A matched pair of test houses with synthetic occupants to investigate summertime overheating

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Abstract

Summertime overheating is increasingly prevalent in both new and existing UK dwellings. High internal temperatures can be dangerous to vulnerable occupants, disrupt sleep and cause thermal discomfort. The mitigation or exacerbation of overheating through simple occupant interventions like window opening and blind use needs better understanding if homes are to be comfortable and safe in summer without the use of air conditioning.

This paper describes the adaptation of two adjoining, semi-detached houses to create a matched pair of test houses for full-scale, side-by-side summertime overheating experiments under real weather conditions. Synthetic occupancy was installed to allow dynamic remote control of actuated windows, motorised curtains, automated internal doors and internal heat gains. The houses were instrumented with calibrated sensors to measure the internal and external environment. These instrumented, matched pair homes have also been used to accurately quantify the effects on energy demand, internal temperatures and air quality of refurbishment strategies, occupant behaviour, and different heating, cooling and ventilation technologies.

Keywords

Overheating; test houses; experiments; synthetic occupancy; measurement.

1. Introduction

Summertime overheating of dwellings is a growing health problem in the UK, with reports of dwellings experiencing high internal temperatures in the present climate[1]. The risk of overheating may be getting worse due to a warming climate with increasingly extreme weather events such as heatwaves; higher levels of home insulation and airtightness that reduce the rate of heat loss generated by internal and solar heat gains; an increasingly urbanised population exposed to urban heat islands, with potentially fewer adaptive opportunities; a reluctance to ventilate by leaving windows open due to pollution, noise and security risk; and an ageing population less able to regulate their body temperature and more likely to be at home at high risk periods (mid-afternoon)[2].

High indoor temperatures are a concern for occupant health. Studies are more actively focusing on overheating in dwellings[1], [3], [4], [5], [6], [7], [8], [9], [10]. The bias is towards modelling studies, which are faster and cheaper than monitoring. Detailed monitoring is however needed to understand the effect of occupant behaviour on overheating and so to produce better models and validate existing ones. A study by Jones *et al*.[11], for example, calls for more monitoring work after observing that two similar homes had very different summertime temperatures, which was attributed to differing occupant behaviour. One method would be to compare two identical houses in the same location whilst occupant behaviour is changed in a measurable and repeatable way.

This paper describes how two adjoining semi-detached houses were adapted and modified into a fully instrumented matched pair test facility for studying the impact of occupant behaviour on indoor temperatures in summer. The houses, which had been used in a previous study[12], were refurbished in the same way and had automatic controls fitted to the windows, curtains, blinds, and internal doors with schedulable internal heat gains implemented in each room. Tests ensured the heat loss and airtightness of the houses was similar. Experiments using the test houses were conducted in summer 2017 and the results will be presented in a future paper.

2. Test houses

2.1 Built form, layout and construction

The test houses comprise a matched pair of two adjoining unoccupied semi-detached two-storey houses (Figure 1 and Figure 2), with a mirrored floor plan (Figure 3). They are naturally ventilated (free running) with no mechanical ventilation. Window sizes and opening areas are identical in each house. Each house has three bedrooms, (UK mean 2.8[13]), a total floor area of 85.4 m^2, (UK mean 94 m^2)[13], and a total volume of 209.2 m^3. Semi-detached homes are the most prevalent housing type in the UK[13]. In common with 16.7% of the UK housing stock[13], the test houses were built in the 1930s in a manner typical of the era, with uninsulated brick cavity walls and uninsulated suspended timber floors ventilated below by air bricks, both elements verified via borescope examination (see Table 1, next page, for assumed U-values).

Figure 1. Loughborough matched pair test houses viewed from the front.

Figure 2. Loughborough matched pair test houses viewed from the rear.

The houses are well matched, having been maintained in the same way by Loughborough University for many years and simultaneously upgraded during the summer of 2016 with 300 mm of loft insulation and double-glazed windows and doors (Table 1). For full details of all the refurbishments' works see Roberts *et al.*[14]. The test houses compare to the UK housing stock where nationally 30.5% have uninsulated cavity walls, 38.5% similar levels of loft insulation and 80.8% are fully double glazed[13].

