Designing dwellings to cope with extreme heat in low-income communities

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1. Abstract

Designing effective passive cooling interventions for dwellings in low-income communities exposed to tropical climates is vital to ensure occupant health and comfort in a warming climate. More knowledge is needed, however, on which interventions would be culturally acceptable, affordable, and effective in reducing high indoor temperatures. Four experimental buildings were built in Ghana to evaluate such interventions. Their initial design was based on a typical home for low-income urban residents in northern Ghana. A multi-disciplinary team contributed to the design and the proposed cooling interventions. Using dynamic thermal simulation, engineers predicted indoor temperatures for different construction materials, shading, and ventilation strategies. Social scientists provided input on the cultural acceptability of the proposed designs. The study showed how simple interventions can achieve worthwhile reductions in indoor temperature. In future work, the dynamic thermal models will be calibrated using data collected inside the real experimental buildings.

Keywords - Extreme heat, overheating, tropical climate, thermal comfort, passive cooling.

2. Introduction

Extreme heat affects the health and wellbeing of millions of people worldwide (Zhao et al., 2021). High indoor temperatures that pose risks to human health have been recorded in informal settlements in the tropics (Wilby et al., 2021). Such communities in the tropical Global South are at particular risk because they are often overcrowded, have poor quality housing, a lack of cooling infrastructure, intermittent water and energy services, and high exposure to urban heat islands (Højgaard Borg et al., 2021; Kayaga et al., 2020; Matthews et al. 2019; Olotuah & Bobadoye, 2009; Scovronick et al., 2015; Wilby, 2007). The design of dwellings and cooling interventions to reduce indoor temperatures is, therefore, of vital importance. A proven cooling solution is air-conditioning. This technology is, however, costly to install, maintain, and operate. Furthermore, unreliable electricity supplies for 3.5 billion people globally means that reliance on air-conditioning for cooling puts people at risk when electricity supplies fail (Ayaburi et al., 2020; Darko et al., 2018). Therefore, passive cooling solutions, which require zero operational energy, and limited or no involvement of the occupants, should be implemented in the first instance.

The way new buildings are designed and the materials they are constructed from influences the indoor temperature. Similarly, retrofits to existing buildings also affect the indoor temperature. Wilby et al. (2021) have shown that roof type and the presence of ceiling insulation directly influence indoor temperature. High thermal mass walls have been shown to reduce peak daytime indoor temperature, although at the expense of higher nighttime temperatures (Amos-Abanyie et al., 2013; Hema et al., 2021; Roberts et al., 2023a; Wilby et al., 2021).

This study sought to develop passive, affordable, culturally acceptable, and locally available means of cooling dwellings and workplaces in Ghana. The work was organised in three phases: (1) dynamic thermal modelling of a common archetype building to allow for multiple cooling interventions to be rapidly and cost-effectively trialled in isolation and in combination; (2) construction of four experimental buildings with measurement of the indoor environment under different cooling retrofit strategies (Figure 1); (3) calibration of dynamic thermal models using measured data for prediction of indoor temperatures under climate change. This paper is a report of Phase 1 and the impact of alternative dwelling and intervention designs on indoor temperatures. This phase included] discussions with local communities to determine whether the proposed interventions would be culturally acceptable and affordable.

Figure 1: The four experimental buildings (test cells) in Tamale, Ghana. The nearest building has a ridge ventilator.

