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Evaluation of indoor environment in super-insulated naturally ventilated housing in the south of the United Kingdom.

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Abstract

Improved energy performance standards are resulting in better insulated and more airtight building. In such buildings ventilation can be provided by natural ventilation and decentralised mechanical systems or with whole-house mechanical ventilation with or without heat recovery. Whole-house mechanical ventilation systems are associated with operational energy use, embodied energy and maintenance. Conversely, natural ventilation systems that provide insufficient fresh air are thought to potentially compromise indoor air quality and may be associated with overheating in summer.

This paper reports on a study funded by the NHBC Foundation of the indoor environment of eight super-insulated naturally ventilated homes in the south of the UK. One year of monitoring temperature, relative humidity, CO_2, CO, NO_2, CH_2O and TVOC was undertaken. In addition a building survey was undertaken and the occupants were interviewed in relation to their perceived comfort levels. The buildings are currently being modelled to simulate changes in occupancy, airtightness and ventilation and construction.

Initial monitoring results suggest good air quality and comfortable internal environments can be achieved with natural ventilation. No correlation was found between CO_2 and TVOC levels. Building occupants were shown to effectively control their environment and in certain cases were instrumental in maintaining comfortable internal temperature.

Keywords: Indoor air quality, thermal comfort, decentralised ventilation

1 Introduction

The quality of the indoor environment of buildings is critical for the wellbeing of its occupants and research suggests it can impact on health and productivity as well as mood and other psychological characteristics (Alker, 2014; Fisk and Rosenfel, 1997; Fisk et al, 2012; Park JS. and Yoon CH., 2011; WHO, 2010; Clancy, 2011). The indoor environment can be characterised by a number of different variables including:

- indoor thermal comfort, which is affected by temperature, relative humidity, air movement, as well as the personal aspects such as activity, clothing and physical characteristics;
- indoor air quality, which is affected by sources of pollution and dilution of pollution;
- quantity and quality of daylight and light, which is affected by the design and configuration of openings in the building and internal finishes and spatial design as well as specification and design of auxiliary lighting;
- acoustic environment, which is affected by building fabric and spatial design;
- the relationship to vegetation, including internally and externally;

- usability of space, including such considerations as accessibility, practical use, and privacy; and
- quality of environment in terms of aesthetics, identity and other psychological aspects associated with buildings and occupants.

The interaction between these characteristics is complex and occupants may not necessarily be aware of what is impacting on their feeling of wellbeing or lack of it. Links have been made between these building characteristics and the occupants' wellbeing and a number of good practice design and development guides focusing on the above list of building characteristics are beginning to be implemented (Delos Living LLC, 2015; Alker, 2014). However, this field still lacks evidence for clear causal relationships between approaches to building design and health of occupants (Ucci, 2016). This research aims to contribute to this field of research by investigating two interrelated indoor environment characteristics namely: indoor air quality and thermal comfort in highly insulated buildings with decentralised ventilation.

The focus on highly insulted buildings with decentralised ventilation systems addresses the current UK building industry debate on how to ventilate buildings efficiently and effectively that have been built with an energy efficient building fabric. To address climate change through reduced carbon emissions, buildings are being built to be better insulated and more airtight. Providing good indoor air quality and thermal comfort is particularly important in this scenario as while better insulated and airtight buildings have advantages, such as warmer buildings in heating-based winter climates, they also have potential disadvantages, such as increased risk of high level of indoor air pollutants as the result of reduced ventilation and airchange rates. Reduced ventilation in more insulated buildings can also contribute to buildings overheating in summer, even in mild maritime climates such as that of the United Kingdom, and overheating in the UK is already being experienced in buildings of different construction types including energy efficient and inefficient construction types (AECOM, 2011; Mavrogianni et al, 2015; NHBC, 2012; Zero Carbon Hub, 2015).

In addition, the Intergovernmental Panel on Climate Change's Fifth Assessment Report on Climate Change (Pachauri and Meyer, 2014) predicts that ambient temperatures will rise and in the south of the United Kingdom and this is expected to result in a 4 °C increase of the mean summer temperatures and a 2 to 3°C increase of the mean winter temperature by the 2080s under a medium emissions scenario (Jenkins et al., 2009). Such temperature increases are not evenly distributed and in particular heat waves within urban environments have been associated with negative health impacts and increased summer deaths. (Watts et al, 2015). Buildings should be able to provide healthy and comfortable environments despite these extreme weather conditions.