The houses are in a suburban residential area of Loughborough, UK (52.771071° N, 1.224264° W). The front of the dwellings face south-southeast (160°) towards a front garden and a road, the rear of the properties faces north to a large back garden. There are neighbouring houses of similar roof heights to the east and west.

Each house is entered on the south side into an entrance hallway with stairs leading to the upper floor; a kitchen to the north; with a separate dining room and living room against the party wall to the north and south of the house respectively. The living rooms feature a

Table 1 – Summary of construction elements, areas and estimated U-values from SAP[15] and calculated U-values from glazing and insulation manufacturer.

Building element	Description	U-value (W/m²K)	Area (m²)
Roof	300 mm fibreglass, pitched with clay tiles over vapour-permeable membrane	0.16	45.6[a]
External walls[b]	Uninsulated brick cavity	1.6	89.2
Internal partition walls	Solid brick covered with gypsum plaster	2.1	53.9
Party wall	Uninsulated brick cavity covered with gypsum plaster	0.5	42.2
Ground floor (except kitchen)	Suspended timber (uninsulated)	0.8	37.6
Ground floors (kitchen)	Solid concrete (uninsulated)	0.7	5.7
Windows (north and south)	uPVC double glazing	1.4	20.3[c]
Windows covered (east and west)	uPVC double glazing with aluminium foil on glazing and 50 mm PIR foil-backed insulation board inserted into the frame.	0.46	2.7[c]
External doors	uPVC with double glazing	1.4	5.5[c]
External door glazing covered (east and west)	uPVC double glazing with 50 mm PIR foil-backed insulation board over glazing only.	0.46	0.51

a. Horizontal area (not pitched) b. Measured at internal wall surface c. Total area including frames

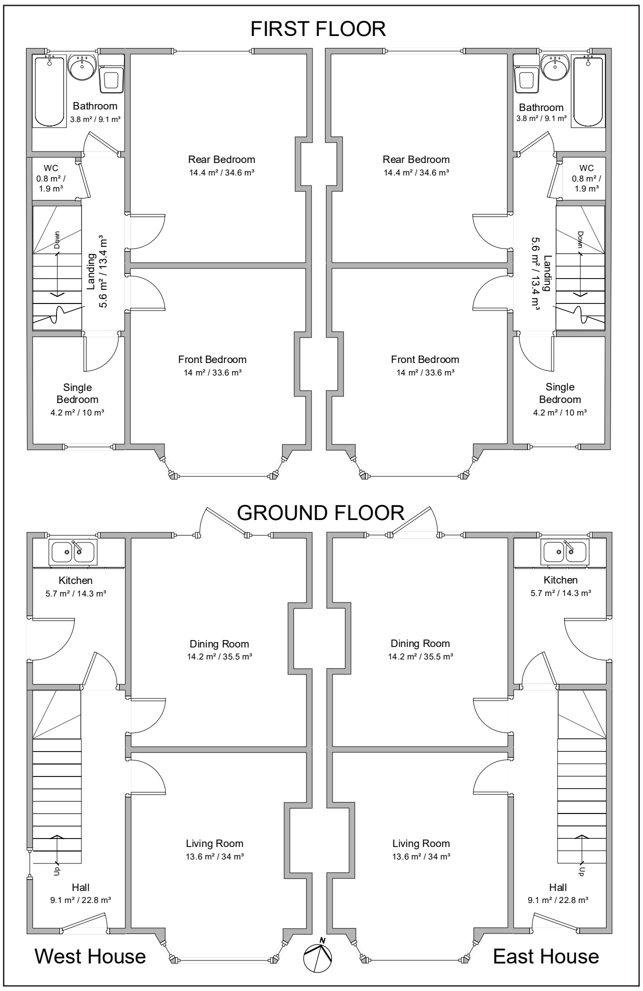

Figure 3. Floor plans of test houses.