3. Methods

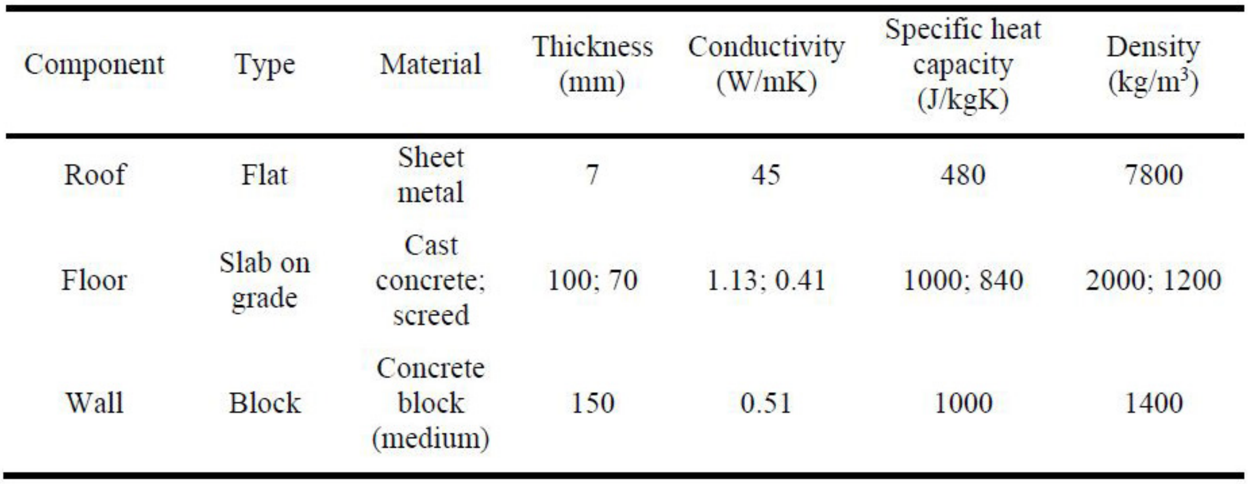
Indoor temperatures were simulated using the dynamic thermal modelling program EnergyPlus via the DesignBuilder graphical user interface. Dynamic thermal models allow for rapid and cost-effective exploration of the effect on indoor temperature when making multiple types and combinations of changes to the design of a new building prior to construction. They can also be used to evaluate retrofit design in existing buildings at an early stage of the process. This reduces the risk of implementing an ineffective retrofit design or construction of a new building which could otherwise harm occupant health and wellbeing. Dynamic thermal modelling also allows for direct comparison between different interventions under identical weather conditions and so the relative effect of each intervention on indoor temperatures can be assessed. A cautionary note to the use of dynamic thermal models is that they do not perfectly represent reality and the results may not be replicable if a different modeller attempts to model the same building due to various, necessary, assumptions and simplifications made during the model building process (Roberts et al., 2019). Models are therefore useful for investigating a large range of options at design stage and their relative effectiveness, but unless validated0F with measured temperatures, should not be relied upon to make accurate predictions of absolute temperature.

3.1 The base case model

The initial base case model design represented a typical urban dwelling in Tamale, Ghana and was given the code [R0]. This location was chosen as it was to be the site of the construction of the real experimental buildings. The base case model geometry was informed by a survey of 47 dwellings in Ghana to derive the mean average floor area and ceiling height (Wilby et al., 2021). The base case model1F had a single storey, with a mono-pitch flat steel

sheet metal roof, concrete block walls, concrete floor (Table 1), no windows, and no heat gains from occupants or appliances. The exterior east-west wall was 4 m in length and the exterior north-south wall was 3 m (i.e., the longest façades faced south/north). Accounting for wall thickness, the floor area was 10.6 m2. The wall height was 3.5 m with no overhang. There were no internal partitions. The infiltration rate was set to 1 ach as there is a lack of relevant measured data. It can be assumed, however, that temperature-driven air changes will be relatively low given that the indoor-outdoor temperature differential in Tamale is generally less than circa 10°C (Wilby et al., 2021) and it has been shown that under these conditions infiltration rates can be low (Roberts et al., 2023b).

Table 1: Base case model components



Component	Type	Material	Thickness (mm)	Conductivity (W/mK)	Specific heat capacity (J/kgK)	Density (kg/m^3)
Roof	Flat	Sheet metal	7	45	480	7800
Floor	Slab on grade	Cast concrete; screed	100; 70	1.13; 0.41	1000; 840	2000; 1200
Wall	Block	Concrete block (medium)	150	0.51	1000	1400

3.2 Weather data

Typical Meteorological Year (TMY) weather data for Tamale were sourced from "Climate.OneBuilding.Org" (Lawrie & Crawley, 2022). This comprised hourly data that covered a full year which allowed for annual simulations of indoor temperature. This was chosen over other sources which did not contain data for ground temperature.