The drive for energy efficient and low carbon building designs in the UK has seen an increased interest and application of centralised systems of mechanical ventilation with and without heat recovery, as well as an increased adoption of the Passivhaus Standard. While post occupancy assessments of Passivhaus developments show a good correlation between post occupancy energy performance and pre-construction simulation and good indoor air quality, some highly insulated buildings with mechanical ventilation and heat recovery (MVHR), including certified Passivhaus dwellings, have been shown to overheat in southern, central and northern Europe (Mcleod et al, 2013). Furthermore, the installation of MVHR represents an additional financial and embodied carbon cost and requires maintenance and replacing at regular intervals (Beko et al, 2008). Most UK dwellings are currently naturally ventilated (Taylor et al., 2014) and when considering an energy performance retrofit, decentralised systems are easier and cheaper to install. Whether centralised mechanical ventilation is always the best solution for the UK climate has also been questioned in terms of effective energy efficiency (Schiano-Phan et al, 2008; Sassi, 2013).

In conclusion, the hypothesis investigated is that decentralised and natural ventilation systems may well provide adequate indoor air quality and thermal comfort while also performing well in terms of energy use. This paper reports on the initial results from the monitoring of eight highly insulated dwellings with decentralised and natural ventilation, in relation to the indoor pollutant levels measured and the building performance in the summer heat wave experienced at the end of June 2015. The research is funded by the NHBC Foundation.

2 Research method

Eight highly-insulated homes ventilated through decentralised and natural systems in the south of the UK were monitored for one year. The dwellings were selected to provide a selection of different construction types, including heavy and light weight construction, and ventilation types, including systems based on the use of passive vents and through the wall mechanical extracts. Buildings detailed plans and specification were used to calculate the key parameters for comparing the buildings and assessing the performance. The dwellings that had not previously been tested for airtightness were tested. The building data was used to simulate the performance of the buildings in IES to simulate changes in occupancy, airtightness and ventilation and allow for more a level of comparison between the building's ventilation systems.

For a period of one year, measurements were taken for temperature and relative humidity at 30 minute intervals. Temperature loggers were placed in 4 rooms of the dwellings on different levels and with different orientations and including a living room and a bedroom. Relative humidity loggers were placed in the living room and one or two other rooms. The loggers used included the Hobo U10 and U12 (Temperature measurement range: -20°C to +70°C, Relative humidity range: 25%(U10)/5%(U12) to 95%) and Tinytag Ultra temperature only and temperature and RH combined (Temperature measurement range: -25 °C to +85°C, Relative humidity range: 0 to 95%). CO_2, CO, NO_2, CH_2O and TVOC measurements were taken over two hour periods on three visits to the dwellings during different seasons. A Wolfsense IQ-604 probe was used with CO_2, CO, temperature and RH sensors installed plus an additional SEN-0-NO_2 Nitrogen Dioxide sensor and SEN-B-VOC-PPB Low range PID sensor b(0-20,000 ppb) for VOC's to take measurements every minute. A Formaldehyde meter (Wolfsense FM-801) was used to measure average levels over a period of an hour. Trend measurements of the indoor air pollutants were taken in one of the case study buildings over several months in winter.

In addition building occupants were interviewed in relation to their perceived comfort levels and their use of the building including their adaptations to achieve comfort at three times throughout the year to gain feedback in respect of different seasons and weather conditions.

3 Indoor air quality: pollutants, their impacts and sources in buildings

Good indoor air quality should have no known contaminants at harmful levels (Clancy, 2011). Potential contaminants of indoor air in buildings include human bioeffluents including carbon dioxide (CO_2), external air, volatile organic compounds (VOCs) including formaldehyde (CH_2O), tobacco smoke, radon, ozone, carbon monoxide (CO),oxides of nitrogen including nitrogen dioxide (NO_2), bacteria, fungal spores, mites and fibres (ISO, 2008). The impact of indoor pollutants depends on the susceptibility of the occupants, their level of exposure and the potential harmful effects of the substance, which can include sensory irritation, causing fatigue, headache and shortness of breath, chronic pulmonary disease, and cancer. (Chianga and Laib, 2002; Clancy, 2011; Daisey et al, 2003; Kephalopoulos et al, 2006; Wargocki et al, 2000; WHO, 2010)

This research focussed on CO_2, CO, NO_2, CH_2O and TVOC, the 'classical' pollutants as defined in the Scientific Committee on Health and Environmental Risks (SCHER, 2007) report "Opinion on risk assessment on indoor air quality" in addition to temperature and relative humidity. CO, CH_2O and NO_2 are classified as high priority chemicals in the European Commission publication "*Critical appraisal of the setting and implementation of indoor exposure limits in the EU"* (Kotzias, 2005).

