Thermal comfort and IAQ in super-insulated housing with natural and decentralized ventilation systems in the south of the United Kingdom.

Improved energy performance standards are resulting in better insulated and more airtight building. In such buildings ventilation can be provided by natural means alone or in conjunction with extract mechanical ventilation or with whole-house mechanical ventilation with or without heat recovery. This paper reports on a study funded by the NHBC Foundation of the indoor environment of eight super-insulated homes with natural and decentralized ventilation systems in the south of the UK. The aim was to examine the effectiveness of such ventilation options. The buildings were monitored for one year in relation to temperature, relative humidity, CO_2, CO, NO_2, CH_2O and TVOC. The building occupants' feedback and IES building modelling triangulated the site data. The study showed that natural and decentralized ventilation systems provided good air quality in the case-study buildings and allowed users to create comfortable thermally differentiate environments in response to their preferences.

Keywords: indoor air quality, thermal comfort, decentralized ventilation, energy efficient buildings.

Introduction

Climate change and the drive for low-energy buildings have resulted in increasingly insulated and airtight buildings. In heating-dominated climates, the better insulated and airtight the buildings are the shorter the heating season and the less energy is needed to create comfortable homes in winter. In the UK, space and water heating account for approximately 80 % of energy consumption (DBEIS, 2016) therefore reducing heating energy is critical to achieving the UK government goal of an 80% reduction in carbon dioxide (CO_2) emissions by 2050 from 1990 levels (UK Government, 2008) and keeping global warming within the 2°C believed to mitigate risks, impacts and damages (Malte Meinshausen et al, 2009).

Creating well-insulated and airtight buildings requires careful consideration of the provision of adequate ventilation to the building to ensure good air quality and thermal comfort. While studies about indoor pollutants and measured indoor temperatures in well-insulated and airtight buildings in the UK are limited; overheating in buildings has been the focus of a number of studies that have highlighted that even in mild maritime climates, such as that of the UK, overheating 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). The overheating potential of buildings is going to increase as ambient temperatures rise with global warming. 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- 3°C increase of the mean winter temperature by the 2080s under a medium emissions scenario (Jenkins et al., 2009).

The ventilation system of a dwelling contributes significantly to its indoor air quality (IAQ) and the thermal comfort of its occupants. Domestic ventilation options include natural, mechanical, centralized and decentralized systems. Within the context of climate change, if adequate ventilation and thermal comfort can be provided by natural and decentralized ventilation systems, these would offer lower embodied energy and maintenance solutions compared to centralized mechanical systems (Beko et al, 2008). Furthermore, they have also been shown to be potentially associated with reduced operational energy (Sassi, 2013). Decentralized systems can also represent less-disruptive and less-expensive solutions for high-performance retrofits of the existing housing stock, which is currently overwhelmingly naturally ventilated (Taylor et al., 2014), thus potentially facilitating the mainstreaming of such work.

This research aimed to identify any clear limitations of relying on natural and decentralized ventilations systems in well-insulated and airtight buildings in respect of IAQ and thermal comfort. The research also aimed to evaluate the operation of such buildings in relation to the occupants' interaction and their perception of comfort.

Eight highly insulted dwellings with decentralized ventilation systems were monitored, including the indoor air quality, the temperature and relative humidity. The research was funded by the NHBC Foundation.

Research method

Eight highly-insulated homes ventilated through decentralized and natural systems in the south of the UK were monitored for one year. The dwellings were chosen 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 specifications were used to calculate the key parameters for comparing the buildings and assessing their performance. The dwellings that had not previously been tested for airtightness were tested. The building data were used to simulate the performance of the buildings in IES to simulate changes in occupancy, airtightness and ventilation and to allow for an additional 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 four rooms of each dwelling 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 - 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 CO2, CO, temperature and RH sensors installed plus an additional SEN-0-NO2 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 the adaptive actions taken to achieve comfort at three times throughout the year to gain feedback in respect of different seasons and weather conditions.

Ventilation strategies selection and effectiveness expectations

Air is introduced in buildings from outside through infiltration and ventilation and this dilutes pollutants in buildings, subject to the air outside being less polluted that that indoor. 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 5m3/hm2 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 decentralized and naturally ventilated systems with operable windows that provide purge ventilation as required. They fall into two of the four main types of ventilation set out in the Building Regulations ADF1 (2010) which include: 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 (centralized or decentralized); and continuous mechanical ventilation with heat recovery (MVHR).

Ventilation systems and differences in effectiveness

Three performance issues were examined in this study. The first relates to air quality. 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 IAQ. The effectiveness of the natural ventilation that uses 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 direction and speed, the internal and external building configuration and the design and use of windows and other openings. The quality of the indoor air can therefore vary and this research aims to establish whether in the case-study buildings the IAQ was sound despite such variations. Mechanical ventilation is independent of variables external to the building and only marginally affected by internal layouts (Clancy, 2011) and mechanically ventilated buildings have been shown to benefit from good IAQ.

The second issue relates to winter thermal comfort and user preferences. Achieving thermal comfort in winter is as dependent on the heating system as the ventilation strategy. Decentralized systems tend to create thermal zones with different temperate within a building, while centralized systems tend to provide uniform temperatures in all rooms. The choice of a heating and ventilation system for winter performance can be more related to user preferences than to system of cost effectiveness. The relationship between heating and ventilation systems and their energy use was not investigated in this research due to the extensive use of timber wood stoves in the case-study buildings.

The third and last point relates to the effectiveness of natural ventilation in achieving summer thermal comfort. Summer thermal comfort in UK homes is predominantly achieved through the opening of windows even in buildings with centralized ventilation systems. While overheating has been recorded in poorly insulated buildings as well as in well-insulated buildings, including certified Passivhaus dwellings (Mcleod et al, 2013; Mavrogianni, 2015; AECOM, 2012), increased insulation of buildings results in the retention of internal and solar gains within the building, potentially creating uncomfortable environments. If ambient temperatures are above the comfort level, then exterior air cannot be used to cool interior environments. At present the ambient temperatures are only seldom above comfort levels and therefore appropriate for providing direct cooling of occupants, subject to the configuration of the building and the ventilation openings providing effective air changes. The effectiveness of the individual ventilation systems and their design was of particular interest in the case-study buildings.