3.3 Interventions

Forty-nine (49) different model variants were created using the base case model. Each were given a code, e.g., [R1], [R2], etc. Changes were made to the wall material, wall thickness, roof material, roof pitch, roof type (monopitch vs. dual-pitch), roof reflectivity, roof overhang, infiltration rate, ventilation schedule, ceiling height, ceiling type (and presence), ceiling material properties, roof ventilation rate, and roof structure. The 49 model variants comprised a single change to the base case model or a combination of changes. Most commonly one intervention at a time was tested, e.g., changing the wall thickness. However, sometimes this was combined with another intervention, e.g., changing wall material type and material thickness, which still allowed the effect of other individual interventions to be studied.

3.4 Data analysis

Comparison of the zone average hourly temperatures produced by the simulations for dry bulb, radiant, and operative temperature revealed negligible differences, and so only dry bulb temperature data were analysed (hereafter referred to as, simply, "temperature"). Temperature against time plots are presented for the day with the highest maximum outdoor temperature. Mean (Tm) and maximum (Tx) indoor temperatures were compared for each of the 49 model variants using the base case model as the benchmark. Thus, the potential cooling efficacy of each intervention was assessed relative to the base case comparator.

4. Results

4.1 Absolute temperatures and heat stress

The annual simulations of indoor temperature in the base case model [R0] predicted a mean indoor temperature of 30.4°C and a maximum temperature of 44.0°C. Some, but not all, model variants reduced the mean and/or maximum indoor temperature compared to the base case model (Figure 1 – where a negative number indicates cooler than the base case model and a positive number warmer than the base case model).

Amongst all the models, the highest annual mean temperature was recorded in a dwelling with sandcrete walls [R5] and was 31.0°C. The highest annual maximum temperature was recorded in a dwelling with wooden walls [R6] and was 52.4°C. The most effective intervention for cooling was a ventilated (open) roof with an insulated ceiling [R61] (Figure 51), which reduced the annual mean temperature to 28.3°C and the maximum temperature to 36.5°C. At the point in time when the predicted indoor temperature was 36.5°C, the outdoor relative humidity was 25%. Assuming the indoor relative humidity is also 25%, the wet bulb temperature would be 21.9°C, which falls below the threshold that threatens human survival (which is around 35.0°C (Lu and Romps, 2023)). This compares to a maximum wet bulb temperature of 28.6°C in the base case model [R0], which is 20% higher than in [R61], yet still below the lethal threshold.

4.2 Comparing model variants to the base case model

Walls constructed from a lower thermal mass material and at 10% of the thickness of the base case wall2F (wood [R6]) had a higher mean and maximum temperature than one with high thermal mass (concrete [R0]) (Figure 1 and Figure 3). The mean temperature, however, was very similar with the wooden and concrete wall because although the daytime temperature was higher in the wooden wall dwelling, the nighttime temperature was lower as the lower heat capacity of the 15 mm wooden walls [R6] allowed for more rapid cooling as the outdoor temperature fell at night (by up to 4.8°C cooler than the base case model).

Roofs made of straw thatch [R13] were effective at reducing mean and maximum temperatures compared to metal [R0] (Figure 1 and Figure 4), but these are increasingly being replaced with sheet metal roofs in Ghana. Insulated roof panels, e.g., polyisocyanate foam adhered to corrugated steel ([R15]: 0.05 m of foam and [R16]: 0.1 m foam) similarly reduced both mean and maximum indoor temperatures respectively ([R15], -1.7 and -7.1°C and [R16], -1.8 and -7.2°C). Alongside being lower, the time of the maximum (peak) temperature was shifted to later in the day with the other roofs tested, compared to metal (Figure 4). Roofs that are lighter in colour may absorb less solar radiation (providing they are clean and well maintained). Changing the roof solar absorption at increments of 0.2 between 0.0 and 1.0 [R30-R35] showed that the mean temperature could range from 2°C less than the base case model (solar absorption 0.0, [R30]) to 0.1°C higher (the base case solar absorption being 0.6 on a flat roof). Similarly, the maximum temperature difference ranged from -4.3°C to 0.6°C from the lowest to highest solar absorption – a 4.9°C range (Figure 2).