CO poisoning is a leading cause of death from indoor chemical (WHO, 2010; Kotzias, 2005). CO is produced as a result of incomplete combustion of fuels in faulty, poorly maintained or ventilated cooking and boiler appliances, or open fires burning biomass fuel. Tobacco smoke also is a source of CO (Kotzias, 2005). CH_2O is a known animal and human carcinogen and even low concentrations, lower than those associated with cancer, can cause sensory irritation (WHO, 2010). Building and furniture board materials are a source of CH_2O as is tobacco smoke. NO_2 results from the burning of fossil fuel and levels elevated in relation to the German indoor guidance level of 60 $\mu g/m^3$ are found in 25% and 45% of dwellings in Germany and Italy respectively (Kotzias, 2005). Furthermore, research linked a 20% increased risk of lower respiratory illness in children with elevated NO_2 levels from 15µg/m3 to 43 µg/m3 (WHO, 2010). For these three chemicals clear guidance on exposure is provided and listed in Table 1.

TVOC is a measure of combined volatile organic compounds. These include such chemicals as benzene, derived from solvents and combustion fuel; toluene and tetrachloroethylene, derived from solvents; and other carbon based chemicals. Sources of VOCs in buildings include materials and furniture, leather and textiles, paints, varnishes, sealants, thinners, adhesives, household products (cleaning products, pesticides, moth repellents, air fresheners) and personal care products (cosmetics, perfumes) (European Commission, 2002). VOCs are differentiated according to their boiling points and classified as VVOC, very volatile organic compounds; VOC, volatile organic compounds SVOC, semivolatile organic compounds. Background levels are around 0.05-.4ppm (Wolfsense, 2014). According to research by Kephalopoulos (2006) more than 900 VOC have been identified in buildings, 250 have been measured at concentrations higher than 1ppm, and typically in one building VOC levels are usually lower than 1-3 mg/m^3. The health impacts are primarily of a sensory nature. Recommended exposure levels are difficult to formulate due to the mixture of chemicals and measuring techniques and WHO does not state any recommended exposure limits. Research attempting to define exposure levels has derived exposure levels from sensory responses or from statistical surveys of existing levels (Seifert, 1999) and a selection of suggested exposure levels classifications are listed in Table 1.

CO_2 is considered to affect the indoor air quality even though it is primarily understood as an indicator of ventilation rates and is not considered a health hazard in its own right (ISO, 2008). As an indicator of ventilation rates CO_2 has been used as a basis for designing ventilation solutions but levels of CO_2 are not necessarily directly linked to levels of other pollutants (Dougan and Damiano, 2004; Nga et al, 2011). As opposed to sources of other pollutants, which are not necessarily linked to occupancy levels in buildings, CO_2 levels are considered to be more accurately linked to levels of bioeffluents and therefore odours that might be unacceptable to occupants (Dougan and Damiano, 2004; Petty, nd). Elevated CO_2 levels have also been shown to moderately to significantly detrimentally affect certain (six to seven out of nine) decision-making office-based activities at 1000ppm and 2500ppm respectively (Satish et al, 2012). Extremely high levels above 10,000 ppm not normally found in buildings can cause drowsiness and at much higher levels can cause unconsciousness (Cancy, 2011).

The sources of pollutions found in the case study buildings included the occupants, building materials and consumer products, but in all case study buildings the occupants were conscious of using consumer products that had low VOCs and only using those they felt really necessary, for instance none of the occupants used air fresheners. Most building materials were typically low emissions options such as timber rather than carpet flooring.

