Topic C6: Low energy buildings

COMPARISON OF INDOOR AIR QUALITY IN MECHANICALLY VENTILATED AND NATURALLY VENTILATED SOCIAL HOUSING- A CASE STUDY

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SUMMARY

There is a significant lack of indoor air quality research in low energy homes. This study compared the indoor air quality (IAQ) of eight new-build case study homes constructed to similar levels of air-tightness and insulation, with two different ventilation strategies (four homes with MVHR/Code level 4; four homes with natural ventilation/Code level 3). IAQ measurements were conducted over a 24 hour period in the living room and main bedroom of each home during the summer season. Simultaneous outside measurements and an occupant diary were also employed during the measurement period. Occupant interviews were conducted to gain information on perceived IAQ, occupant behaviour and building related illnesses. Knowledge of the MVHR system including ventilation related behaviour was also studied. The results suggest IAQ problems in both the mechanically ventilated and naturally ventilated homes. Lower humidities were recorded in the Code 4 homes, possibly due to use of MVHR.

INTRODUCTION

There exists a significant need for IAQ research in contemporary energy efficient dwellings. As suggested by a number of recent reports, the impact of energy efficient design strategies on the quality of the indoor environment remains largely under-researched, with a worrying absence of skills and knowledge in this area (Crump et al., 2009; Innovation & Growth Team, 2010; Sullivan et al., 2013). This is despite research suggesting that the tightening of building envelopes, reduction of ventilation rates, use of new building materials and techniques with unknown consequences and the reliance on technology to provide sufficient ventilation may significantly diminish the quality of indoor air.

In particular, studies are needed to compare IAQ in low energy dwellings with IAQ in otherwise similar non-low energy dwellings. As suggested by Mendell (2013), future research questions should focus on specific energy-related factors (such as air exchange rate or ventilation strategy) and compare buildings as alike as possible excluding the particular energy related factor under consideration.

Numerous studies investigating the effects of energy efficient retrofits have been conducted, however similar studies investigating new builds are significantly lacking. For example, a study by Less and Walker (2013) investigated IAQ in 17 mechanically ventilated and naturally ventilated deep energy retrofits and found a number of faults with the mechanical ventilation systems including air recirculation, clogged outside air inlets and failed attachment of ducts to units. Studies on IAQ and energy efficiency have also focused on apartments or detached homes as opposed to terraced/ semi-detached homes (for example, Aizlewood and Dimitroulopoulou, 2006).

Furthermore, social housing is generally under-researched despite the fact that low-income households have a greater risk of exposure to indoor air pollution (Krieger et al., 2002). For example, a study by Fung et al. (2006) looked at the conflict between air quality and energy efficiency in social housing, with particular reference to occupant behavior. The results suggest a risk of negative health impact from indoor air pollution in the social housing sector. Similarly, a case study investigation of low energy social housing by Ward (2008) suggests recent changes to the UK building regulations on the provision of natural ventilation in dwellings do not ensure adequate supply of fresh air. The poor perception of ventilation by the social tenants was also highlighted.

Despite this, there remains significant emphasis on energy efficiency and fuel poverty in the social housing sector, with limited attention to indoor environmental quality (IEQ). For instance, there remains greater obligation on local authorities to adopt energy efficient design strategies for new build housing projects and for the retrofitting of existing housing stock. Also, unlike owner-occupied new build dwellings, the Homes and Community agency in the UK require new build affordable/social housing to meet the Code for Sustainable Homes Level 3 or above (Department for Communities and Local Government, 2012). The effect however of the Code for Sustainable Homes on indoor air quality is significantly under-researched.

This study aims to 1) investigate the IAQ of new build social housing in a UK context and 2) compare the results of homes designed to meet the Code for Sustainable Homes (CSH's) level 3 and level 4. This was conducted through physical IAQ measurements alongside occupant diaries, in eight new build dwellings (4x Code level 3 and 4x Code level 4). Occupant interviews were also conducted to gain information on occupants' perception of indoor air quality and thermal comfort, sick building syndrome symptoms and occupant behaviour. Building surveys were conducted on the day of the measurements to record information on general building conditions. This paper discusses the methodological approach followed by presentation of results and discussion. Finally, conclusions and further research opportunities are described.