Alongside the roof, ceiling presence and material properties were also influential. Installing a plywood ceiling with a thermal conductivity ranging from 1 W/mK [R52] to 0.001 W/mK [R55], reduced the maximum temperature by between 1 and 4°C, with the lowest conductivity ceiling [R55] yielding the greatest reduction. Overall, the most effective intervention of all those investigated to reduce maximum temperature (excluding the unrealistic measures of total solar shading [R22] and no solar radiation [R36]) was ventilating the roof structure with a 2.5 m overhang above an insulated ceiling [R61]. This reduced the maximum indoor temperature by 7.5°C compared to the base case model [R0], and mean indoor temperature by 1.8°C.

To investigate the theoretical limit for the possible effectiveness of shading, one model variant was constructed with an adiabatic material suspended above the building which blocked all solar radiation falling on the building and immediate surrounding area. This endeavour yielded a maximum indoor temperature reduction of 8.4°C [R22]. Removing solar radiation from the weather file reduced the maximum indoor temperature by 10.4°C [R36] – these are the upper bound temperature reductions in maximum temperature. Set against the theoretical limit of temperature reduction in model variants [R22] and [R36], the mean and maximum temperature reductions achieved by a ventilated (open) roof structure and insulated ceiling [R61] are worthy of further investigation in the real experimental buildings.