Table 1 - Chemical exposure limits in indoor environments for selected chemicals

CHEMICAL	WHO (2010) *exposure limits*	Building Regulations F1 (2010) *exposure limits*	Baubiologie (Baubiologie Maes, 2008)	*Level of concern*	EPA_ National Ambient Air Quality Standards (EPA, 2016) *exposure limits*	The Well building standard (Delos Living LLC, 2015) *exposure limits*	Other sources of standards
CO_2			<600ppm 600-1000ppm 1000-1500ppm > 1500ppm	None Slight Severe Extreme		800 ppm	School average levels for full day not to exceed 1500ppm (Building Bulletin, 2006)
CO	90ppm - 15 mins 25ppm - 1 hour 10ppm - 8 hours 6ppm - 24 hours	90ppm - 15 mins 50ppm - 30 mins 25ppm - 1 hour 10ppm - 8 hours			35ppm - 1 hour 9ppm - 8 hours and not to be exceeded more than once per year	9 ppm	
NO_2	200 µg/m^3 (100ppb) exposure limit 1 hr 40 µg/m^3(20ppb) exposure limit annual average	150ppb - 1 hour 20ppb long term exposure			100ppb - 1hr (98th percentile of 1hr daily max. concentrations, averaged over 3 years) 53ppb - 1 yr (an. mean)		
CH_2O	100 µg/m^3 (80ppb) over a 30-min period and long term exposure		<16 µg/m^3 (13ppb) 16-40 µg/m^3(13-33ppb) 40-80 µg/m^3(33-65ppb) >80 µg/m^3(65ppb)	None Slight Severe Extreme		27 ppb	China, Japan, Portugal and UAE cite 80ppb maximum for their IAQ standards. France has 40ppb and Hong Kong's "excellent class" IAQ requirement is at 25ppb. (Wolfsense, 2015)
TVOC		300 µg/m^3	< 100 µg/m^3 100-300 µg/m^3 300-1000 µg/m^3 > 1000 µg/m^3	None Slight Severe Extreme		500 µg/m^3	China/Portugal - 600µg/m^3 / Dubai 300µg/m^3 LEED (before occupancy) 500µg/m^3 (Wolfsense, 2014)
							<200 µg/ m^3 Comfort range 200–3000 µg/ m^3 Multifactorial exposure 3000–25,000 µg/ m^3 Discomfort >25,000 µg/ m^3 Toxic (Mølhave, 1991)
							The value of 300 µg/m^3 was suggested by Seifert (1999) based on statistical surveys of German homes. 1000µg/m^3 was set as exposure limits in German standard (AGÖF, 2013)

4 Ventilation and infiltration

Air is introduced in buildings from outside through infiltration and ventilation and this dilutes pollutants in buildings, subject to the air outside being pollutant-free. Infiltration is defined in the Building Regulations (2010:13) Approved Document F1, Means of Ventilation as “the uncontrolled air exchange between the inside and outside of a building through a wide range of air leakage paths in the building structure”. This is in contrast with ventilation that is controlled and provided through natural or mechanical means (Building Regulations, 2010). The regulations differentiate between buildings with higher and lower infiltration rates and require different solutions for each. Buildings that are tested to have a higher infiltration rate than $5m^3/hm^2$ at 50 Pa are assumed to have air change rate per hour of 0.15 at ambient pressure, which will contribute to the fresh air provision in the building and consequently the area of controlled ventilation can be reduced compared to buildings with less air infiltration.

The case study buildings all have decentralised and naturally ventilated systems. The Building Regulations ADF1 (2010) list four main types of ventilation: trickle and other vents in conjunction with intermittent mechanical extract (five of the case studies can be classed as operating with such a system); passive stack ventilation system (three case studies use this system); continuous mechanical extract (centralised or decentralised); and continuous MVHR. All case study buildings have operable windows that provide purge ventilation as required.

The effectiveness of the natural ventilation that uses natural systems such as temperature differences and wind pressure to drive the ventilation through a passive stack system or windows is subject to the external weather conditions, obstructions, wind and the internal building configuration and the design of window and other openings. Mechanical ventilation is independent of variables external to the building and only marginally affected by internal layouts (Clancy, 2011).

The provision of fresh air in relation to the volume of the building together with the control of sources of indoor air pollutants are the main influences on indoor air quality.

5 Overheating in dwellings

The effectiveness of the natural ventilation will also have an impact on the risk of overheating, as do other building fabric elements such as thermal insulation, thermal mass, shading and the potential for temperature stratification. (Mavrogianni, 2014; Porritt, 2011; Porritt, 2012). In naturally ventilated buildings the occupants have the benefit of being able to manipulate their building to make it more comfortable and this control facility is also known to make occupants more tolerant of their environment. (Baker and Standeven, 1996; Brager and de Dear, 1998).

