Ventilation Performance and Hygrothermal Conditions in New-build UK Housing

Gráinne McGill[1], Tim Sharpe[1], Lynette Robertson[1], Rajat Gupta[2], Ian Mawditt[3]

[1]Mackintosh Environmental Architecture Research Unit, Glasgow School of Art, UK,
[2]Low Carbon Building Group, School of Architecture, Oxford Brookes University, UK,
[3]Fourwalls, Bristol, UK, [*]*Corresponding email: gmcgill@gsa.ac.uk*

SUMMARY

Providing a high quality indoor environment is important to protect occupant's health and well-being, particularly in the home where we spend a significant amount of time. This paper explores indoor environmental conditions in mechanically and naturally ventilated new-build low-energy housing in the UK. Indoor air temperature, relative humidity and carbon dioxide data were collated and analysed from 53 dwellings across 20 different new-build demonstration projects (consisting of public and private developments). The results raise concerns regarding ventilation performance in new-build homes, particularly homes with natural/mechanical extract ventilation (MEV). Significantly less variation of temperature and relative humidity levels were observed in homes with balanced mechanical ventilation with heat recovery systems ($p=<0.001$), suggesting these systems may help to provide a more stable indoor hygrothermal environment. Average indoor air relative humidity levels were consistently higher in MVHR dwellings. The findings suggest that the type of ventilation strategy can play a significant role in regulating indoor relative humidity and air temperature in new-build thermally efficient homes.

KEYWORDS

Ventilation; Hygrothermal performance; Carbon dioxide; Indoor air quality; Moisture

1 INTRODUCTION

Dwellings consume a significant proportion of the total energy consumption for heating, hot water and electrical purposes. Consequently, to reduce greenhouse gas emissions, to improve the energy efficiency of buildings and to mitigate and adapt to climate change, a range of policies and legislations have been introduced by the UK Government. It is important to determine the impact of changes to UK domestic building regulations on the quality of the indoor environment. Growing scientific evidence indicates that energy efficiency measures do not always achieve intended results, demonstrating a gap between as-designed and as-built performance (ZCH, 2010). Moreover, some studies have highlighted potential unintended consequences of energy efficiency measures on indoor air quality and ventilation in new-build homes (McGill et al. 2016; Sharpe et al. 2014), attributed to problems at design, construction, installation and operational stages. The aim of this study was to investigate ventilation performance and hygrothermal conditions in 53 low-energy UK demonstration homes. The objectives were to: i) compare temperature and relative humidity levels in homes with and without mechanical ventilation with heat recovery (MVHR) systems, ii) identify the percentage of homes with carbon dioxide (CO_2) levels exceeding 1,000 ppm (as an indicator of ventilation performance) (Persily, 1997), iii) examine the seasonal, spatial and temporal variations of indoor conditions, and iv) identify bedroom vapour pressure levels to establish the risk of moisture problems indoors.

2 METHODS

Temperature, relative humidity and carbon dioxide data was acquired as part of the UK Building Performance Evaluation (BPE) programme, funded by Innovate UK; the aim of which was to support a range of post-occupancy evaluation and monitoring studies of low-energy demonstration projects over a two-year period (2012-2014). Data was collected in living rooms and bedrooms at five minute intervals, following requirements set out in the BPE Programme protocol. Data was collected in a centralised database (EMBED). Analysis was performed in Excel and SPSS, following cleaning of the data and manual checking to identify any sensor failures or major irregularities. Data distributions were also checked for outliers and normality. