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BEDROOM ENVIRONMENTAL CONDITIONS IN AIRTIGHT MECHANICALLY VENTILATED DWELLINGS

Gráinne McGill[1,*], Lukumon Oyedele[2], Greg Keeffe[3], Keith McAllister[3], Tim Sharpe[1]

[1] Mackintosh Environmental Architecture Research Unit (MEARU), Mackintosh School of Architecture, The Glasgow School of Art, Glasgow, UK, G3 6RQ
[2] Bristol Enterprise Research and Innovation Centre (BERIC), University of West of England, Bristol, UK, BS16 1QY
[3] School of Planning, Architecture and Civil Engineering, Queen's University Belfast, UK, BT9 5AG

[*]Corresponding email: g.mcgill@gsa.ac.uk

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SUMMARY

The indoor environmental quality in energy efficient dwellings is a significantly important yet under-researched area, particularly in bedrooms where people spend much of their time and adaptive ventilation behaviour is restricted. This paper presents the results of an indoor environmental assessment of four new build energy efficient social housing projects; focusing specifically on bedroom conditions. The study involved monitoring of bedroom temperature, relative humidity and carbon dioxide levels during summer and winter seasons, the use of an occupant diary to record conditions during the monitoring period in conjunction with occupant interviews to examine perception of the indoor environment and occupant behaviour in the dwellings. The findings indicate significant issues with night time ventilation; which suggests inadequate ventilation strategies in the case study dwellings. In addition, temperature and relative humidity levels regularly exceeded recommended levels for comfort and health. The findings demonstrate a potential negative effect of contemporary energy efficient housing design strategies on bedroom environmental conditions; highlighting a possible risk to occupant health and wellbeing.

INTRODUCTION

Bedrooms are the spaces in which occupants spend the most uninterrupted time, typically 7–8 hours, and children may also use bedrooms for socialising and schoolwork in which case they could spend almost all their time at home in the bedroom. Furthermore, bedrooms over-night present steady-state conditions with occupants asleep, with little or no adaptive behaviour – ventilation regimes established at the time of going to bed remain in force overnight. Accordingly, environmental conditions in bedroom spaces are of particular interest when examining indoor air quality (IAQ). Not only do these spaces provide the greatest exposure to occupants, but confounding variables in respect of ventilation effects are minimised. Yet the bedroom environment is often neglected in IAQ research. This may be attributed by issues regarding access to privatised spaces in dwellings and the potential for disruption to sleep from research equipment noise or lights. However increasing public concern regarding IAQ and sleep quality has emphasised the need to assess the quality of the bedroom environment, particularly in contemporary airtight dwellings.

Ventilation is considered one of the most substantial determinants of IAQ (Persily, 2006), which in turn can have a significant effect on occupant health, comfort and productivity (Wargocki, 2013). Previous research has identified ventilation as an area of concern in European dwellings (Dimitroulopoulou, 2012). Whole house ventilation rates above 0.5 air changes per hour (ACH) are recommended to reduce the risk of house dust mite proliferation (Wargocki et al., 2002) allergic manifestations, asthma symptoms (Sundell et al., 2011), and condensation indoors (BRE, 1989). However, a number of studies have identified significantly lower dwelling ventilation rates in practice (Dimitroulopoulou et al., 2005; Sharpe et al., 2014b).

For instance, a recent study funded by the Scottish Government demonstrates fundamental issues with the provision of adequate ventilation in naturally ventilated bedrooms (Sharpe et al., 2014a). This was attributed to a number of factors, including window opening, wind conditions, trickle vent positioning, and internal door opening. As a result, proposals have been made for amendments to the Building Regulations in Scotland to make carbon dioxide (CO_2) meters in principle bedrooms compulsory in dwellings constructed to an airtightness of less than 15 $m^3/hr/m^2$ @50Pa. It is anticipated that this would help raise awareness of elevated CO_2 levels (and therefore ventilation) in bedroom environments, which is currently lacking.

Correspondingly, apprehensions of inadequate ventilation provision in dwellings with Mechanical Ventilation with Heat Recovery (MVHR) systems have been expressed (Crump et al., 2009; Sullivan et al., 2013). As described by the Innovation and Growth Team (2010), 'The industry has a lot to learn about how these new homes will perform, especially with inter-related issues such as summer overheating, air-tightness and indoor air quality.' Studies have demonstrated significant shortcomings in the installation (DCLG, 2008), commissioning (Balvers et al., 2012), performance (Macintosh and Steemers, 2005), use (Dengel and Swainson, 2013) and maintenance (Leyten and Kurvers, 2006) of MVHR systems in practice. The need to monitor and evaluate IAQ therefore is paramount to ensure occupant health and wellbeing is not adversely affected in the drive towards energy efficiency.