The temperature considered to constitute overheating in naturally ventilated buildings is higher than in mechanically ventilated buildings, and this is now not only documented in research related to adaptive thermal comfort (Nicol and Humphreys, 2002; 2009) but integrated to some degree in the British Standard (2007) BS EN 15251:2007 and ASHRAE (2010) Standard 55.

The indoor comfort temperature set by CIBSE Guide A (2006) for the summer are 25°C for living rooms and 23°C for bedrooms and overheating is deemed to have occurred if one percent of the occupied hours over one year exceed 28°C and 26°C for living and bedrooms respectively. CIBSE Guide A (2006) also notes that temperatures over 24°C can impair sleeping and this suggests that it is important to differentiate when the peak temperatures occur.

According to BS EN 15251:2007 the acceptable internal temperatures would rise with the external temperatures in line with the adaptive thermal comfort model. The formula to calculate the indoor maximum compared with external temperature is:

indoor maximum = 0,33 external temperature + 18,8 + 2 (or +3 or +4 depending on the predicted percentage of persons dissatisfied (PPD) with the elevated temperature).

This would mean that an external temperature of 28°C would result in internal temperature of 30°C-32°C to feel acceptable for 85-94% of people.

The monitored temperatures will be related to both CIBSE Guide A (2006) and BS EN 15251:2007 standards.

6 Results: Indoor Air Quality

Winter measurements of indoor air quality were overall adequate to good (Table 2). The CO levels were well within all recommended levels. CH_2O levels were sound in relation to the WHO (2010) standard of 80ppb but if the Baubiologie Standard (Baubiologie Maes, 2008) were considered one reading in particular would be considered 'severe concern' at 63ppb and also in excess of The Well Building Standard (Delos Living LLD, 2015) of 27ppb. It is worth noting that case studies 1, 4, 5, 7 and 8 all had wood burning stoves and the occupants of case study 6 were tobacco smokers. These aspects would impact on the CH_2O and NO_2 levels. The elevated reading was taken in case study 4 which had no other particularly elevated readings and did contain a significant amount of decorative objects and fabrics, which could have contributed to the elevated readings. The monitoring is continuing for another winter which will allow for further readings to be taken. TVOC levels were all within the The Well Building Standard of 500 µg/m³. The highest levels were measured in case study 6 where the occupants smoke indoors (446 µg/m³), and these exceed the Building Regulations (2010) standard of 300 µg/m³, which is also the top limit of Baubiologie Standard's "slight concern". Case study 5 measurements for TVOCs is slightly about 300 µg/m³ and this could be the results of craft products used in the home.

The CO_2 levels measure in half the case studies were within The Well Building Standard (Delos Living LLD, 2015) limit of 800ppm and half above that but within the Building Bulletin (2006) target of 1500. The Baubiologie Standard (Baubiologie Maes, 2008) would class all but one as of 'slight concern' and one of 'severe concern'. However, as discussed above the levels of CO_2 are more representative of the sensory quality of the air and the occupants in the case study house all reported the quality of air to be good on a seven point likert scale, suggesting the air change rate was sufficient to provide air quality perceived to be good.

The chemical concentrations that appear of concern are those of NO_2 which were all measured to be above the recommended by WHO (2010) and case study 3 and 8 have higher levels than the EPA (2016) recommendation of 53ppb. The fact that the 72 ppb were measured in case study 3 located in central London and the fact that case study 3 had very high air change rates of 10 ach, much higher than all the other case studies, would suggest that the external air might be the cause for the elevated levels.

Table 2 – Winter measurements of indoor air quality, temperature and relative humidity over a period of 90 minutes average.

Case study	CO_2 ppm	CO ppm	NO_2 ppb	CH_2O ppb	TVOC µg/m³	Temperature °C	Relative Humidity %RH
1	814.5	1.3	44	10-15	277.0	18.7	48.9
2	1151.7	1.2	44	10-15	274.0	21.5	47.9
3	702.7	0.1	72	10	10.3	25.0	23.3
4	732.5	1.83	40	62	81.5	19.6	48.9
5	697.34	1.02	46	17	332.7	19.7	48.2
6	1045.7	5.0	43	10-20	446.1	21.5	42.9
7	734.0	0.5	43	32	59.8	20.3	47.6
8	1071.6	0.07	56	20-29	208.7	21.2	40.3

The results support the view that CO_2 levels are not necessarily related to the indoor air pollutant levels. As shown on Figure 1, the levels of CO_2 rise with occupancy while the TVOC levels slightly decrease. And as discussed above the occupant feedback correlates more accurately with the levels of CO_2 than the levels of any other chemical.