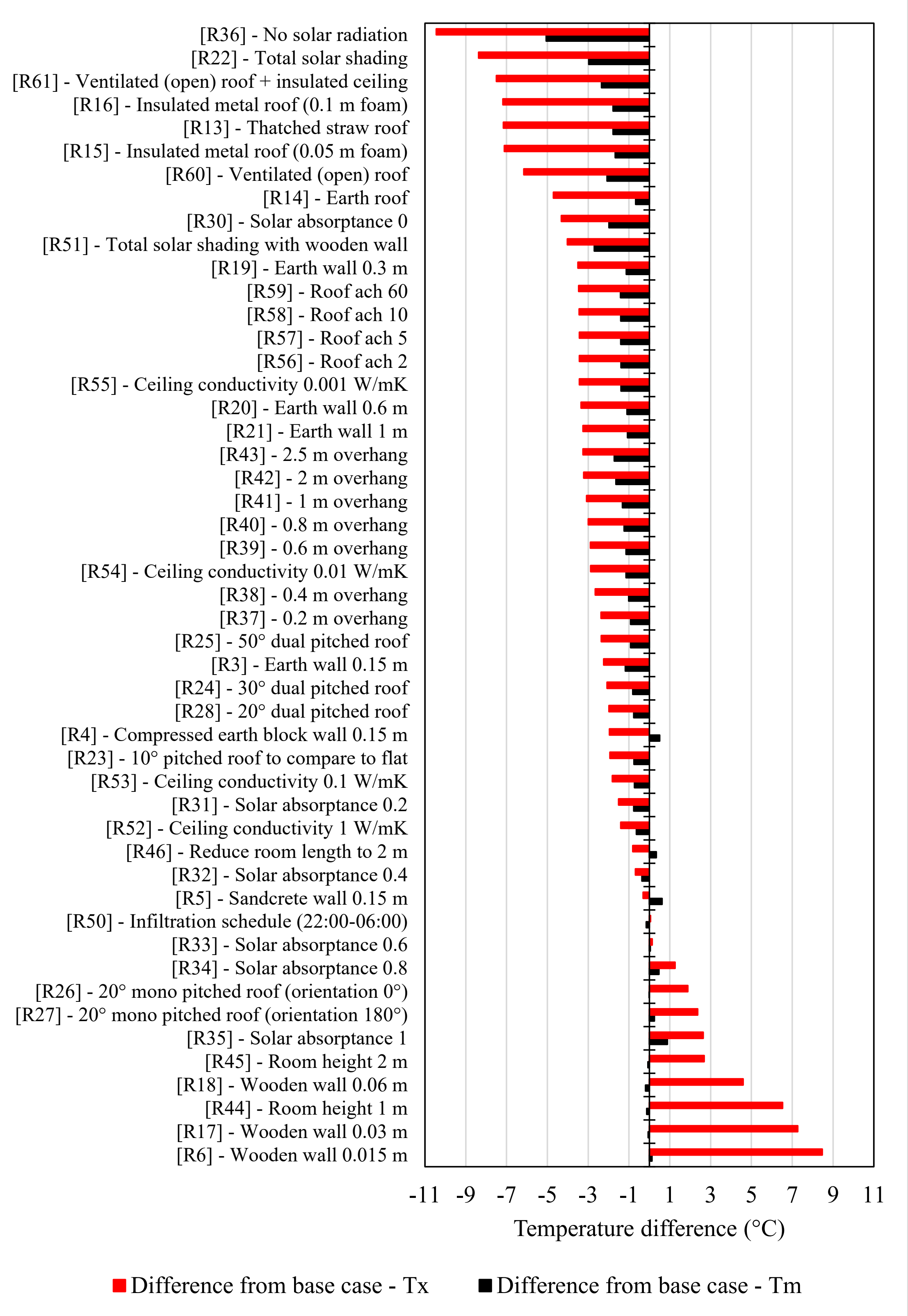


Figure 2: Comparing maximum (Tx) and mean (Tm) temperature difference relative to the base case model.

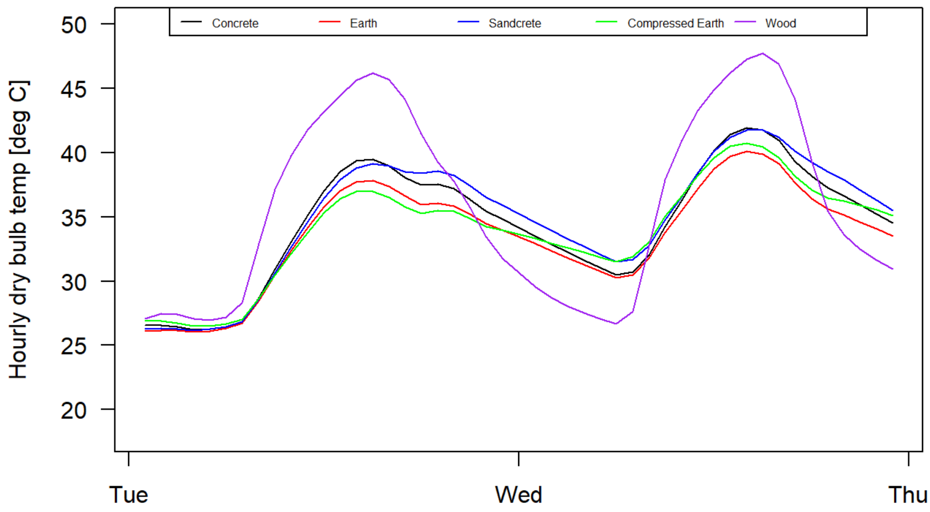


Figure 3: Diurnal indoor dry bulb temperature for model variants with different wall types on the day with the highest maximum outdoor temperature.

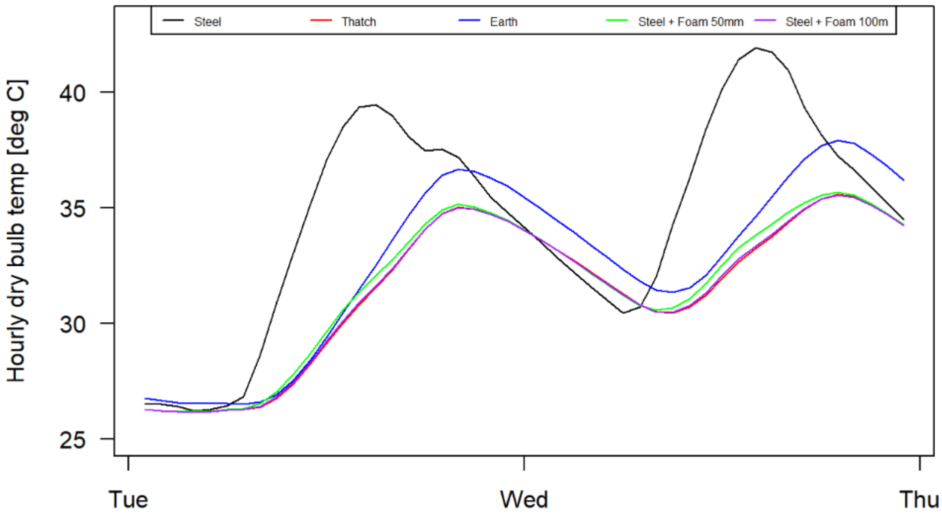


Figure 4: Diurnal indoor dry bulb temperature for model variants with different roof types on the day with the highest maximum outdoor temperature.

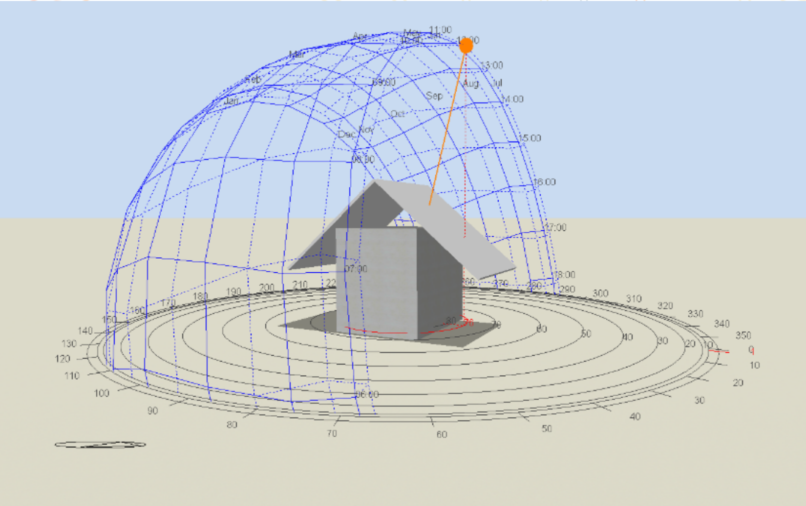


Figure 5: Variant R61 with a ventilated (open) roof structure with a large (2.5 m) overhang and an insulated ceiling.

5. Discussion

Dynamic thermal modelling of an archetype dwelling found in Tamale, Ghana revealed that to reduce the maximum indoor temperature – i.e., protect the building occupants from the most severe occurrence of extreme heat – the most effective passive cooling intervention was constructing a ventilated (open) roof structure with a large overhang, combined with an insulated ceiling below (annual maximum temperature 7.5°C lower). Walls of low thermal mass, e.g., wood, increased the maximum temperature by 8.5°C, but these dwellings are cooler at night (by up to 4.8°C compared to the base case model with concrete walls). A simple recommendation to reduce peak temperatures is to avoid a dwelling of low thermal mass construction. For a dwelling that is occupied only at night, however, dwellings with less thermal mass may cool more rapidly at night when the outdoor temperature decreases and so may be preferential. These findings are in general agreement with empirical studies (Hema et al., 2021; Roberts et al., 2023a; Wilby et al., 2021) and give confidence in the model results. In contrast with other research (e.g., Ali-Obaidi et al., 2014), decreasing the solar absorptance of the roof material was effective, but by no means the most effective cooling intervention. Overhangs to shade the walls, for example, were a more effective cooling intervention and these might be easier to maintain than light coloured roofs which require frequent cleaning and/or re-painting.