Figure 4. Application of foil and insulation to landing windows to reduce east/west solar gain.

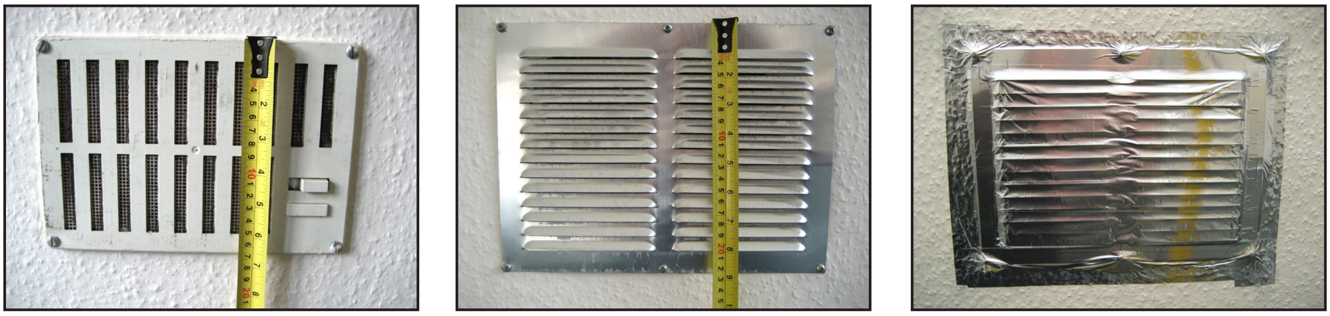

Figure 5. Fireplace vents sealed with aluminium tape to ensure uniformity between houses.

bay window and the dining rooms a glazed door to the garden. On the upper floor the rooms off the landing include a small WC and a separate bathroom on the north side. The three bedrooms comprise a small box-room to the south and two large bedrooms to the north and south over the dining and living rooms. The south-facing double bedroom also features a bay window (Figure 3).

The side-by-side adjoining houses will inevitably influence each other. One house will shade the other at points throughout the day. One house will shelter the other from the wind. There will be some heat transfer between the two houses via the party wall. However, the party wall is of cavity construction and unsealed at the top. This is likely to reduce the heat transfer between dwellings, while providing another heat loss path. In summer there is a small difference between the inside and outdoor air temperature. In the winter heating season there is usually a greater difference. During winter testing the party wall will be a greater source of heat loss than in summer.

2.2 Modifications for testing

Modifications were carried out to the houses to ensure that the thermal performance was the same. The primary concern was they would receive different solar gains through the side windows: east facing windows in one house and the west facing in the other. To limit this difference, aluminium foil was taped to the glass on the inside of each of the side windows and 50 mm polyisocyanurate insulation boards, with a low emissivity foil-facing, were taped across the entire opening (Figure 4). The U-value of the blocked windows is lower than the external walls (Table 1).

The chimney breasts in the living and dining rooms had been bricked up at some unspecified point in the past and fitted with vents. The vents differed in sizes between houses so were sealed using aluminium tape (Figure 5). Air vents in the external walls of the upstairs bedrooms were also sealed with aluminium tape. Sub-floor airbricks were left unblocked.

3. Comparing the thermal performance of the test houses

Thermal performance and airtightness testing was carried out to confirm that the two test houses were closely matched. A co-heating test was used to measure the heat transfer coefficient and a series of blower door tests to measure the airtightness. All performance tests were conducted after the double-glazed windows and doors, loft insulation and new roof had been installed and after the modification work of blocking east and west facing windows and chimney/room vents had been carried out.

3.1 Co-heating test

The co-heating test measures the heat transfer coefficient (HTC) of a building. The HTC has units of Watts per Kelvin (W/K) and combines transmission and ventilation heat loss[16]. Co-heating tests were conducted simultaneously in both houses from 7 December to 31 December 2016 (25 days) following the methodology set out by Johnston *et al*.[17]. Bauwens *et al*.[16] achieved satisfactory thermal characterisation results in two weeks, so 25 days was deemed sufficient.