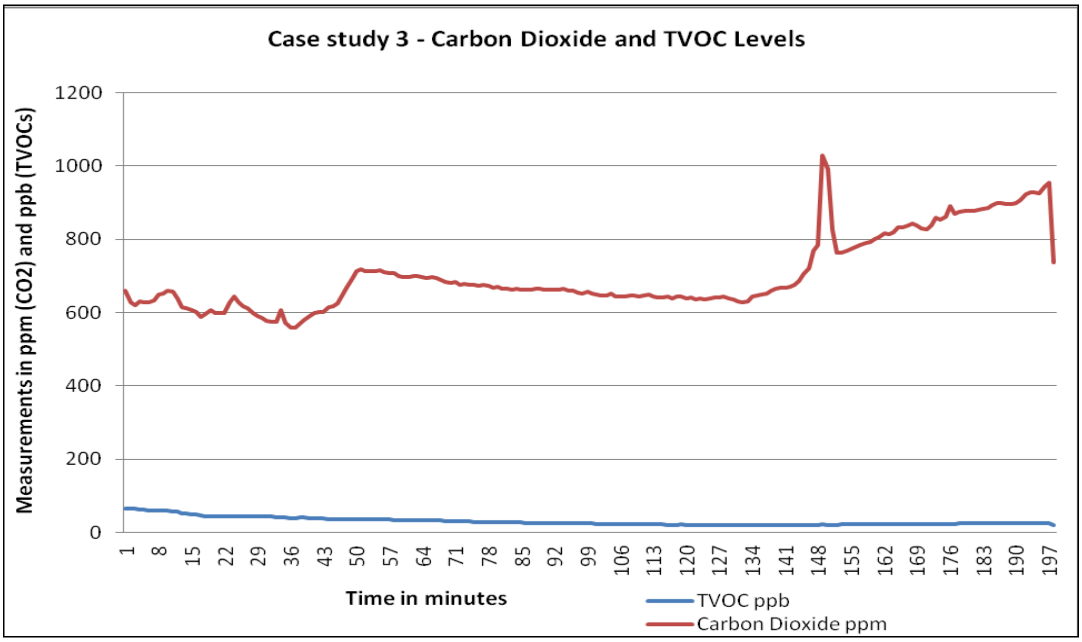

Figure 1 – Example of relation of CO_2 to TVOC levels

The results overall suggest that decentralised ventilation systems can provide adequate to good indoor air quality during the winter period when ventilation is kept to a minimum and infiltration can be at times the main source of fresh air. In view of the somewhat elevated NO_2 levels a second set of winter readings will be taken to confirm and allow a second examination of the existing readings.

7 Results summer overheating

In respect of the summer indoor environment quality and overheating during peak summer temperatures, the living spaces, which were all situated on the ground floor, performed well in relation to CIBSE Guide A (2006) limit of 25°C for living rooms (Table 3) over a two week period, which included the heat wave experienced at the end of June 2015 . During the two week heat wave case study 4, which experienced the highest peak temperatures outside London, experienced temperatures over 25°C in the living room for only a small percentage of hours (4.7%) (Table 4). In the bedrooms over the two week period the temperature exceeded 24°C between 22.00-8.00 for 7.5 hours of which 4 hours were below 25°C.

Table 3 – Temperatures in °C monitored during summer heat wave June-July 2015 (minimum and maximum temperatures are shown in parentheses).

CASE STUDIES M=masonry T=timber frame MV=vents and decentralised extracts PV=Passive vent system	living room south ground floor	living room west	kitchen north	living room north ground floor	bedroom east ground floor	living room south north facing	room 1st fl. south facing	bedroom 1st fl. north facing	bedroom 2nd fl. south facing	bedroom 2nd fl. north facing	external temperature
1 - Oxfordshire - M - MV	22.02 (20.5) (23.4)						23.28 (20.9) (27.4)	23.37 (22.0) (25.9)	25.12 (21.6) (29.2)		18.68 (32.2) (11)
2 - Oxfordshire - M - MV	21.72 (19.9) (23.7)								24.20 (19.8) (32.2)		18.68 (32.2) (11)
3 - London - T - MV	25.82 (21.3) (33.7)					24.45 (19.5) (33.7)	25.94 (21.3) (34.1)		26.24 (19.8) (39.8)		20.93 (38.5) (11.3)
4 - Gloucestershire - T - MV	21.09 (15.0) (30.0)			20.80 (14.5) (29.4)			21.33 (15.5) (29.7)			20.85 (14.3) (30.2)	17.94 (31.1) (10.2)
5 - Gloucestershire - T - MV note a	23.03 (20.0) (27.5)			23.11 (20.2) (27.7)			25.16 (21.9) (30.0)			25.04 (22.0) (29.7)	17.94 (31.1) (10.2)
6 - Somerset - T - PV note b	20.81 (18.4) (19.2)		20.25 (19.1) (20.1)				21.10 (18.6) (21.7)	22.54 (21.3) (22.4)			17.65 (27.1) (12.2)
7 - Somerset - M - PV note b	23.37 (21.9) (24.9)				23.94 (23.3) (24.5)		22.46 (21.5) (23.4)	23.39 (22.3) (28.7)			17.65 (27.1) (12.2)
8 - Somerset - M - PV note b	19.44 (19.1) (20.1)	18.73 (18.4) (19.1)					21.92 (21.3) (22.4)	20.43 (18.6) (21.7)			17.65 (27.1) (12.2)

Note a - occupants on holiday over two week monitoring period of heat wave

Note b - monitoring period 24th-27th June did not include peak heat wave

Table 4 - Distribution of temperatures in °C measured in living room in case study 4 as percentage of overall hours over heat wave period.

15°C	16°C	17°C	18°C	19°C	20°C	21°C	22°C	23°C	24°C	25°C	26°C	27°C	28°C	29°C	30°C
1.2%	1.5%	3.6%	8.5%	20.4%	22.2%	15.3%	10.9%	7.6%	2.1%	2.0%	1.4%	1.2%	1.1%	0.9%	0.2%

The relationship between interior temperatures and building level and orientation can be best illustrated in case study 6 where the ground floor rooms are cooler than the first floor rooms and the south facing rooms warmer than the north facing rooms. This difference can be seem to different degrees in all case studies and whether or not they are heavy or light construction does not seem to impact on this relationship between building levels and orientation. Some apparent anomalies such as case study 7 north facing bedroom being hotter than the south facing bedroom can be explained by the existence of a large rooflight in the north facing room.

There was no direct correlation evident between overheating in lightweight and heavy weight construction. While all the case studies were different in design and context and it would have been difficult to assess through monitoring the impact of thermal mass, the results suggest that through appropriate design a comfortable environment can be achieved in the current UK climate with light weight construction. The modelling of the case studies will be able to test thermal mass as a variable for each case study to establish the difference in performance and the impact of future climatic contexts.