IAQ and measurement results

Contaminants of indoor air in buildings can include human bioeffluents (including carbon dioxide (CO2)), external pollution from vehicles, volatile organic compounds (VOCs) (including formaldehyde (CH2O)), tobacco smoke, radon, ozone, carbon monoxide (CO), oxides of nitrogen (including nitrogen dioxide (NO2)), bacteria, fungal spores, mites and fibres (ISO 2008).

Airtight construction in conjunction with natural ventilation, which is not automatically controlled, can result in reduced air changes and heighten the risk of an accumulation of pollutants and CO2. In addition to the infiltration rates (which in the buildings analysed varied between 0.4 and 7 air changes per hour at 50 Pascals), the concentration of pollutants and CO_2 is also related to the volume of air in the building within which the pollutants can diffuse and the occupation density (which in the buildings analysed ranged from $66m^3$ of air per person to $240m^3$ per person).

In all case-study buildings 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.

Indoor pollutants can have minor to severe impacts on occupant's health, which, depending on the susceptibility of the occupants and their level of exposure, can include sensory irritation, causing fatigue, headache and shortness of breath, chronic pulmonary disease, cancer and death (Chianga and Laib, 2002; Clancy, 2011; Daisey et al, 2003; Kephalopoulos et al, 2006; WHO, 2010).

Of the 'classical' pollutants monitored (CO_2, CO, NO_2, CH_2O and TVOC), as defined by the Scientific Committee on Health and Environmental Risks (SCHER, 2007), 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).

Carbon monoxide (CO) and formaldehyde CH2O

CO poisoning is a leading cause of death from indoor chemical pollution (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 at low concentrations, lower than those associated with cancer, it can cause sensory irritation (WHO, 2010). Building and furniture board materials are a source of CH_2O as is tobacco smoke. All monitored buildings had low levels of CO and CH_2O and the results' confidence was high (Table 1).

Table 1 – Winter measurements of IAQ taken in the eight case-study buildings, over a period of 90 min average and selected exposure standards.

Chemical	CO ppm	CH_2O ppb	NO_2 ppb	TVOC $\mu g/m^3$	CO_2 ppm
Compulsory standards and exposure limits and WHO (2010) standard	90ppm - 15 mins 50ppm - 30 mins 25ppm - 1 hour 10ppm - 8 hours Building Regs F1 (2010)	80ppb over a 30-min period and long term exposure WHO (2010)	150ppb - 1 hour 20ppb long term exposure Building Regulations F1 (2010)	300 $\mu g/m^3$ Building Regulations F1 (2010)	School average levels for full day not to exceed 1500ppm (Building Bulletin, 2006)
Voluntary Well Building Standard (Delos Living LLC , 2015)	9ppm	27ppb		500 $\mu g/m^3$	800ppm
Case-study 1	1.2	10-15	0-49	257	838
Case-study 2	1.6	10-15	12-55	307	1224
Case-study 3	0.1	10	35-75	66	706
Case-study 4	1.7	25	0-45	289	747
Case-study 5	1.1	10	0-39	307	691
Case-study 6	4.3	10-20	0-47	573	1086
Case-study 7	0.4	11	0-44	297	735
Case-study 8	0.1	20-29	16-52	205	1087

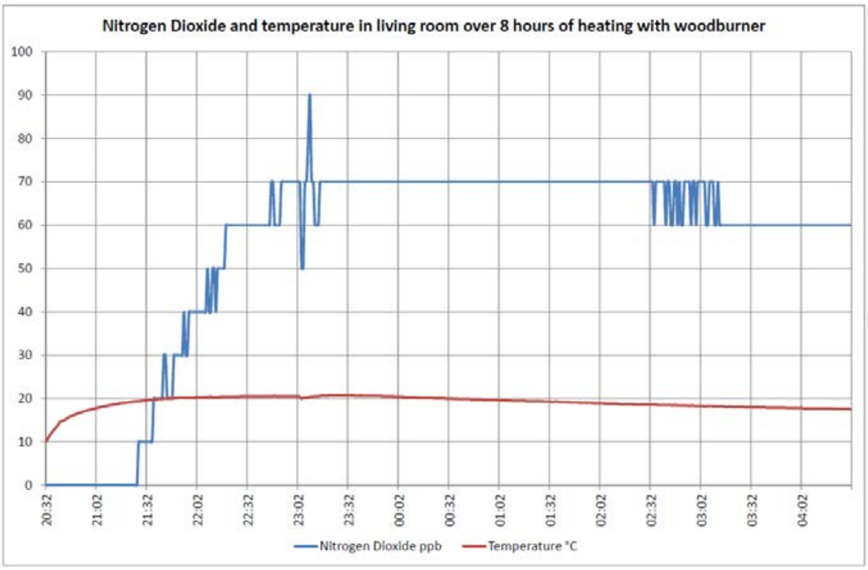
4.2 Nitrogen Dioxide (NO_2)

NO_2 results from the burning of fossil fuel both indoors (cooking and heating appliances) and outdoors (motor vehicles). Elevated levels in relation to the German indoor guidance level of 60 µg/m3 (31ppb) were found in 25% and 45% of dwellings in Germany and Italy respectively (Kotzias, 2005). WHO identified research suggesting

NO_2 being linked to an impairment of bronchial function including research that linked a 20% increased risk of lower respiratory illness in children exposed to elevated NO_2 levels from 15μg/m3 (8ppb) to 43 μg/m3 (23ppb) (WHO, 2010). The monitored equipment used in this research lacked adequate sensitivity to provide high confidence in the results taken over a period of typically only one hour. However some elevated levels were noted in case studies 2, 3 and 8, with potential sources being external traffic, cooking and wood-burning appliances respectively. It is worth noting that in addition to Case Study 8 also case studies 1, 4, 5 and 7 had wood-burning stoves but elevated levels of NO_2 were not noted.

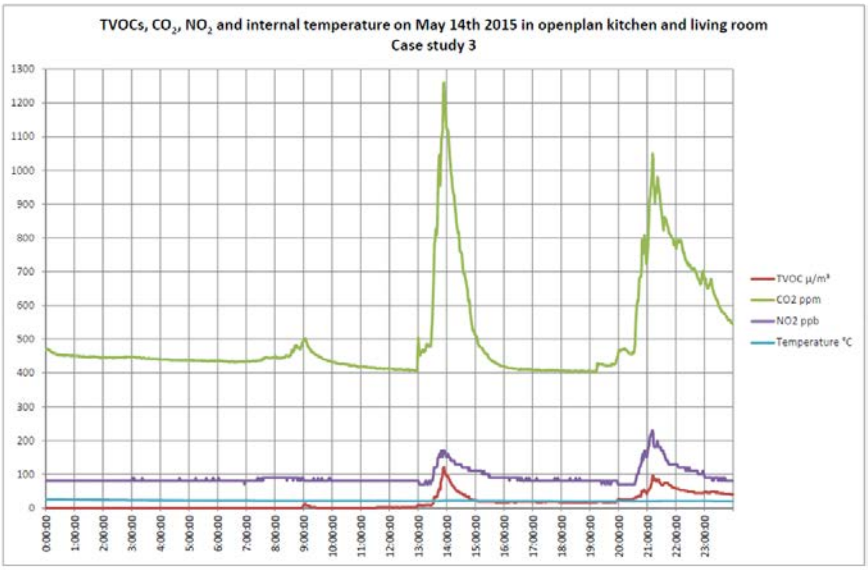
Additional experiments in two non-insulated and non-airtight homes confirmed that cooking with gas and wood-burning stoves are significant sources of NO_2. The first experiment measured the NO_2 emissions from a woodburning stove. Figure 1 shows a temperature rise from 10°C to 20°C when the woodburner was lit. NO_2 is formed at high temperatures therefore for the first hour NO_2 levels in the living room are around zero. As the woodburner reaches sufficiently high temperatures NO_2 is formed and NO_2 levels in the living room reach 60-70ppb. Even after six hours NO_2 levels are still above recommended long term exposure levels.

Figure 1 – Nitrogen dioxide emissions from woodburning stove



The second experiment simulated a 25-minute cooking process using two gas burners. Five ventilation options were tested and the levels of NO_2, CO_2, CO and TVOC were measured. CO and TVOC were not of concern, but NO_2 and CO_2 levels peaked at 356ppb and over 4000ppb respectively in the poorly ventilated options tested and took half an hour to drop back to normal levels. Opening internal or external doors and windows as well as using the extract hood proved effective in keeping all chemical levels below those of concern. The impact of gas cooking could also be clearly seen in Case Study 3's open plan kitchen living room (Figure 2). NO_2, CO_2 and TVOCs rise in line with cooking activities on a gas hob. While TVOCs and CO_2 peak below the levels of concern, the levels of NO_2 are briefly above the levels of concern set by the WHO.

Figure 2 - Nitrogen dioxide emissions from cooking in Case-study 3



Total Volatile Organic compounds (TVOCs)

TVOC is a measure of combined volatile organic compounds. These include such chemicals such as benzene, toluene and tetrachloroethylene 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). The TVOC levels measured in the case-study buildings were all within the The Well Building Standard of 500 µg/m³ and of a high confidence level. 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. Slightly elevated measurements were noted and ascribed to the use of craft and similar products associated with leisure activities.

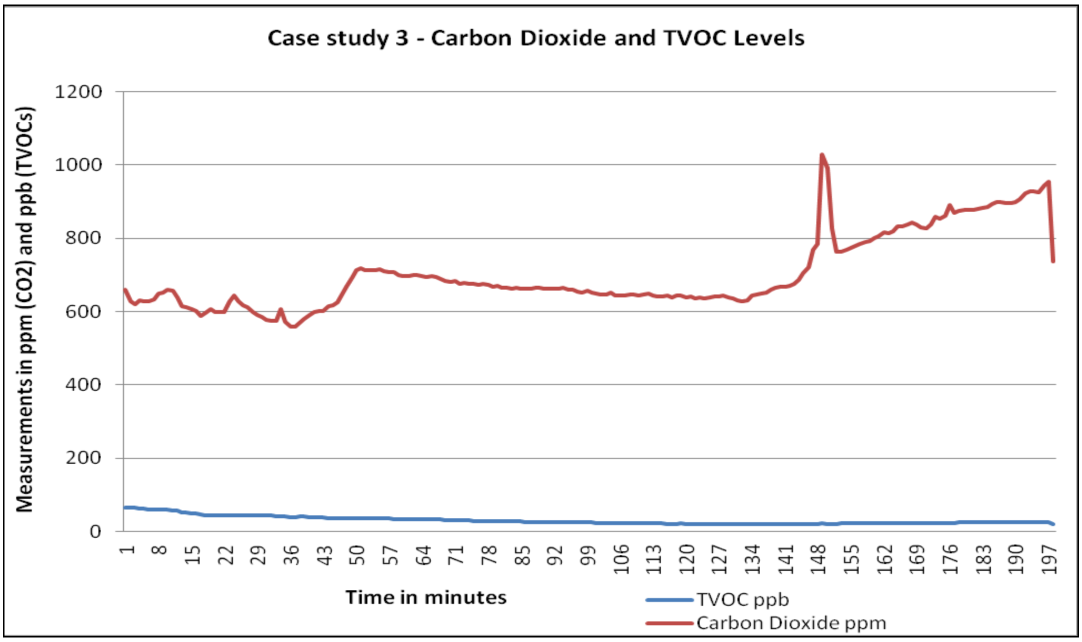
Carbon dioxide CO_2

CO_2 is not considered a health hazard in its own right (ISO, 2008). Extremely high levels above 10,000 ppm of CO_2, which are not normally found in buildings, can cause drowsiness and at much higher levels can cause unconsciousness (Clancy, 2011). However, lower levels that can be found in buildings, such as 1000-2500ppm, have been found to moderately (1000ppm) to significantly (2500ppm) detrimentally affect approximately two thirds of specific decision-making office-based activities (Satish et al, 2012) but have no physiological impact.