During the test, the houses were heated to a constant 25°C air temperature using electric fan heaters in every room (Figure 6). The heaters were controlled using a thermostat located on a tripod in the volumetric centre of the room and shielded from solar radiation using thin foil-covered insulation. Floor-mounted fans ensured mixing and circulation of air in and between zones. Heaters faced away from walls to heat room air, not the building fabric. Fans faced away from external walls to avoid increasing the surface heat transfer coefficient[18]. Internal doors, blinds and curtains were fully open. External doors, windows and trickle vents remained shut throughout testing. No occupancy was simulated, and the gas central heating was turned off.

Figure 7. Qualitative air leakage testing using smoke sticks.

Figure 6. Co-heating equipment deployed in each room.

Table 2 – Results from co-heating tests

West house (W/K)	East house (W/K)	Difference
223	216	5.6%

Power measuring plugs (Figure 14, see p35) recorded electrical heat input from all electrical devices. U-type thermistors placed on shielded tripods measured indoor air temperature at one-minute intervals. Another shielded thermistor measured outdoor air temperature on the north side of the house. All thermistors were calibrated at five points using a water bath and calibrated thermometer. Global horizontal solar radiation data was sourced from Sutton Bonington Weather Station 5.38 km from the test houses[19]. Prior to the test starting the houses were pre-heated to 25°C using the electric heaters for three days to warm the thermal mass. During this pre-test phase, the thermostatic controllers were adjusted to achieve the same temperature in each room as recorded by calibrated thermistors.

Data was analysed using the Siviour linear regression method[18]. The results for the two houses (Table 2) were within the uncertainty of the co-heating test method of ±8-10%[18], [20]. This demonstrates that the houses are thermally matched.

3.2 Blower door test

Blower door airtightness testing was conducted by the same operator on 12 separate days between 4 January 2017 and 15 March 2017. A total of 34 tests were carried out in the west house and 16 in the east house. More tests were carried out in the west house due to research associated with Roberts *et al.*[14]. The airtightness was measured by fan depressurisation using a Model 3 Minneapolis blower door located in the rear door. This method was selected due to its speed and simplicity and was found to produce consistent results in a variety of weather conditions[14].

Table 3 – Mean q50 results from blower door tests

West house q50 ($m^3/h/m^2$ @ 50Pa)	East house q50 ($m^3/h/m^2$ @ 50Pa)	Difference
14.7	14.9	1.4%

Tests were carried out in accordance with the ATTMA protocol[21]: all external doors and windows were closed and internal doors propped open; water traps in sinks and baths were filled with water and wall vents and fireplace vents were sealed with aluminium tape; gas central heating was turned off during testing; trickle vents were closed.

The tests showed that the houses have similar airtightness with only 1.4% difference (Table 3). The mean q50 value of 34 tests in the west house was 14.7 $m^3/h/m^2$ with a standard deviation of 0.26 $m^3/h/m^2$ and a standard error of 0.05 $m^3/h/m^2$. The mean q50 value for 16 tests in the east house was 14.9 $m^3/h/m^2$ with a standard deviation of 0.4 $m^3/h/m^2$ and a standard error of 0.09 $m^3/h/m^2$. The higher standard error in the east house is due to the smaller sample size. The repeatability of these blower door tests is discussed in Roberts *et al.*[14].

At points during testing smoke sticks were used to identify air leakage paths. The leakage paths in both houses were similar: under window ledges, through gaps in skirting boards, around plumbing and electricity services, at the edge of the suspended timber floor, and into the loft hatch (Figure 7). The windows were well sealed but there was some leakage through closed trickle vents.

4. Synthetic occupancy

To replicate real people, synthetic occupancy was installed in both houses to control window opening, blind and curtain use, internal door opening and internal heat gains. A wireless smart home controller (Figure 8) was used to set time schedules for each device or to respond to triggers, such as temperature thresholds.

Synthetic occupancy provides the ability to define precise behaviours that are performed at specific times: producing heat from metabolic processes and using appliances; and opening and closing doors, windows, curtains and blinds. Synthetic occupants can do these things with far less variability than real occupants, which has both positive and negative implications for research. There is a high degree

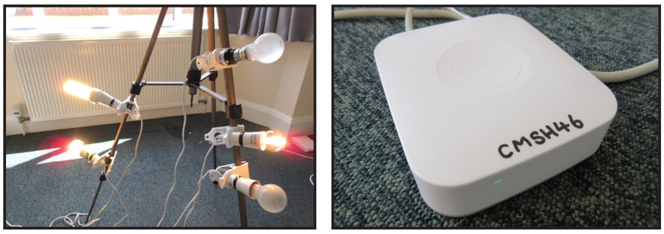

Figure 8. Left – Lightbulbs connected to smart plugs. Right – smart home controller used to control all synthetic occupancy devices in the test houses.

of certainty that the behaviours are being performed at specific times, but synthetic occupants can never truly represent the inherent psychological, sociological, cultural and irrational drivers of human behaviour.

Internal heat gains, to represent people and appliances, were generated using electric lightbulbs connected to smart plugs (Figure 8). Lightbulbs were sized to produce specific heat gains in each location and were the same in both houses.

Chain actuators were installed to open and close windows. For security reasons, and to prevent rain ingress, only top-hung windows were actuated (Figure 9). Larger side-hung windows may provide greater ventilation rates, but people may be reluctant to use them for security reasons and their use was not practical in unoccupied test houses, which are unattended for long periods. All rooms had at least one actuated window. Every actuated window was controlled independently, with signals from the smart home controller via a dedicated wireless receiver (Figure 10).

Window opening can respond reactively to temperature and occupancy stimuli or statically to fixed schedules independent of temperature. For reactive window opening, windows opened when specific air temperature thresholds were exceeded, and the room was deemed to be occupied. Windows closed when the temperature fell below a specified value or the room became unoccupied. Internal temperature data was transmitted to the smart home controller from room-specific sensors placed in the centre of each room on the tripod under a radiation shield (Figure 10).

A window control program was written using "Apache Groovy" programming language which used conditional statements to perform window opening actions based on true or false conditions. Namely "if" the room indoor air temperature exceeded a set value and the room was scheduled to be occupied "then" a window open signal was sent by the controller to open the window in that room, "else"

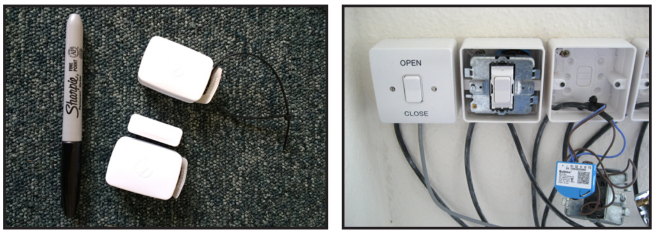

Figure 10. Left – wireless temperature sensor which relayed room air temperature data to the controller. Right – wireless receiver embedded behind each window switch which controlled window opening.

Figure 11. Automated curtains and blinds used in the test houses.

a close signal was sent. For windows to open both temperature and occupancy requirements must be satisfied (above threshold and occupied). However, windows closed if either the room temperature fell below the set threshold or the room became occupied. Occupancy schedules were inputted into the control program along with window open temperature thresholds.

Curtains were controlled via motorised toothed-rails and blinds via a motorised roller. Curtains with a curved rail were used in the living room and front bedroom to fit the bay window. Curtains on a straight rail were used in the dining room, front single bedroom and rear bedroom. Roller blinds were used in the kitchen and bathroom (Figure 11). Each window covering was connected to a wireless receiver and programmed to open or close based on time of day via the smart home controller.

Chain actuators were used on internal doors, controlled by a wireless receiver connected to the smart controller (Figure 12). Spring closers were used on each door along with a flexible connection between

Figure 9. Windows controlled by chain actuators.

Figure 12. Internal doors controlled by a chain actuator.

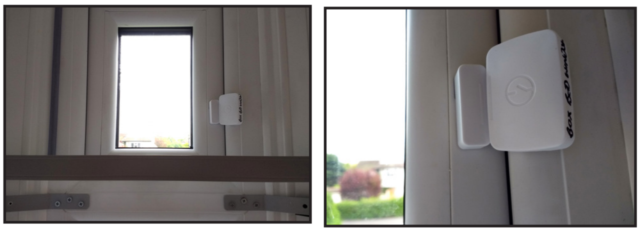

Figure 13. Contact sensor recording window opening.

Figure 14. Electricity meter logger plug.

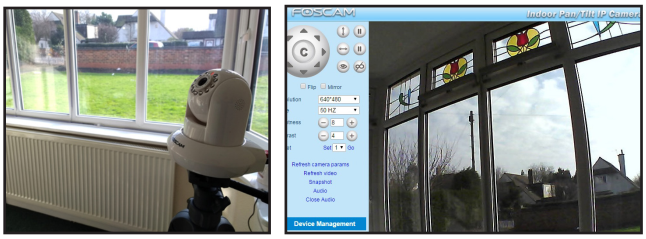

Figure 15. Internet connected camera and camera output.

the chain and the door. This was so that doors could always be opened, even when actuated closed, preventing trapping.

It was important to continuously monitor the performance of the synthetic occupancy devices to ensure that what was programmed to happen, did happen. Synthetic occupancy monitoring devices were chosen to be accessed remotely so as not to disrupt the tests. Contact sensors were placed on all opening windows with open/close status recorded to a cloud storage database whenever a change in state occurred (Figure 13). Metering plugs measured the electricity consumed by every internal heat gain and allowed detection of failed heat emitters (Figure 14). Internet connected cameras, with pan and tilt control, were used to remotely view the rooms and check for correct internal door and curtain operation (Figure 15).

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5. Monitoring temperatures, comfort and weather

Internal dry bulb air temperature was measured at one-minute intervals using U-type thermistors (±0.2°C) wired into a datalogger, calibrated using a temperature-controlled water bath and calibrated thermometer. The thermistor was hung on a tripod at a height of 1.1 m and protected from incoming solar radiation using a shield made of foil-backed bubble-wrap held in a cylinder with aluminium tape (Figure 16). Care was taken to avoid the thermistor touching the tripod or radiation shield. One thermistor was placed on a tripod in the centre of every room, including the hall. In the living room and double bedrooms, in addition to the central thermistor, three shielded U-type thermistors were placed at 0.1 m, 0.6 m and 1.1 m (Figure 17) in the assumed position of a seating area or bed.

Operative temperature was measured in every room at one-minute intervals using a 40 mm black globe[22], [23] attached to a calibrated U-type thermistor wired into a datalogger. In the living room and large bedrooms, black globes were mounted at 0.6 m from the floor

Figure 16. Left – shielded tripod covering wired U-type thermistor. Middle – 40 mm black globe on a U-type thermistor taped to a tripod. Right – battery powered T-type thermocouple.

in the assumed position of a seating area or bed. In all other rooms the black globes were placed centrally in the room at 1.1 m from the floor, attached to a different tripod than used for the air temperature measurements, to avoid obstruction from the radiant shield (Figure 16). Care was taken to avoid direct sunlight falling on the black globe. Additional battery-powered T-type thermocouple loggers with 40 mm black globes (±0.2°C) (Figure 16) were positioned on each tripod as a backup should wired thermistors fail.

In the living room of each house, operative temperature data were collected at thermal comfort stations sited at the assumed position of a seating area. Thermal comfort stations comprised measurements of dry bulb temperature, omni-directional air velocity and direction at three heights (0.1, 0.6 and 1.1 m from floor), and a direct measurement of operative temperature using a grey ellipsoid probe (±0.2°C) (Figure 17: Left). The operative probe was angled 30° from vertical at 0.6 m from the floor to represent a seated person (Figure 17: Right). Thermal comfort station sensors logged at ten-minute intervals to allow adequate sensor response time.