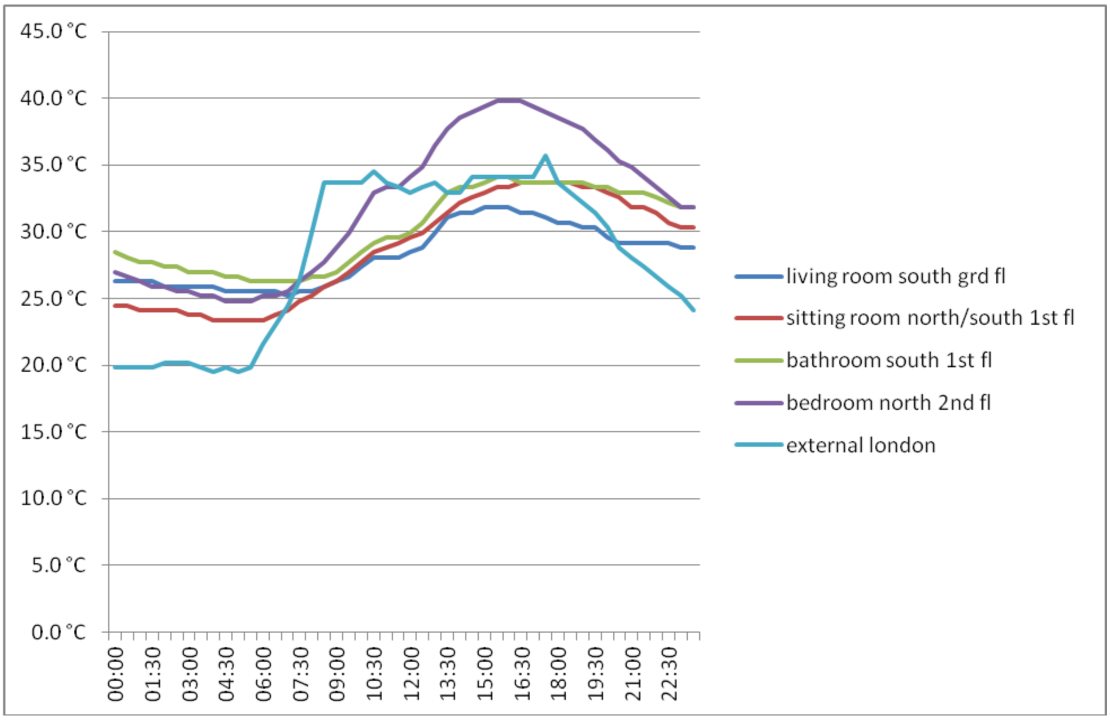

Figure 2 – A 24 hour period in case study 3 in London shows how the external temperature is significantly lower than the internal suggesting a missed opportunity for cooling.

Some effective cooling strategies were described by the occupants. One design included a generous central stairs with rooflights at the top to exhaust the air and ample windows to allow fresh cooler air into the building. By adopting this simple strategy the occupants reported immediate cooling benefits. The most problematic case study was the one located in London, which experienced higher ambient temperatures. Despite the more challenging context, as shown on Figure 2 the external temperature at the beginning of the day was significantly lower than the internal suggesting the full cooling potential of cool night air was not being realised. The design of ventilation has a good potential to contribute to thermal comfort the current UK climate, however the design of windows and other openings needs to be more carefully considered, as well as the air flow path. Case study 1 also has a central stairs and rooflights at the top of the stairs as case study 4, but the occupants reported it to be ineffective as a means of driving airflow for cooling. The relationships between windows, internal layouts, and the height of the building are critical to the effectiveness of ventilation.

8 Conclusion and further development

The case studies monitored had a variety of infiltration rates and ventilation systems, the contexts varied as well as the building designs and construction. A direct comparison between case studies is not appropriate but some general lessons can be learnt. Overall the study suggests that decentralised ventilation systems in highly insulated buildings can provide adequate to good indoor air quality. The study also suggests that overheating can be addressed in both heavy mass and lightweight well insulated construction in the current UK climate. A number of additional conclusions can be drawn.

1 - The study found no relation between CO_2 and TVOC levels or other chemicals and therefore confirms the literature that emphasises the role of CO_2 as an indicator of perceived quality of air as opposed to actual pollutants. In the case studies investigated the CO_2 levels were above the ideal, however the perception of the occupants was still of good air quality.

2 - The contributors to indoor air pollutants have to be carefully investigated. The study highlighted some instances where high pollutants levels were measured without a clear source. Some clear sources such as tobacco smoking and stoves can be easily identified, but other more subtle sources such as craft materials and cleaning products have to be taken into account. The occupants' survey included a list of potential sources of pollutants for the occupants to identify any they used and a visual inspection identified materials and products that could be a source of pollutants. However, to fully understand where the pollutants come from a more extensive investigation needs to be undertaken.

3 - In the London case study where overheating did occur, the ability to adjust the internal environment by opening windows and doors and shading the space from the sun, resulted in the occupants experiencing the well-understood 'forgiveness factor' and despite the elevated temperatures not feeling uncomfortable. Similar tolerance was noted with most of the occupants interviewed.

4 – The building occupants' knowledge of how to 'use' the building was invaluable in terms of making it comfortable. It was very evident that the occupants were able to maximise what the building could do in terms of creating a comfortable

environment. Such knowledge is key in maximising building efficiency as well as comfort.

Finally, as mentioned in the introduction, the relationship between all building characteristics that contribute to a healthy indoor environment is very complex and even just the relationship of the indoor air quality, thermal comfort and ventilation system studied in this research can only provide a suggestion of the causal links. More data is required from more and different building types. In particular, it has been shown that poorly insulated buildings suffer from overheating (Mavrogianni et al, 2015) but there is little data on the indoor air quality of such buildings. A more comprehensive survey of the indoor air environments of dwellings including all the variables is required.

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