METHODOLOGY

A case study approach was adopted in order to gain a comprehensive understanding of IAQ in new build social housing. This included an investigation on the effect of occupant behaviour/use on IAQ, the performance of MVHR systems and occupant knowledge of these systems, building related health and perception of IAQ in the Code 3 and 4 homes.

The case study homes were selected based on a number of criteria: single family social housing, availability, terraced or semi-detached, new build (≥2010), similar location and similar levels of airtightness. Each household was approached initially through the housing association, followed by a phone call to explain the study and a subsequent meeting. Simultaneous air quality measurements were then conducted in the main bedroom, living room and outside during the summer months, between July and August 2013. An occupant diary was employed during the measurements to gain information on occupancy levels and activities which may have influenced the results. For example, occupants were asked to record various activities such as opening windows, use of air polluting products, smoking, cooking, use of boost mode function, opening of internal doors and measurement room/household occupancy each hour. The diary was condensed to one A4 page for each measurement day.

Physical IAQ measurements were conducted in the main living room and bedroom at a height of approximately 1.1m above finished floor level, in accordance with ISO: 16000-1. Parameters included temperature, relative humidity and carbon dioxide, which were monitored in the living room with an Extech IAQ datalogger (Easyview EA80- RH resolution 0.1%, accuracy ±3-5%, temperature resolution 0.1° C, accuracy ±0.5 °C, carbon dioxide resolution 1ppm, accuracy ±3% or ±50ppm) and in the main bedroom and outside with Wohler CO2 datalogger (CDL 210- RH resolution 0.1%, accuracy ±3-5%, temperature resolution 0.1° C, accuracy ±0.6 °C, carbon dioxide resolution 1ppm, accuracy ±5% or ±50ppm). Formaldehyde was also monitored using a HalTech handheld formaldehyde meter (HAL-HFX205- resolution 0.01ppm, accuracy ±2%). Outside conditions were monitored with use of a weather station (Watson W-8681 Solar weather station- resolution: temperature 0.1 °C, relative humidity 1%, rain volume 0.1mm, Air pressure 0.1hPa) and data obtained from a local air quality monitoring site.

To gain information on occupant use, knowledge of the MVHR system (where applicable), perception of indoor air quality and thermal comfort, and building related health; structured occupant interviews were conducted with each household. A number of questionnaires were devised utilizing validated procedures (Berry et al., 1996; Raw et al., 1996); one for each household, one for each occupant and one for each child. A building survey was also conducted after each interview, to gain information on general building conditions.

Building Characteristics

The Code 3 (C3) and Code 4 (C4) homes are both located in Northern Ireland, within 0.3 miles of each other. The homes are all 2/3 bedroom semi-detached/town houses. As illustrated in Table 1, all Code 4 homes utilise Mechanical Ventilation with Heat Recovery (MVHR) systems for ventilation, where-as the Code 3 homes are all naturally ventilated with trickle ventilation. The dwellings are part of two new-build social housing developments; the Code 3 homes were completed in December 2010 and the Code 4 in February 2013.

Table 1. Building characteristics of Code 3 and Code 4 dwellings.

House No.	Cooking fuel	Heating fuel	Ventilation	Household occupancy	No. of smokers
C4:No.1	Gas	Gas	MVHR	3-4	2
C4:No.2	Electric	Gas	MVHR	3	0
C4:No.3	Electric	Gas	MVHR	6	2
C4:No.4	Electric	Gas	MVHR	5	1
C3:No.1	Electric	Gas	Natural	3	0
C3:No.2	Gas	Gas	Natural	2	0
C3:No.3	Electric	Gas	Natural	3	1
C3:No.4	Gas	Gas	Natural	2	1

Household occupancy levels vary from 2-6 people. In five out of eight households, at least one occupant smoked; however all households stated cigarettes were not smoked in the home, with the exception of C3: No.4. Dwelling construction of the Code 3 and Code 4 homes is outlined in Table 2.

Dwelling construction

Table 2. Construction of Code 3 and Code 4 dwellings.

Features	Code 3 dwellings	Code 4 dwellings
Construction	Cavity wall, brick outer leaf	Cavity wall, brick outer leaf
Glazing	Double glazing	Triple glazing
Floor area	2 bed 75.6m^2/ 3 bed 94.9m^2	100.9 m^2
No. of storeys	Two	Three
Orientation	East/West	North/South

RESULTS

Carbon dioxide

Carbon dioxide levels were significantly high in the living room of C4: No.3, peaking at 2558ppm (as illustrated in Table 3). High levels (above 1,000ppm) were also recorded in C4:No.2 and C4:No.4, and in C3:No.3 and C3:No.4. Mean living room carbon dioxide levels remained below the recommended guideline of 1,000ppm in all dwellings. In the main bedroom however, mean carbon dioxide levels were recorded above 1,000ppm in two Code 3 homes (C3:No.1 and C3:No.3) and in one Code 4 home (C4:No.3); with maximum levels reaching 4,173ppm (C3:No.1) and 3,751ppm (C3:No.3). In C3:No.1 and C3:No.3 the bedroom door was closed during the night, which may have contributed to the high readings. All the Code 4 homes and two Code 3 homes (C3:No.3 and C3:No.4) had the window open during the night. Figure 1 presents the carbon dioxide levels over the 24 hour period in the living room of C4: No.3.

Results from the occupant interviews suggest inadequate knowledge of the ventilation system, with all Code 4 homes stating 'not sure' when asked about various features of the MVHR system, including the current settings, changing of filters, boost mode function and location of controls. Furthermore, problems with noise of the MVHR system were reported in C4:No.1 and C4:No.4. In the Code 3 homes, three dwellings were aware of the presence of trickle vents, and stated that they were 'constantly' used for background ventilation. One dwelling (C3: No.1) however stated 'not sure' when asked about the presence of trickle vents.

Table 3. Summer carbon dioxide levels in living room (ppm).

Descriptive statistics	Code 4 (C4)				Code 3 (C3)			
	No.1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
Maximum	764	1181	2558	1474	844	752	1696	1679
Minimum	453	731	448	431	602	452	458	427
Standard Deviation	74.2	91.2	437.7	224.9	10.0	84.4	255.2	212.3
Mean	548.3	825.9	989.4	621.5	723.0	599.0	760.9	648.1

Table 4. Summer carbon dioxide levels in main bedroom (ppm).

Descriptive statistics	Code 4 (C4)				Code 3 (C3)			
	No.1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
Maximum	968	664	1153	965	4173	1771	3761	1244
Minimum	437	424	418	412	463	417	435	405
Standard deviation	191.3	67.0	254.3	189.3	1247.3	440.3	1102.2	262.5
Mean	601.5	522	674.0	645.5	1639.0	905.5	1453.9	688.9

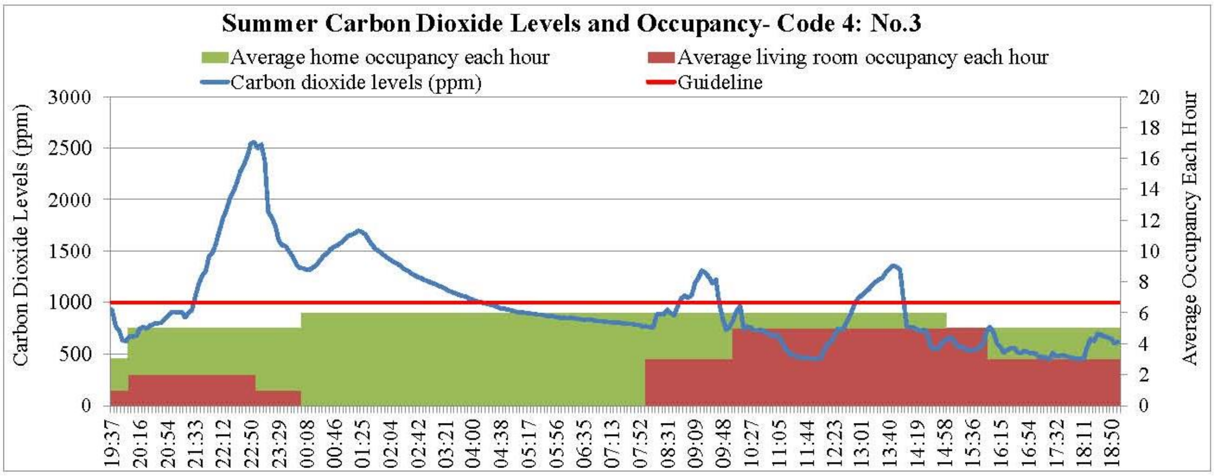

Figure 1. Carbon dioxide levels and occupancy in living room of Code 4: No.3

Temperature

As illustrated in Table 5, living room temperatures peaked at 28°C in C4: No.4, and 27°C in C4:No.2, which suggests problems with overheating. Bedroom temperatures were lower, peaking at 25.9°C (C4: No.2). Similar temperatures were recorded in the Code 3 homes, with living room temperatures in C3:No.4 reaching 27.5°C (Table 6). Average living room and bedroom temperatures ranged from 23-25°C in the Code 3 dwellings and 21-25°C in the Code 4 dwellings. During the interview process, all Code 4 households stated problems with overheating in the home, with C4:No.1 and C4:No.3 explaining it gets too warm at night. Similarly, two Code 3 households (C3:No.2 and C3:No.4) stated problems with overheating.

Table 5. Temperature (degrees Celsius) in *L: living room, *B: Main bedroom and *O: Outside in Code level 4 homes

	Code 4 (C4)											
	No.1			No.2			No.3			No.4		
	*L	*B	*O	*L	*B	*O	*L	*B	*O	*L	*B	*O
Max	25.3	23.6	25.8	27.8	25.9	27.6	25.8	22.6	24.2	28.1	22.6	27.7
Min	22.0	20.3	14.2	22.2	22.9	14.1	22.7	20.6	13.5	22.4	21.7	13.8
S.D	0.7	0.7	3.2	0.9	0.6	3.2	0.7	0.4	3.3	0.8	0.2	3.7
Mean	23.0	21.5	17.9	25.2	24.5	17.7	24.5	21.9	17.3	23.5	22.2	18.2

Table 6. Temperature (degrees Celsius) in living room and outside in Code level 3 homes.

	Code 3 (C3)											
	No.1			No.2			No.3			No.4		
	*L	*B	*O	*L	*B	*O	*L	*B	*O	*L	*B	*O
Max	25	24.9	22.9	25.4	23.9	22.5	24.8	24.6	23.2	27.5	24.6	29.9
Min	24.3	22.9	14.4	23.3	22.6	13.1	22	22.1	13.2	21.3	21.7	13.8
S.D	0.0	0.5	2.6	0.5	0.5	2.6	0.7	0.7	2.7	1.2	0.7	5.0
Mean	25.0	24.5	17.7	24.5	23.3	17.7	23.8	23.6	17.1	24.1	22.5	19.5

Relative humidity

Levels of relative humidity remained below 60% in the living room and bedroom of all Code 4 homes, with mean levels ranging from 45-54%. In comparison, relative humidity levels peaked above 60% in the living room and bedroom of C3:No.2 and C3:No.3 (Table 8). In C3:No.3, living room levels reached 70.4%, which suggests the potential for mould growth. This corresponds with the results from the interview process, as C3:No.3 reported the presence of mould in the last 12 months, on the bedroom ceilings. Mean levels of all Code 3 homes however remained below 60%.

Table 7. Relative humidity levels (%) in *L: Living room, *B: Main bedroom and *O: Outside in Code 4 homes.