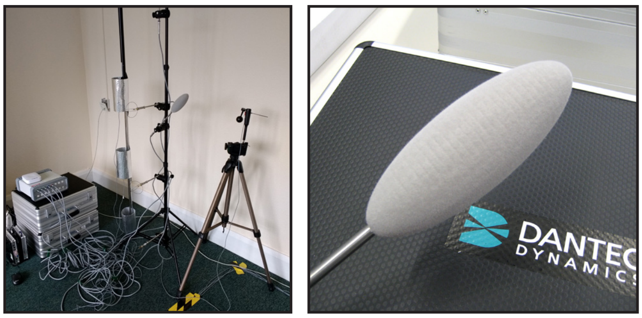

Figure 17. Left – thermal comfort station. Right – Ellipsoidal operative probe.

Figure 19. Naturally-aspirated radiation shield for external air temperature monitoring.

The ellipsoidal operative probes were calibrated in a climate chamber which itself had been calibrated (Figure 18). A U-type thermistor, calibrated in a water bath against a calibrated thermometer, was placed inside the climate chamber as a secondary comparison to ensure the chamber was at the correct temperature.

External dry-bulb air temperature was measured using a calibrated U-type thermistor connected to the indoor data logger. The external thermistor was shielded by a naturally-aspirated radiation shield. One external thermistor was used per house, as a precaution should one fail. Wind speed and direction was sourced from the University weather station, 1km from the test houses. The same weather station also provided global horizontal solar radiation data. There may be small differences between the weather at the test houses and weather station due to the differing topography and sheltering or canyoning effects of surrounding buildings and trees.

Figure 18. Calibrating operative probes in a climate chamber using a previously calibrated U-type thermistor.

6. Proposed experimental programme

The houses will be used to investigate the mitigation of summertime overheating through various interventions such as dynamic ventilation in response to specific indoor temperatures, night ventilation and the use of internal blinds. The experimental programme will comprise side-by-side paired tests with different occupant behaviours enacted in each house. This gives the ability to make direct comparisons between two sets of behaviours and analyse their effects on internal temperature, thermal comfort and compliance with overheating criteria. The data gathered will help build better, more accurate models of overheating risk in UK homes and provide a better understanding of the effect of occupant behaviour on internal temperatures during heatwaves.

This unique facility can be used to directly compare the impact of occupant behaviours, fabric upgrades, heating/cooling systems and their controls in any season. It is being used in a wide range of research projects.

7. Conclusion

Summertime overheating in UK dwellings is a growing problem. The effect of occupant behaviour on overheating is expected to be significant, yet is poorly understood. This paper has described a synthetically-occupied, matched pair of test houses prepared for conducting a range of overheating experiments under UK summer weather conditions. They have the same construction, having been built at the same time and renovated in tandem since then. The houses were modified and tested to ensure that they were matched in their thermal performance. They were also modified to minimise the effect of unequal solar gains.

The co-heating test showed a 5.6% difference in heat transfer coefficients between houses. Blower door tests demonstrated similar airtightness (1.4% difference) and qualitative smoke-stick analysis identified similar air leakage paths. A range of devices were installed to replicate the behaviour of human occupants and sensors were installed to measure the internal and external conditions. This test facility provides the opportunity to enact different occupant behaviours in nominally identical houses and directly compare the differences in internal temperatures and thermal comfort under the same weather conditions.

Future planned work will identify how occupants can reduce overheating risk. These matched pair homes can be used to accurately quantify the effects on energy demand, internal temperatures and air quality of different occupant behaviours, heating, cooling and ventilation technologies.

Note: This paper is based on Roberts et al.[24] *to which additions and amendments were made following peer review for this journal.*

Acknowledgements

This research was made possible by Engineering and Physical Sciences Research Council (EPSRC) support for the London-Loughborough Centre for Doctoral Research in Energy Demand (grant EP/L01517X/1). Loughborough University is acknowledged for funding the continued maintenance of the test houses and providing 24-hour security.

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