Occupants are the main source of CO_2 as well as other bioeffluents (such as body odour) that might be unacceptable to other occupants (Dougan and Damiano, 2004; Petty, nd). Being linked to occupancy, particularly in commercial buildings, CO_2 has been used as an indicator of ventilation rates and used as a basis for designing ventilation solutions; however levels of CO_2 are not necessarily directly linked to levels of other pollutants (Dougan and Damiano, 2004; Nga et al, 2011). The measurements taken in the case-study buildings illustrate this point. Figure 3 shows levels of CO_2 rise with occupancy while the TVOC levels slightly decrease, indicating the two are not linked.

The CO_2 levels measured 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 1500ppm. Despite the level being above the 800ppm, the occupants who rated their environment on a seven-point Likert scale perceive their environment as being fresh and not stuff or smelly.

Figure 3 – Example of relation of CO_2 to TVOC levels



Conclusion related to IAQ

While the small sample of case studies precludes any generalisations, this research has not shown any reasons in relation to IAQ to discourage the use of natural and decentralized ventilation systems in airtight and well-insulated housing.

Thermal comfort and measurements results

To help define acceptable indoor temperatures the following standards and guidance were considered: ASHRAE Standard 55 (2010), the British Standard (2007) BS Q8 EN15251:2007 and CIBSE Guide A: Environmental Design (2015).

For summer comfort, 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 (Tmax) = 0.33 *external running mean temperature (Trm) + 18.8 + 2, +3, or +4 depending on the category of building being monitored. This building should be classed at ‘category 2’ (normal expectation should be used for new buildings and renovations) for which the equation for maximum recommended temperature is given by

$$T_{max} - 0.33 * T_{rm} + 21.8$$

Note that T_{rm} is the running mean of the outdoor temperature, not the daily maximum

This would mean that an external running mean temperature of 20°C (fairly normal in UK summer conditions) would result in a maximum internal temperature of 21.8 + 6.6 = 28.4°C to feel acceptable for occupants. For conditions such as those shown in Figure 7 with a Trm of about 16°C the maximum acceptable temperature will be about 27°C. This model acknowledges that human adaptation through clothing but also a physiological adaptation can raise the maximum temperature considered comfortable by most people in summer.

For winter comfort, the BS EN 15251:2007 standard recommends 18-21°C in living spaces, including bedrooms, and 14-18°C for other spaces such as storage and halls. These limits probably apply in the conditions shown in figures 4 and 5 where the mean external temperature is below 10°C. CIBSE Guide A: Environmental Design suggests a wider range of temperatures for different rooms and seasons (Table 2).

Table 2 – Range of internal temperatures in °C considered appropriate for different rooms in dwellings during winter and summer from CIBSE Guide A.

	winter	summer
bathrooms	26–27	26-27
bedrooms	17–19	23-25
hall/stairs/landings	19–24	21-25
kitchen	17–19	21-23
living rooms	22–23	23-25
toilets	19–21	21-23

The indoor comfort temperature set by CIBSE Guide A (2006) for the summer are 25°C for living rooms and 23°C for bedrooms. Overheating is deemed to have occurred if three percent of the occupied hours over one year exceed the recommended maximum indoor temperature T_{max} . CIBSE Guide A also notes that high bedroom temperatures over can impair sleeping and this suggests that it is important to differentiate when the peak temperatures occur.

The thermal experience in well-insulated and airtight buildings: the principles

Air and radiant temperature, air movement, humidity and the user activity, clothing habits and ability to control their environment affect the user perception of thermal comfort (Nicol, 2012). Winter and summer comfort parameters are discussed below.

Regardless of the ventilation strategy, a highly insulated building fabric creates internal surfaces that are warmer than in poorly insulated buildings. The human body's perception of thermal comfort is affected significantly by the radiant heat exchange with surrounding surfaces. If those surfaces are cold, like that of a single glazed window, the air temperature needs to be suitably high to offset the heat loss experienced through radiant heat exchange with the cold surface. If the internal building surfaces are warm, the internal air temperature can be lower and still provide a comfortable environment for the occupants. In relation to air movement, in airtight buildings users tend to experience draughts less.

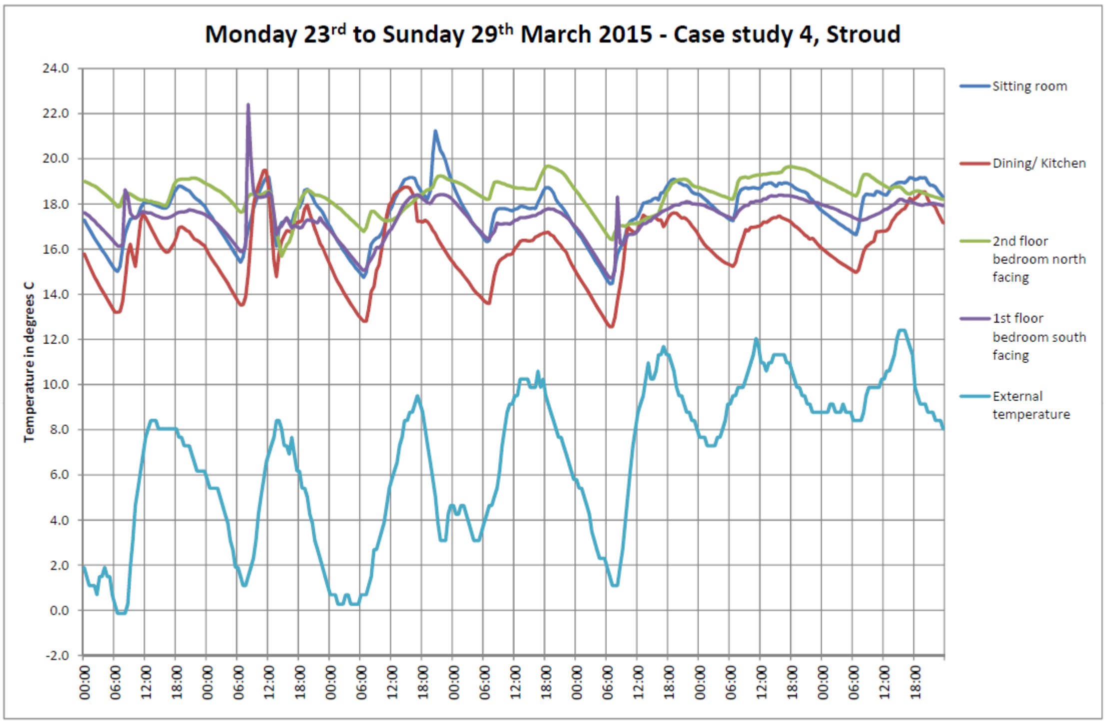
The ventilation strategy can affect the winter comfort experience due to its impact on the humidity, temperature distribution and the perceived control of the users to influence their environment. The typically higher ventilation rates experienced in mechanically ventilated buildings can cause low relative humidity levels, which when below 30% can cause dryness to the skin and mucus membranes, potentially increasing the vulnerability of throat and nose to viruses. Conversely where ventilation rates are low the relative humidity levels can rise above recommended levels and while this may not be perceived by users, it can cause mould growth, notably where cold bridges occur in the construction. The perceived personal control of the internal temperature can be missing in centrally mechanically ventilated buildings, and even though control is typically available it may appear complex and unusual. In contrast 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 distribution is affected by the system of heat provision in the building and in mechanically ventilated homes, especially those with heat recovery and top-up heating integrated within the ventilation systems, the temperature tends to be constant throughout the whole building. Decentralized ventilation systems in conjunction with room controlled heating sources can more readily create different thermal zones within a building that respond to different users' preferences.

