the maximum acceptable

1. Introduction

As one of the most impoverished East African countries, Uganda is likely to be dramatically affected by climate change. Nearly 38% of the country's population live below the income poverty line of $1.25 [1] and only 8% of rural families have access to electricity [1], while they account for around 85% of the total population [2]. Besides, over 60% of the country's urban population live in slums [3,4] and around 50% live in single-roomed overcrowded properties [5].

Detached houses (58%) are the most common housing types in Uganda [6] and the average number of people sleeping in one room is four or more [7]. Over 60% of homes in Uganda have iron sheets roof (Figure 1) and 37% are thatched. Brick followed by mud & poles are the most common walling materials with 57% and 39% of the constructed wall, respectively. Cement/concert is also predominant flooring material in urban areas of the country. Around 70% of the houses in urban areas have concrete flooring [5,8].

Figure 1. Low-income housing and slums.

Uganda has a moderate tropical climate with annual temperature ranging between 16 °C and 30 °C [9]. However, climate change and global warming are expected to increase the average air temperature by 3–4 °C during the next 70 years [10]. Indeed, climate change is expected to dramatically affect the health and wellbeing of the low-income populations in low-income countries. Low income populations will be hit the worst by the negative effects of climate change. Moreover, the growing trend of moving away from sustainable traditional building materials, such as adobe and thatched roofs, toward less sustainable and environmentally damaging materials, such as concrete and iron sheet roofs, is contributing to concerns over the effects of climate change on thermal comfort in low-income housing in Uganda [11]. Due to the lack of access to adequate resources, low-income people are less able to adapt to climate change putting them in an even more vulnerable position.

This paper aims to evaluate the effects of natural ventilation strategies on the risk and extent of thermal discomfort in low-income houses in Uganda. The paper is a part of a series of publications on the effects of climate change on thermal comfort in low-income housing in Uganda. The effects of alternative construction methods and materials as well as refurbishment and solar shading strategies on thermal comfort have been reported in other papers [12,13,14].

2. Methodology

Dynamic thermal simulations were conducted in EnergyPlus to evaluate the effects of various building geometries and ventilation strategies on thermal comfort. The Test Reference Year (TRY) for Kisumu in Kenya was used for the purpose of simulations as the closest city to Kampala with similar climatic conditions. The materials' properties were defined based on the available information in Perez

(2015) [6] and CIBSE Guide A {15]. Table 1 summarises the properties of the materials used for simulations.

Table 1. Material properties used in the simulations.

Material	Thermal Conductivity (W/m·K)	Thickness (m)	Density (Kg/m3)
Brick	1.00	0.200	1900
Hollow Concrete Block	0.86	0.200	875
Iron sheet roof (0.7 solar absorptance value)	37.00	0.003	7800
Concrete	1.31	0.100	2240
Insulation	0.04	0.050	240
Glass	0.90	0.006	-
Window frame	5.00	0.050	-

According to the statistical data above, a 3 × 3 × 3m single-zone property with four occupants with a south facing 2 × 1 m door and a 1 × 1 m single glazed window with effective opening areas of 80% was modelled, as the representative of a low-income house in urban areas of Uganda. Permanent background ventilators were also considered above all the window and doors, as a common practice in Uganda (Figure 2). "AirflowNetwork" was used to accurately simulate natural ventilation through the openings.

Figure 2. Permanent ventilators on windows and doors

The occupancy profile was defined as fully occupied from 6 pm to 8 am and one occupant from 8 am to 6 pm. The occupants' behaviours were defined as [16]: windows open 6:30 am - 6:30pm; doors open 7 am–8 pm. For night ventilation strategies, windows and roof vents were considered to be open permanently including during nights. Adaptive method and overheating criteria, defined in BS EN 15251 [17] and CIBSE TM52 [18], are used to evaluate the risk of thermal discomfort. Table 2 summarises the overheating criteria used for thermal comfort assessments.

Table 2. Overheating assessment criteria.

Assessment Criteria *		Acceptable Deviation
Criterion 1	Percentage of occupied hours during which ΔT ($\Delta T = T_{op} - T_{max}$ rounded to the nearest whole degree) is greater than or equal to 1°K	Up to 3% of occupied hours

Criterion 2	"Daily weighted exceedance" (W_e) in any one day >6° h	0 day
Criterion 3	Maximum temperature level (T_{upp}) $\Delta T > 4°$ K	0 h

* Refer to nomenclature for more information.