	Code 4 (C4)											
	No.1			No.2			No.3			No.4		
	*L	*B	*O	*L	*B	*O	*L	*B	*O	*L	*B	*O
Max	55.3	56.9	84.6	53.3	54.1	97.5	51.4	53.8	72.8	54.5	50.5	84.4
Min	46.0	50.0	43.8	38.6	38.1	34.4	39.6	44.2	30.7	36.3	41.3	27.9
S.D	1.7	1.9	10.1	3.7	4.7	20.2	2.5	2.1	11.5	2.8	1.9	14.7
Mean	51.1	53.8	67.0	46.3	46.7	69.9	45.2	47.7	56.2	48.7	47.6	64.2

Table 8. Relative humidity levels (%) in *L: Living room, *B: Main bedroom and *O: Outside in Code 3 homes.

	Code 3 (C3)											
	No.1			No.2			No.3			No.4		
	*L	*B	*O	*L	*B	*O	*L	*B	*O	*L	*B	*O
Max	58.4	59.7	75	63.2	60.1	75.5	70.4	67.2	97.8	57.3	53.4	71.4
Min	41.5	44.2	48.5	47.4	47.3	47.5	53.4	45.6	47.7	39.9	42.8	22.2
S.D	0.9	3.5	7.5	4.1	3.1	6.1	4.4	5.8	16.9	2.8	2.6	13.8
Mean	56.6	54.6	65.2	51.1	51.7	65.9	58.1	57.6	79.7	49.0	49.5	54.8

Formaldehyde

As illustrated in Table 9, levels of formaldehyde peaked above the recommended level of 0.08ppm in two Code 4 (C4:No.2 and C4:No.4) and two Code 3 (C3:No.1 and C3:No.3) homes. Mean levels in all dwellings remained below 0.08ppm. All Code 4 households and three Code 3 households (C3:No.1, C3:No.2 and C3: No.3) reported using air-fresheners, scented candles or incense on a daily basis, which may have contributed to the results.

Table 9. Summer formaldehyde levels in living room (ppm).

Descriptive Statistics	Code 4 (C4)				Code 3 (C3)			
	No.1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
Maximum	0.00	1.85	0.03	0.18	1.02	0.04	0.10	0.00
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Standard Deviation	0.00	0.11	0.00	0.01	0.08	0.00	0.01	0.00
Mean	0.00	0.01	0.00	0.00	0.02	0.00	0.00	0.00

DISCUSSION

Recorded carbon dioxide levels peaked above 1,000ppm in the living room of three out of four Code 4 homes and two out of three Code 3 homes, and in the main bedroom of one Code 4 home and all Code 3 homes. In two of the Code 3 bedrooms, levels reached above 3,500ppm. These results suggest significant problems with ventilation in both Code 3 and Code 4 dwellings. During the measurement period, trickle vents were opened in the main bedroom of all Code 3 dwellings and the living room of three Code 3 dwellings (C3:No.1, C3:No.2 and C3:No.3). This suggests that trickle vents alone were not capable of achieving adequate background ventilation under typical conditions, particularly in the main bedroom.

Knowledge of the MVHR system was considerably lacking in the Code 4 homes. All households stated that they did not know where the controls for the system were located, or how to change the settings. The MVHR systems were located in the roof-space, which meant access to the systems was difficult. Furthermore, the lack of occupant awareness and knowledge of the system could cause significant problems in the future if the system breaks down or maintenance is required. This is particularly problematic in the social housing context as responsibility of maintaining the MVHR system may not be clearly specified. Periodic checks by the housing association therefore may be required to ensure adequate performance and maintenance.

Overheating was reported in two Code 3 and all four Code 4 homes, with IAQ measurements recording peak temperatures above 27°C in one Code 3 and two Code 4 dwellings. Overheating is emerging as a significant issue in new build dwellings, with particular concern over the lack of solar shading, inadequate ventilation and/or free cooling in low energy homes. The findings from this study suggest greater protection from over-heating may be required in the Code for Sustainable Homes rating scheme, to ensure comfortable interior environments during the summer months. Furthermore, the results raise questions about the restriction of ventilation rates and the levels of airtightness being sought in UK housing sector and whether or not it is appropriate considering future climate predictions.

Relative humidity levels rose above 70% in C3:No.3, which corresponds with the results of the interview since the presence of mould was reported in this home in the last 12 months. Levels were recorded above 60% in the living room and bedroom of C3:No.2 and C3:No.3, however all Code 4 homes remained below this level. Outside mean and peak humidity levels were higher during the measurements of all Code 4 dwellings (with the exception of C4:No.3), thus outside conditions did not significantly affect the results. Furthermore, occupant activities did not appear to affect the results. For instance, in two Code 4 homes

(C4:No.2 and C4:No.3), occupants stated that clothes were naturally dried indoors during the monitoring period, yet the relative humidity levels were generally lower than the Code 3 homes where occupants stated no clothes were naturally dried indoors. The presence of MVHR systems therefore may have contributed to the lower humidity levels. Formaldehyde levels peaked above the recommended limits of 0.08ppm in two Code 3 and two Code 4 dwellings. However, all mean values were recorded below 0.08ppm, which suggests intermittent sources may have affected the results.

CONCLUSIONS

This study investigated only a limited number of homes, thus generalisation of the results is not possible. However, the findings suggest inadequate IAQ and thermal comfort in both Code 3 and Code 4 dwellings. Lower humidities were recorded in the Code 4 homes, possibly through the use of MVHR systems. Future studies are required to investigate IAQ in low energy social housing on a larger scale, including strategies to ensure IAQ is adequately considered in the design, construction, operation and maintenance of these homes.

REFERENCES

Aizlewood C, Dimitroulopoulou C (2006) The HOPE project: the UK experience. *Indoor and Built Environment* 15(5): 393-409.

Berry RW, Brown VM, Coward SKD et al. (1996) *Indoor Air Quality in Homes: Part 1, the Buildng Research Establishment Indoor Environment Study*. Bracknell: IHS BRE Press, 1-118.

Crump D, Dengel A and Swainson M (2009) *Indoor Air Quality in Highly Energy Efficient Homes- a Review, NF 18*. Watford: IHS BRE press, 1-58.

DCLG (2012) *Improving the Energy Efficiency of Buildings and using Planning to Protect the Environment*. Available at: https://www.gov.uk/government/policies/improving-the-energy-efficiency-of-buildings-and-using-planning-to-protect-the-environment#issue.

Fung J, Porteous CDA and Sharpe T (2006) *Lifestyle as a Mediator between Energy Efficiency and Air Quality in the Home. in: Proceedings of Healthy Buildings: Creating a Healthy Indoor Environment for People, Lisboa, 4-8 June, Vol. 3, P. 11-15.*

Innovation & Growth Team (2010) *Low Carbon Construction: Final Report*. London: HM Government.

Krieger JK, Takaro TK, Allen C, et al. (2002) The Seattle-King County Healthy Homes Project: implementation of a comprehensive approach to improving indoor environmental quality for low-income children with asthma. *Environmental Health Perspectives* 110(Suppl 2): 311.

Less. B and Walker. I (2013) *Indoor Air Quality and Ventilation in Residential Deep Energy Retrofits. In Proceedings of ASHRAE IAQ: Environmental Health in Low Energy Buildings, Vancouver, Canada, 15-18 October, 2013, Pp 553-560.*

Mendell MJ (2013) *Do we Know Much about Low Energy Buildings and Health? Plenary Lecture: ASHRAE IAQ: Environmental Health in Low Energy Buildings, Vancouver, Canada, 15-18 October, 2013.*

Raw GJ, Roys MS, Whitehead C et al. (1996) Questionnaire design for sick building syndrome: an empirical comparison of options. *Environment International* 22(1): 61-72.

Sullivan L, Smith N, Adams D et al. (2013) *Mechanical Ventilation with Heat Recovery in New Homes*. London: NHBC, Zero Carbon Hub.

Ward IC (2008) The potential impact of the new (UK) building regulations on the provision of natural ventilation in dwellings - A case study of low energy social housing. *International Journal of Ventilation* 7: 77-88.