The summer comfort within a building depends on the building's ability to exclude solar gains with insulation and shading, draw in and move cooler air within the building and expel hot air from the building, and absorb excessive heat within the building fabric to avoid raising the internal temperature (Mavrogianni, 2014; Porritt, 2011; Porritt, 2012). The choice of mechanical centralized ventilation is particularly aimed at achieving good winter performance and in summer such buildings often also use the opening of windows as a means of cooling the space. The use of MVHR per se has not been shown to avoid overheating, and buildings with MVHR, including certified Passivhaus dwellings, have been shown to overheat in southern, central and northern Europe (Mcleod et al, 2013).

The thermal experience in well-insulated and airtight buildings: the experience in the case-study buildings in winter

The winter experience in the case-study buildings reflected the impact of the radiant surface temperature on the perception of thermal comfort. All occupants reported temperatures between 17°C and 22 °C being comfortable, suggesting that the impact on higher radiant surfaces could have improved the perceived comfort at lower temperatures. Three buildings experienced lower than 17°C temperatures, two of which were the same building design that included a lower level kitchen, which the users considered cool to cold at between 15°C and generally not more than 18°C (Figure 4). The third building experienced temperatures of 15-16°C at times in the living room with an average temperate of 17°C during daytime hours in winter, but the users considered the environment comfortable. The latter example may well have combined the physiological impact of radiant temperatures with the psychological impact of having control over the environment and indeed having designed the space, as the owner is also the building designer.

Figure 4 – Typical winter performance of case-study building showing cool to cold kitchen area.



The user feedback also reflected the fact that occupants in less airtight buildings can experience more air movement. However the case-study occupants who noted the air movement did not consider that uncomfortable and did not express a wish to reduce the air movement.

User preferences also clearly manifested themselves in the monitoring data. The thermal requirements of different rooms in a house depend on how the building is used, whether it is used by a family or single persons or as shared house. For instance, Case-study 6 is used as a family home and Figure 5 shows how the kitchen and living room are heated to 21-22°C, while the bedrooms are between 16°C and 20°C. Case Study 1 (Figure 6) is a shared house and the occupants choose to heat their own rooms according to their personal preferences. Both Case Studies 1 and 6 successfully provide the opportunity to create different thermal zones that suit a variety of potential users. Most traditional homes with cellular arrangements of spaces offer the opportunity to create separate thermal zones.

Figure 5 – The living and kitchen rooms are between 2-4°C warmer than the bedrooms.

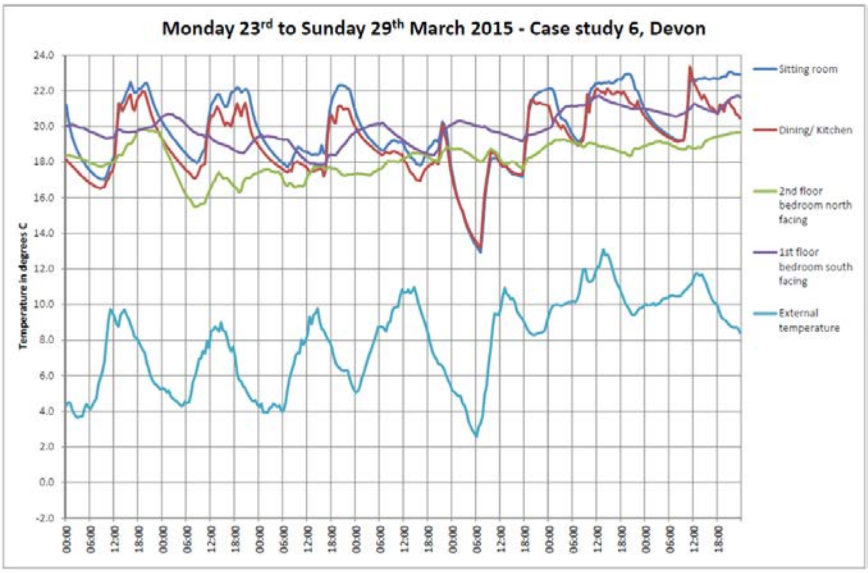
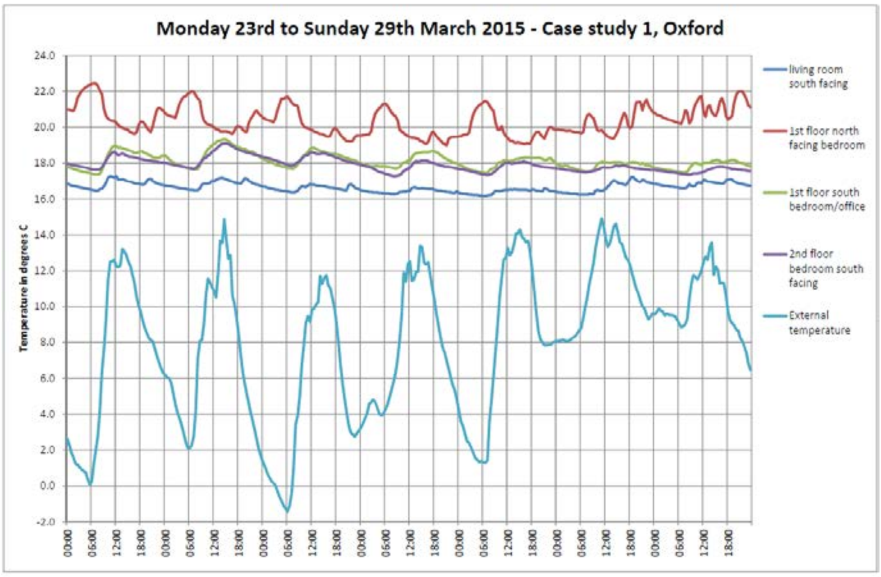


Figure 6 – In this shared house each occupant heats their personal space to their preferred temperature. The living room is less used by the occupants and not heated as much, not only because it is used infrequently but also because it is open plan and linked to a dining area and therefore constitutes a large and difficult to heat space.



The thermal experience in well-insulated and airtight buildings: the experience in the case-study buildings in summer

The summer performance of the case-study buildings relied, like most dwelling in the UK, on opening windows to provide ventilation. One of the case studies only had shading on the whole south-facing façade, the other cases studies had limited shading provided by curtains. Three of the case studies had thermally massive floor and walls with timber framed roof, the others had a thermally massive ground floor and timber framed walls and roof. The case studies monitoring highlighted a number of phenomena that are instructive when considering the design for summer comfort through natural ventilation. Some confirm or question well-understood principles, others relate to less common considerations.

Rooflights

Avoiding solar gains is a fundamental aim of creating a thermally comfortable internal environment in summer. During the summer months when the sun is at its highest point in the sky, the most exposed glazed surfaces are those that are horizontal. Therefore at the hottest time of the year, rooflights provide significant unwanted heat gains. Data from Case-study 3 illustrated this in relation to the small bedroom on the second floor which has a large roolight. On one of the hottest days of 2016 the building was unoccupied and sealed. The internal temperatures in second floor bedroom rose from 25°C to 40°C in 10 hours before the occupant returned and opened the rooflight, allowing in external air, which at 34°C was still very hot but cooler than the internal air. It is important to note that all other spaces with south-facing vertical glazing were 6 °C cooler (peaking at 34°C). If rooflights are needed, providing external shading or roller shutters that can prevent the solar gains to enter the building is essential.

Thermal mass

The data showed no direct relationship between overheating in lightweight compared to 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 in IES confirmed only minimal impact of thermal mass in the case-study buildings.

Ventilation design

To provide effective cross or single-sided ventilation, stack ventilation or night time ventilation the window design and the configuration of openings is critical. The case studies included examples of effective cross and stack ventilation.

The effectiveness of cross ventilation can be seen in Case-study 2 bedroom on the second floor. Figure 7 shows how upon return to the house at 18.30, the occupant of the bedroom opens the window and rooflights on either side of the room (Figures 8 and 9) and the temperature drops 3 °C in three hours. At just above 21 °C the window is closed as the temperature is considered comfortable. It is also worth noting that the north-east facing bedroom on the 1st floor with no direct solar gain and very well insulated in all directions (floor, roof and walls) retains a stable temperature of between 20.5 °C and 21.5 °C through the whole day.

Figures 7 – Case-study 2 temperature experienced in three locations within the building on a typical warm to hot day.

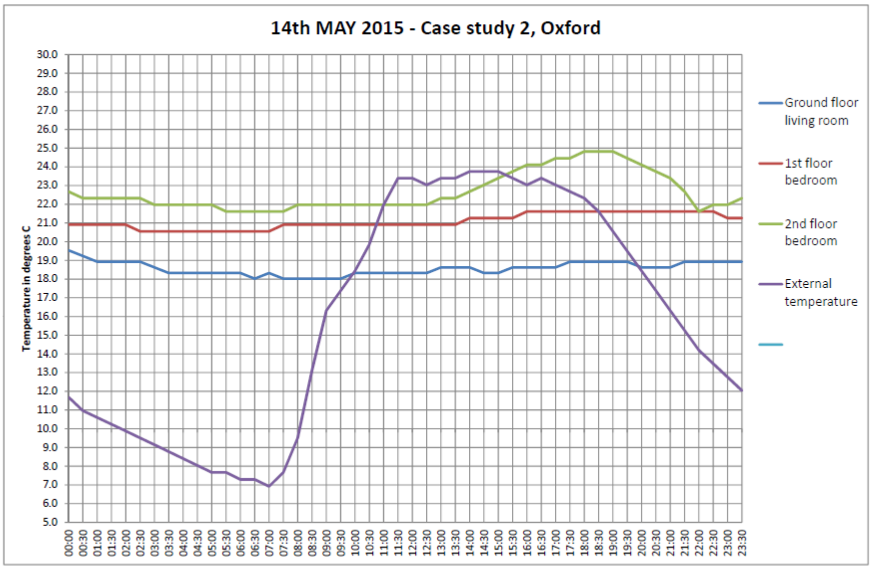


Figure 8. Case Study 2 top floor bedroom has good cross-ventilation. View of the rooflight on one side of the room.

Figure 9. Case Study 2 view of the window on south-west side of the room to provide cross-ventilation.