3. Results

Overall, twenty-four different combination scenarios were simulated. The results are reported for six distinct zones for three building geometries, two main construction methods, and two ventilation strategies as follows:

Geometry:

- One window (single sided ventilation)
- Two windows (cross ventilation)
- Two windows and roof vent

Construction method:

- Walls:

1. Brick walls
2. Hollow concrete walls

- Roof:

3. • Iron sheet
4. • Insulated iron sheet

Ventilation strategies

- SV: Normal ventilation (windows/vents open 6:30 am-6:30pm; doors open 7 am-8 pm)
- NV: Night Ventilation (windows/vents opened permanently; doors open 7 am-8 pm)

Previous studies revealed the excessive effects of iron sheet roof on indoor conditions [14] in low-income housing in Uganda. The scenarios were therefore categorised under two different categories of A) normal roof: iron sheet and B) insulated roof: internally insulated iron sheet, to assess the effects of natural ventilation strategies in both conditions. For the purpose of the analysis and ease of reference, an ID has been allocated to each simulated scenario. The SV refers to Simple/Normal Ventilation and NV refers to Night Ventilation. Table 3 summarises the analysed combinations.

Table 3. Tested scenarios

Category A: Uninsulated roof						
ID	1 SV/NV	2 SV/NV	3 SV/NV	4 SV/NV	5 SV/NV	6 SV/NV
Zones	Z1	Z2	Z3	Z4	Z5	Z6
Wall Construction	Brick	Hollow Concrete	Brick	Hollow Concrete	Brick	Hollow Concrete
Roof construction	Iron sheet	Iron sheet	Iron sheet	Iron sheet	Iron sheet	Iron sheet
Windows	1	1	2	2	2	2
Roof Vent	None	None	None	None	1	1
Doors	1	1	1	1	1	1
TV	2	2	3	3	3	3

Category B: Insulated roof						
ID Zones	7 SV/NV Z7	8 SV/NV Z8	9 SV/NV Z9	10 SV/NV Z10	11 SV/NV Z11	12 SV/NV Z12
Wall Construction	Brick	Hollow Concrete	Brick	Hollow Concrete	Brick	Hollow Concrete
Roof construction	Insulated iron sheet	Insulated iron sheet	Insulated iron sheet	Insulated iron sheet	Insulated iron sheet	Insulated iron sheet
Windows	1	1	2	2	2	2
Roof Vent	None	None	None	None	1	1
Doors	1	1	1	1	1	1
TV	2	2	3	3	3	3

Category A: Natural ventilation in buildings with iron sheet roof

According to the results, although there were some improvements, for category A with iron sheet roof, none of the natural ventilations strategies were effective enough to pass thermal comfort requirements.

Table 4 and Table 5 summarise the results of simulations for daytime and night ventilation strategies. The results indicate that, compared to daytime ventilation, there has been marginal improvement for all similar scenarios when night ventilation is considered (e.g. 1 SV compared to 7 NV). Similar improvements are observed for cross ventilation compared to single sided ventilation. The situation is enhanced when cross ventilation is combined with roof vent.

Thermal comfort conditions are significantly better for brick walls compared with hollow concrete walls however ventilation strategies seem to be more effective for buildings with hollow concrete walls. improvements are more significant. According to the results the best performance is achieved for buildings with brick walls when cross and roof ventilation along with night ventilation are introduced (ID: 11 NV). For this scenario, compared to the base case scenario (ID: 1 SV); there have been 22%, 38% and 43% improvements for criteria 1, 2, and 3, respectively.

Table 4. Thermal comfort criteria for continuous daytime ventilation with iron sheet roof.

ID	Description*	Criterion 1 (%)	Criterion 2 (Daily degree-hours over 6)	Criterion 3 (ΔT over 4 K)
1 SV	B wall, 1 W	12.69%	127	14
2 SV	HC wall, 1 W	18.74%	232	163
3 SV	B wall, 2 W	12.07%	119	14
4 SV	HC wall, 2 W	17.66%	211	121
5 SV	B wall, 2 W & RV	10.35%	82	9
6 SV	HC wall, 2 W & RV	16.03%	191	75

* B: Brick; HC: Hollow Concrete; W: Window; RV: Roof Vent

Table 5: Thermal comfort criteria for continuous daytime and night ventilation with iron sheet roof

ID	Description*	Criterion 1 (%)	Criterion 2 (Daily degree-hours over 6)	Criterion 3 (ΔT over 4 K)
7 NV	B wall, 1 W	12.39%	123	14
8 NV	HC wall, 1 W	18.58%	232	159
9 NV	B wall, 2 W	11.63%	109	13
10 NV	HC wall, 2 W	17.39%	210	118

11 NV	B wall, 2 W & RV	9.93%	79	8
12 NV	HC wall, 2 W & RV	15.80%	188	74

* B: Brick; HC: Hollow Concrete; W: Window; RV: Roof Vent

Category B: Natural ventilation in buildings with insulated iron sheet roof

Thermal comfort conditions significantly improved for insulated roof (Table 6 and 7). Indeed, insulated roof alone has been much more effective than ventilation strategies. Unlike Category A, all buildings with brick walls, regardless of ventilation strategy and geometry, passed thermal comfort requirements (IDs 13, 15, 17, 19, 21 and 23 SV/NV). However, although significant, improvements have not been enough for any of the buildings with hollow concrete walls to pass the requirements.

Table 6. Thermal comfort criteria for continuous daytime ventilation with insulated iron sheet roof

ID	Description*	Criterion 1 (%)	Criterion 2 (Daily degree-hours over 6)	Criterion 3 (ΔT over 4 K)
13 SV	B wall, 1 W	0.86%	4	0
14 SV	HC wall, 1 W	4.65%	25	0
15 SV	B wall, 2 W	1.13%	8	0
16 SV	HC wall, 2 W	4.60%	25	0
17 SV	B wall, 2 W & RV	1.08%	7	0
18 SV	HC wall, 2 W & RV	4.46%	25	1

* B: Brick; HC: Hollow Concrete; W: Window; RV: Roof Vent

Table 7. Thermal comfort criteria for continuous daytime and night ventilation with insulated iron sheet roof

ID	Description*	Criterion 1 (%)	Criterion 2 (Daily degree-hours over 6)	Criterion 3 (ΔT over 4 K)
19 NV	B wall, 1 W	0.68%	3	0
20 NV	HC wall, 1 W	4.34%	24	0
21 NV	B wall, 2 W	0.86%	6	0
22 NV	HC wall, 2 W	4.22%	25	0
23 NV	B wall, 2 W & RV	0.95%	6	0
24 NV	HC wall, 2 W & RV	4.30%	25	0

* B: Brick; HC: Hollow Concrete; W: Window; RV: Roof Vent

Similar to Category A, night ventilation has overall improved the conditions. However, the results indicate that unlike category A, where cross and roof ventilations have improved the conditions, the situation for buildings with brick walls has slightly deteriorated for these scenarios compared to the base case (i.e. ID 13 SV and 19 NV). Indeed, the best performances have been achieved for single sided ventilation without a roof vent. A possible explanation for this is the increased level of solar heat gain due to increased number of openings which has deteriorated comfort conditions. Further investigation is required to study the effects of ventilation combined with shading strategies to assess whether thermal comfort conditions improve.

The results also indicate that, similar to Category A, buildings with brick walls have performed considerably better compared with hollow concrete walls. Overall, it could be argued that construction methods and materials have been more effective than ventilation strategies in improving indoor conditions. Therefore, improving construction methods/materials are arguably the first strategy that should be considered to improve thermal comfort conditions in low-income tropical housing.

4. Conclusions

This paper investigated the effects of natural ventilation strategies on thermal comfort in low-income housing in Uganda. According to the results of this study, although natural ventilation strategies improved the conditions, such improvements were enough to pass the assessment criteria set by CIBSE TM52 and BS EN 15251 standards. Natural ventilation should therefore be considered along with other strategies, such as solar shading, in order to further improve the conditions. In contrast, using appropriate construction methods/materials such as brick walls and insulated roof, significantly improved the comfort conditions. Yet, due to the extremely bad comfort conditions in houses covered with iron sheet, ventilation strategies seemed to be more effective in improving the conditions compared to insulated roofs. The best conditions were achieved when cross ventilation and night ventilation were considered together. More investigation is required to assess the effects of natural ventilation in conjunction with solar shading and refurbishment strategies in low-income housing.

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