The fact that a passive cooling intervention based on ventilation3F was the single most effective option for reducing indoor temperature is important. Previous studies in the tropics have focused on the properties of building construction materials (Hashemi, 2017; Hema et al., 2021; Roberts et al., 2023a), whereas this research brings a renewed focus on the importance of ventilation for cooling. Incorporating higher rates of natural ventilation into dwellings in informal settlements might be one of the cheapest and simplest interventions to retrofit. For instance, opening roof spaces involves the removal of materials and will only require small amounts of mosquito mesh to be purchased and affixed. A ventilation intervention may, therefore, be more likely to be implemented in the communities. Although, there remains the issue of dust ingress which is a concern to those living in these communities and may be exacerbated by greater ventilation rates. Innovative ventilation solutions which reduce mosquito and dust ingress, whilst providing security from burglar entry must be sought.

Contrast ventilation with another effective cooling method: installing insulated roof panels [R15 and R16]. Foam adhered to corrugated steel may not be a locally available or affordable intervention. The longevity of foams exposed to extreme heat is also a concern as is their resistance to fire. Nonetheless, cost permitting, this may be more acceptable than thatched roofs [R13] which, whilst comparable to foam insulation in terms of the ability to reduce indoor temperature, is increasingly difficult to source in northern Ghana. Thatch is also disliked due to the risk of fire and harbouring insects and reptiles, and is viewed as being old-fashioned (Gough et al. 2019).
At present, the dynamic thermal model simulations described herein are unvalidated. This is a key limitation of the work and means that the predictions of indoor temperature should be taken with caution given the uncertainty present with dynamic thermal models and their operators (Judkoff et al., 2008; Roberts et al., 2019). To overcome this limitation, four experimental buildings have been constructed in Tamale, Ghana (Figure 1). Their design and choice of passive cooling interventions were informed by the simulations presented here. Future work will measure the indoor environment and use these data to validate the above dynamic thermal modelling results.
A second limitation of this work is the focus on dry bulb temperature which neglects air movement and relative humidity – both of which are important modifiers of thermal comfort. Future instrumentation and measurement in the experimental buildings should consider these factors alongside subjective human thermal comfort preferences.

6. Conclusion

The effectiveness of passive cooling interventions to reduce indoor temperatures were investigated using dynamic thermal modelling of a typical dwelling located in Tamale, Ghana. The key findings are:

1. A ventilated (open) roof structure with large overhang above an insulated ceiling [R61] was the most effective realistic intervention for cooling the dwellings when considering both mean and maximum temperature reduction. The mean and maximum temperatures were reduced by 1.8°C and 7.5°C respectively relative to the base case model [R0].

2. A thin (0.015 m) wooden wall [R6] resulted in the greatest increase in maximum (peak) temperature by 8.5°C compared to the 0.15 m medium density concrete block used in the base case model. But lower nighttime temperatures in rooms with less thermal mass make these suitable places to occupy at night. E.g., [R6] was up to 4.8°C cooler than [R0].

3. Reducing roof solar absorptance was effective at reducing indoor temperatures ([R30] Tx 4.3°C cooler than R0), but other interventions such as installing a plywood ceiling ([R53] Tx -1.8°C), earth roof ([R14] Tx -4.7°C), overhangs (even relatively short 0.2 m [R37] Tx -2.4°C), earth wall ([R3] Tx -2.2°C), thatch roof ([R13] Tx -7.2°C), insulated roof ([R16] Tx -7.2°C), and ventilated roof with overhang ([R60] Tx 6.2°C), and a ventilated roof with overhang and an insulated ceiling ([R61] Tx -7.5°C) were all more effective cooling interventions.

This work has informed the design of four experimental buildings (test cells) that were constructed in Tamale, Ghana. Future work will test cooling interventions, measure the indoor temperatures, and use these data to validate dynamic thermal models. In due course, these verified models can be used to investigate the efficacy of different interventions – whether in isolation or combination – under plausible climate change projections.

7. Acknowledgements

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