Case Studies 4 and 5 are examples of effective stack ventilation in practice. Both have the same design that includes a large stair case that is open to the lower two split levels. This configuration allows air to move freely and creates an effective stack effect where hot air can exit through a rooflight at the top of the stairs. Case Study 1 also has a central stairs designed to draw air up, but the stair small and enclosed and the lack of connections to the living spaces around it means it is not perceived by the occupants as working effectively as a means of passive stack ventilation.

Safety is an increasing concern and it was noted that several of the occupants did not open the windows when they were outside the home for safety reasons. Safe ventilation options are available to address such concerns. The Hanson EcoHouse at the BRE Innovation Park includes windows with safe night ventilation louvers (Figure 10), which may need to become more commonly used.

Figure 10 – Louvered window proving safe ventilation.

Thermal zones

The performance during a two-week period (which included a heat wave) demonstrated a clear distribution of heat in all the case-study buildings, which was primarily vertical. Case Study 1 ground floor was cooler than the first floor which was cooler than the second floor. Similar stratification can be seen in the other case studies in Table 3 regardless of whether including heavy or lightweight construction. To a lesser degree the south-facing spaces were warmer than the north facing ones. 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.

Table 3 also shows the peak temperatures reached during a two-week hot period and it is worth noting that virtually all case studies performed reasonably well in relation to the CIBSE Guide A (2006). For instance, 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 and 8.00 for

7.5 hours of which 4 hours were below 25°C. Also important to note is that the occupants overall felt comfortable in their homes, even if they judged the environment to be slightly warm or even too warm.

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 decentralized 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 (11) (32.2)
2 - Oxfordshire - M - MV	21.72 (19.9) (23.7)								24.20 (19.8) (32.2)		18.68 (11) (32.2)
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 (11.3) (38.5)
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 (10.2) (31.1)
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 (10.2) (31.1)
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 (12.2) (27.1)
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 (12.2) (27.1)
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 (12.2) (27.1)
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%

Discussion and conclusion

The case studies monitored were sufficiently varied that a direct comparison between case studies is not appropriate but some observations can contribute to a better understanding and design of ventilation system and buildings.

IAQ

1. (1) Overall the study suggests that decentralized ventilation systems in highly insulated buildings can provide adequate to good indoor air quality. While IAQ measurements taken in summer time, when the windows were mainly kept open, were better than in winter, the pollutants levels measured in winter do not suggest unhealthy environments.
2. (2) While the data related to the case-study buildings were unclear, additional tests showed that any burning of fossil fuels can be associated with NO2 emissions and that while these are short-lived and local their avoidance would be preferable.
3. (3) The data also confirm other studies that found no direct relation between CO2 levels and levels of TVOC or other chemicals. In the case studies investigated the CO2 levels in some case studies were above the Well Building Standard recommendations of 800ppm; however the perception of the occupants was still of good air quality.

Thermal comfort

4. (1) The occupants' surveys reflected a high level of thermal satisfaction experienced by all occupants. Even when the spaces were considered slightly too warm or slightly too cold the satisfaction was reported as high. Considering that the internal temperatures were often not in line with what the

thermal comfort standards recommend, it is worth considering that the standards may not yet reflect the wide range of thermal preferences experienced in reality.

5. (2) The user satisfaction cannot be considered without acknowledging the ‘forgiveness factor’ of failings experienced by users of spaces they are emotionally attached to, such the overheating experienced in Case-study 3. Also, having emotionally invested in a building, meant in relation to the case studies that the occupants mainly, but not without exception, knew how to best manipulate their home to create a comfortable environment.
6. (3) The case-study data identified some examples of good and effective practice, such as effective cross and stack ventilation, but an equal number of ineffective solutions, which suggests a lack of adequate knowledge in the industry.
7. (4) The study also highlighted that some solutions, which would help us to create more comfortable environments especially in a scenario of climate change, are still underused in the industry, for instance external shutters and shading and secure ventilation openings.
8. (5) The thermal zones identified in the study also appear to be underappreciated by building designers and could be considered in the design of buildings with natural and decentralized ventilation systems.

In conclusion, the study supports the potential for the use of decentralized and natural ventilation in housing in a mild climate, such as that of the southern UK. However, the study also shows that while the case-study buildings overall work well, some of the ventilation and thermal comfort solutions applied in the case-study buildings could be improved. Considering that architects were involved in the design of all case-study buildings, and keeping in mind the other reports of building failures related to well-insulated buildings (AECOM, 2011; Mavrogianni et al, 2015; NHBC, 2012; Zero Carbon Hub, 2015) one could conclude that it is essential for the building industry to achieve a better understanding of the operation of well-insulated buildings and in particular their ventilation, if the industry is to provide the enhanced energy building performance required to reduce the risk of climate change. To support such improvements building professionals need to be aware of the significance of good ventilation design on the performance and perceptual success of designs. More research work is also required as well as the development of effective vehicles for disseminating the good practice in the field.

References

AECOM, 2012. Investigation into overheating in homes: Literature review. London: Department for Communities and Local Government.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). 2010. Standard 55 Thermal Environment Conditions for Human Occupancy. Atlanta, GA: ASHRAE.

Baker, N.V.; Standeven, M.A., 1996. Thermal comfort in free-running buildings. *Energy and Buildings* 1996,23, 175–182.

Beko, G.; Clausen, G.; Weschler, C., 2008. Is the Use Of Particle Air Filtration Justified? Costs and benefits of filtration with regard to health effects, building cleaning and occupant productivity. *Building and Environ*ment 2008, 43, 1647–1657.

Brager, G.S.; de Dear, R.J., 1998. Thermal adaptation in the built environment: A literature review. *Energy and Buildings*. 1998, 27, 83–96.

BSI (British Standards Institution). (2007). *BS EN 15251: 2007, Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*. London: BSI.

Building Bulletin, 2006. *Building Bulletin 101. Ventilation of School Buildings. Regulations Standards Design Guidance*. Version 1.4 – 5th July 2006

Building Regulations, 2010. *Building Regulations Approved Document F1, Means of Ventilation.* London: NBS.

Chianga,C. and Laib, C., 2002. A study on the comprehensive indicator of indoor environment assessment for occupants' health in Taiwan. *Building and Environment*. 37 (2002) 387–392.

CIBSE, 2015. *CIBSE Guide A: Environmental Design*. London: Chartered Institution of Building Services Engineers.

Clancy, E., 2011. *Indoor Air Quality and Ventilation. CIBSE Knowledge Series: KS17*. London: The Chartered Institution of Building Services Engineers.

Daisey, J.M., Angell, W.J., Apte, M.G. 2003. IAQventilation and health symptoms in schools: an analysis of existing information, *Indoor Air* 13 (1) (2003) 53–64.

Delos Living LLC, 2015. The Well Building Standard. New York: International Well Building Institute.

Department of Business, Energy and Industrial Strategy (DBEIS) (2016) Energy Consumption in the UK. London: DBEIS.

Dougan D.S. and Damiano L., 2004. CO2 -based demand control ventilation. Do risks outweigh potential rewards? ASHRAE Journal, October 2004: 47-53.

European Commission, 2002. *Screening study to identify reductions in VOC emissions due to the restrictions in the VOC content of products. Final Report. February 2002*, Brussels: European Commission.

ISO (International Standards), 2008. *Building environment design — IAQ— Methods of expressing the quality of indoor air for human occupancy ISO 16814:2008(E).* Geneva: International Standards.

Jenkins, G. J., Murphy, J. M., Sexton, D. M. H., Lowe, J. A., Jones, P., & Kilsby, C. G., 2009. *UK climate projections: Briefing report.* Exeter, UK: Met Office Hadley Centre, United Kingdom Climate Impacts Programme.

Kephalopoulos, S., Koistinen, K., and Kotzias, D. 2006. *Strategies to determine and control the contributions of indoor air pollution to total inhalation exposure*

(STRATEX). European Collaborative Action Report No 25. Luxembourg: European Commission.

Kotzias, D., Koistinen, K., Schlitt, C., Carrer, P., Maroni, M., Jantunen, M. 2004. *Summary of recommendations and management options. Critical appraisal of the setting and implementation of indoor exposure limits in the EU. EUR 21590 EN. INDEX project*. Ispra, Italy: European Commission, Joint Research Centre.

Malte Meinshausen et al (2009) Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature* 458, 1158-1162 (30 April 2009)

Mavrogianni, A., Davies, M., Taylor, J., Chalabi, Z., Biddulph, P., Oikonomou, E., Jones, B., 2014. The Impact of Occupancy Patterns, Occupant-controlled Ventilation and Shading on Indoor Overheating Risk in Domestic Environments. *Building and Environment*, 78, 183–198.

Mavrogianni, A., Taylor, J., Davies, M., Thoua, C. and Kolm-Murray, J., 2015. Urban social housing resilience to excess summer heat. *Building Research & Information*, 43:3, 316-333.

Mcleod, R.S. , Hopfe, C. J., Kwan, A., 2013. An investigation into future performance and overheating risks in Passivhaus dwellings. *Building and Environment*, Dec, 2013, Vol.70, (21) p.189-209.

Nga,M.O., Qua,M., Zhen,P., Li, Z., Hanga, Y., 2011. CO_2-based demand controlled ventilation under new ASHRAE Standard 62.1-2010: a case-study for a gymnasium of an elementary school at West Lafayette, Indiana. *Energy and Buildings* 43 (2011) 3216–3225).

Nicol, F. Humphreys M and Roaf, S (2012) *Adaptive Thermal Comfort. Principles and practice*. London: Routledge

NHBC, 2012. *Overheating in new homes. A review of the evidence. NF 46*. Milton Keynes: NHBC Foundation.

Pachauri, R.K. and Meyer, L.A. eds., 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Geneva, Switzerland: IPCC.

Petty, S., nd. Summary of ASHRAE'S Position on Carbon Dioxide (CO2) Levels in Spaces, *Energy & Environmental Solutions*, Inc. www.eesinc.cc/downloads/CO2positionpaper.pdf accessed 26 January 2016).

Porritt, S. M., Shao, L., Cropper, P. C., & Goodier, C. I., 2011. Adapting dwellings for heat waves. *Sustainable Cities and Society*, 1, 81-90.

Porritt, S. M., Cropper, P. C., Shao, L., & Goodier, C. I., 2012. Ranking of interventions to reduce dwelling overheating during heat waves. *Energy and Buildings*, 55, 16–27.

Sassi, P., 2013. A Natural Ventilation Alternative to the Passivhaus Standard for a Mild Maritime Climate. *Buildings* 2013, 3, 61-78.

Satish,U., Mendell, M.J., Shekhar, K., Hotchi, T., Sullivan, D., Streufert, S., Fisk W.J., 2012. Is CO_2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO_2 Concentrations on Human Decision-making Performance. *Environmental Health Perspectives.* 120 (12) 1671-7.

SCHER (Scientific Committee on Health and Environmental Risks) 2007. *Opinion on risk assessment on indoor air quality, 29 May 2007.* Brussels: European Commission

Seifert, B., 1999. Richtwerte für die Innenraumluft. Die Beurteilung der Innenraumluftqualität mit Hilfe der Summe der flüchtigen organischen Verbindungen (TVOC-Wert). *Bundesgesundheitsblatt, Gesundheitsforsch – Gesundheitsschutz,* 1999 42: 270–278.

Taylor, J., Shrubsole, C., Davies, M., Biddulph, P., Das, P., Hamilton, I., Oikonomou, E., 2014. The modifying effect of the building envelope on population exposure to PM2.5 from outdoor sources. *Indoor Air*, 24(6), 639–651.

UK Government (2008) *Climate Change Act 2008*. Chapter 27. The Stationery Office: Norwich, UK.

Wolfsense, 2014. *Utilizing PIDs (forVOCs) During IAQ Investigations. Application Note PID-IAQ-R2 8/14.* Shelton: Wolfsense.

WHO, 2010. *WHO guidelines for indoor air quality: selected pollutants*. Bonn: World Health Organisation European Centre for Environment and Health.

Zero Carbon Hub, 2015. *Impact of overheating. Evidence review*. London: Zero Carbon Hub.