This study focused on new build dwellings constructed to airtightness levels of less than 5 $m^3/hr/m^2$ @50Pa; ventilated using MVHR, Mechanical Extract Ventilation (MEV) or trickle vents. Night time bedroom environmental conditions were investigated under typical occupancy conditions to evaluate the effectiveness of ventilation strategies in the contemporary airtight dwellings. A range of building typologies was considered, specifically timber frame and cavity wall constructions. The effect of occupant behaviour (including window opening, occupancy levels and internal door opening) was also examined.

METHODOLOGIES

A Case Study methodology was employed, which consisted of an investigation of four new build contemporary social housing projects located in the United Kingdom

(Northern Ireland and England). A description of the case study projects is presented in Table 1. The Case Study dwellings were designed to various levels of the Code for Sustainable Homes rating scheme (level 3 to level 6), with five dwellings also achieving the German 'Passivhaus' accreditation. The dwellings were constructed to an airtightness level of less than $5m^3/hr/m^2$, with cavity wall or timber frame construction methods.

Table 1. Case study information

Case study	Building type	House No.	Airtightness ($m^3/h.m^2$)	Construction type	Glazing	Ventilation strategy	Dwelling constructed
1	Code 6	No.1	2.71	Cavity wall	Triple	MVHR	Jan-13
		No.2	2.71	Cavity wall	Triple	MVHR	Jan-13
		No.3	2.71	Cavity wall	Triple	MVHR	Jan-13
	Passivhaus	No.1	0.44	Cavity wall	Triple	MVHR	Mar-13
		No.2	0.42	Cavity wall	Triple	MVHR	Mar-13
	Code 3	No.1	4.85	Timber frame	Double	MEV	Jan-13
		No.2	4.98	Timber frame	Double	MEV	Jan-13
2	Code 4	No.1	1.40	Timber frame	Triple	MVHR	Mar-11
		No.2	1.50	Timber frame	Triple	MVHR	Mar-11
		No.3	2.40	Timber frame	Triple	MVHR	Mar-11
		No.4	2.20	Timber frame	Triple	MVHR	Mar-11
		No.5	2.20	Timber frame	Triple	MVHR	Mar-11
		No.6	2.20	Timber frame	Triple	MVHR	Mar-11
3	Code 4	No.1	2.10	Cavity wall	Triple	MVHR	Feb-13
		No.2	2.04	Cavity wall	Triple	MVHR	Feb-13
		No.3	2.04	Cavity wall	Triple	MVHR	Feb-13
		No.4	2.04	Cavity wall	Triple	MVHR	Feb-13
	Code 3	No.1	4.80	Timber frame	Double	Natural	Nov-10
		No.2	4.60	Timber frame	Double	Natural	Nov-10
		No.3	4.20	Timber frame	Double	Natural	Nov-10
		No.4	4.80	Timber frame	Double	Natural	Nov-10
4	Passivhaus	No.1	0.65	Timber frame	Triple	MVHR	Apr-12
		No.2	0.65	Timber frame	Triple	MVHR	Apr-12
		No.3	0.62	Timber frame	Triple	MVHR	Apr-12

Physical IAQ measurements were conducted in the bedroom of the Case Study dwellings over a 24 hour period, during the summer season. Winter measurements were also conducted in eight dwellings in Case Study 3. Measurements included bedroom temperature (resolution 0.1°C, accuracy ±0.6°C), relative humidity (resolution 0.1%, accuracy ±3-5%) and CO_2 levels (resolution 1ppm, accuracy ±3% or ±50ppm) utilising a Wohler (CDL 210) data logger. Simultaneous measurements of outside conditions were conducted utilising a weather station (Watson W-8681), which was supported by data collected from local monitoring centres. Monitoring equipment was positioned at least 1 metre from walls and 1.2 metres above finished floor level, in accordance with ISO: 16000.1. The equipment was placed away from direct pollutant sources (such as the head of the bed) and supply air vents. An occupant diary was also employed to gain information on bedroom conditions and occupancy levels during the measurement period.

RESULTS AND DISCUSSION

Bedroom environmental conditions were monitored in all dwellings during the summer season, as illustrated in Table 2. There is a general acceptance that CO_2 keeps 'bad company' and that levels above 1000 ppm are indicative of poor ventilation rates. The provenance of this is well evidenced (Porteous, 2011) and corresponds well with a ventilation rate of 8 l/s per person (Appleby, 1990). A recent paper by Wargocki (2013) identified associations between CO_2 levels and health and concluded "The ventilation rates above 0.4 h-1 or CO_2 below 900 ppm in homes seem to be the minimum level to protect against health risks based on the studies reported in the scientific literature". CO_2 levels in the Case Study dwellings exceeded 1000 ppm in all naturally ventilated and mechanical extract ventilated homes; and in 39% of dwellings with MVHR. In the naturally ventilated Code 3 dwellings in case study 3, average bedroom CO_2 levels of 2981 ppm (C3:No.1) and 3094 ppm (C3:No.3) were recorded; calculated from the reported time occupants went to bed until the reported time they got up. Night time airflow rates were calculated based on the measured CO_2 levels, utilising the constant-injection technique described by Persily (1997), and more recently Sharpe et al. (2014b);

$$Q_O = \frac{10^6 \times G}{(C_{in.eq} - C_{out})} \tag{1}$$

where:

Q_O outdoor airflow rate into space (l/s)
G CO_2 generation rate in the space (l/s)
$C_{in.eq}$ equilibrium CO_2 concentration in the space (ppm)
C_{out} outdoor CO_2 concentration (ppm)

The calculated CO_2 generation rate in the space (l/s) is based on the following assumptions:

- A metabolic rate of 41 W/m^2 (based on a person sleeping (CIBSE, 2006))
- An average body surface area of 1.8m^2 (adult) and 1m^2 (child) (Persily, 1997)
- Constant outdoor CO_2 concentration of 380 ppm
- Constant CO_2 generation rate from occupants, with no other CO_2 sources
- No significant airflow from conjoining rooms into monitored bedroom

The following formula was used to calculate the CO_2 generation rate in the space (l/s) for each person; as described in BS 5925 (1991);

$$CO_2P_P = 0.00004\ M \tag{2}$$

where:

CO_2P_P CO_2 production rate per person (l/s)
M Metabolic rate (W)

Table 2. Bedroom night time conditions during the summer monitoring period

Case study	Building Type	House No.	Window status	Door status	Bedroom	Occupancy A=Adult, C=Child	Mean CO_2 (ppm)	Max CO_2 (ppm)	Calculated outdoor airflow (l/s/p)	Mean temp. (°C)	Peak temp. (°C)	Mean RH (%)	Peak RH (%)
1	Code 6	No.1	Closed	Closed	Main	1A 1C	1031	1139	3.53	18.6	19.3	58.7	60.0
		No.2	Closed	Open	Kids	2C	663	870	5.80	20.2	21.2	43.2	45.0
		No.3	Closed	Open	Main	2A	1237	1559	3.44	24.9	25.1	50.1	50.7
	Passivhaus	No.1	Closed	Closed	Main	2A	858	967	6.17	21.4	22.1	53.4	54.4
		No.2	Closed	Open	Kids	1C	583	651	8.09	20.7	21.2	37.5	38.4
	Code 3	No.1	Closed	Closed	Main	1A	1053	1468	4.38	22.1	22.8	40.4	41.9
		No.2	Closed	Closed	Main	1A 2C	955	1489	3.61	19.8	20.7	54.1	55.5
2	Code 4	No.1	Closed	Closed	Main	2A	1231	1453	3.47	21.7	22.2	50.3	51.1
		No.2	Closed	Closed	Main	2A 1C	1091	1402	3.54	24.2	24.5	55.7	57.0
		No.3	Closed	Open	Main	1A	630	687	11.81	23.5	23.8	58.0	61.4
		No.4	Closed	Open	Kids	1C	787	886	4.03	22.6	22.9	47.2	48.6
		No.5	Open	Open	Main	2A	555	752	16.84	24.6	24.7	46.3	47.1
		No.6	Open	Closed	Main	2A	702	826	9.16	22.7	23.2	49.5	51.4
3	Code 4	No.1	Open	Closed	Main	2A	869	968	6.03	21.4	21.6	56.0	56.6
		No.2	Open	Open	Main	1A 1C	598	664	10.53	24.6	25.4	50.1	52.0
		No.3	Open	Closed	Main	2A	965	1153	5.05	21.9	22.4	49.8	51.7
		No.4	Open	Closed	Main	2A	835	965	6.49	22.4	22.6	47.9	49.6
	Code 3	No.1	Closed	Closed	Main	2A	2981	4173	1.13	24.8	24.8	57.7	59.7
		No.2	Closed	Open	Main	1A	1382	1721	2.95	23.7	23.9	50.3	51.3
		No.3	Open	Closed	Main	1A 2C	3094	3745	0.77	24.5	24.6	62.0	64.8
		No.4	Open	Open	Main	1A 1C	1002	1244	3.69	22.4	22.7	51.8	53.4
4	Passivhaus	No.1	Open	Closed	Main	1A	734	804	8.34	23.6	23.9	39.9	43.3
		No.2	Open	Closed	Main	2A	988	1520	4.86	21.8	22.5	45.1	50.3
		No.3	Open	Closed	Main	2A	1289	2557	3.25	22.0	22.6	42.2	45.3

The results suggest inadequate ventilation rates in the majority of bedrooms overnight, with ventilation rates less than 8 l/s/p in all naturally ventilated and MEV dwellings; and in 67% of dwellings with MVHR. Of the six dwellings with bedroom ventilation rates greater than 8 l/s/p, four stated that windows were open during monitoring. The lowest outdoor airflow rate was observed in one of the Case Study 3 dwellings (C3:No.3) at 0.77 l/s/p. This is of interest as the bedroom trickle vents were open in this dwelling during the monitoring period, which suggests they were not effective at maintaining adequate ventilation rates under typical occupancy. In fact, calculated outdoor ventilation rates were significantly low (<4 l/s/p) in all naturally ventilated bedrooms, despite trickle vents being opened.

Table 3. Bedroom night time conditions during winter monitoring (Case study 3)

Building type	Code 4				Code 3			
House No.	No.1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
Window status	Closed	Closed	Open	Open	Closed	Closed	Open	Open
Door status	Closed	Open	Closed	Closed	Closed	Closed	Closed	Closed
Bedroom	Main	Main	Main	Main	Main	Main	Main	Main
Occupancy (A=Adult, C=Child)	2A	1A 1C	2A	2A	2A	1A	1A 1C	1A 1C
Mean CO_2 (ppm)	929	941	1291	1169	3518	1107	2817	2004
Maximum CO_2 (ppm)	1407	1076	1578	1479	4456	1521	3268	2584
Calculated outdoor airflow (l/s/p)	5.38	4.09	3.24	3.74	0.94	4.06	0.63	1.41
Mean temperature (°C)	19.9	22.6	20.6	20.0	21.6	19.6	21.4	20.4
Peak temperature (°C)	20.4	23.3	21.2	22.2	22.7	20.1	23.7	20.7
Mean RH (%)	38.6	40.1	45.2	51.9	60.8	56.0	62.9	56.3
Peak RH (%)	39.3	41.0	47.1	54.5	63.8	58.1	65.9	58.3

Summer bedroom relative humidity levels exceeded 60% in one MVHR ventilated dwelling (case study 2: No.3) and one naturally ventilated dwelling (case study 3, C3: No.3). All average values were between 30% and 60%; with the exception of case study 3- C3:No.3 which recorded a mean value of 62%. To reduce the proliferation of house dust mites however, a threshold level of 45% relative humidity (@20-23°C) (Korsgaard, 1998) or 50% (@26°C) (Arlian et al., 1999) has been proposed; below which point house dust mites desiccate and die. Mean relative humidity levels during the night exceeded the threshold level of 45% in 79% of case study dwellings.

Mean summer bedroom temperatures exceeded 24°C in 25% of the case study dwellings, which suggests issues with night-time overheating. As demonstrated by a study of UK subjects by Humphreys (1979), sleep quality and thermal comfort begin to decrease if bedroom temperature exceeds 24°C (CIBSE, 2006). During the winter monitoring period (Table 3), mean bedroom temperatures in the case study 3 dwellings ranged from 19.6°C to 22.6°C, suggesting comfortable sleeping conditions.

Low ventilation rates during the winter season (<8 l/s/p) were observed in the main bedroom of all Case Study 3 dwellings. CO_2 concentrations peaked above 1000 ppm in the bedrooms of all case study 3 dwellings; with average concentrations exceeding 2000 ppm in three out of four code level 3 dwellings. Trickle vents were opened during monitoring in all code 3 bedrooms. The opening of bedroom windows or doors during the monitoring period did not appear to affect the results; however the degree to which the windows and doors were opened was not recorded. In addition, window and door opening data was acquired from the occupant diary, therefore the reliability of the data cannot be guaranteed.

Mean bedroom relative humidity levels during winter exceeded 60% in two code 3 dwellings, with levels peaking above 60% in three code 3 dwellings. In the code 4 dwellings, bedroom relative humidity levels remained between 30% and 60% during the night time monitoring period. Outside humidity levels ranged from 64.8% (C4: No.1) to 90.3% (C4: No.2). In the mechanically ventilated dwellings with heat recovery, outside relative humidity levels did not appear to have a significant effect on bedroom levels.

CONCLUSIONS

The results demonstrate significantly high night time CO_2 levels in the case study bedrooms, with levels reaching as high as 4,000ppm in some cases. Calculated bedroom ventilation rates did not meet the recommended 8 l/s/p in all case study dwellings during winter; and all MEV, naturally ventilated dwellings, and 67% of MVHR dwellings during summer. Issues with overheating were also identified, with 25% of dwellings recording mean night time bedroom temperatures above 24°C.

The ventilation rate results were calculated using the constant-injection method; therefore are based on a number of assumptions. In addition, the physical measurements were conducted over a short period of time, therefore may not be representative of bedroom conditions for each season. However they do indicate significant problems with bedroom ventilation in the case study dwellings. These findings cannot be generalised as they are based on a limited sample, however they do support the need for an urgent review of current Building Regulations, to ensure adequate bedroom environmental quality in all new build dwellings.

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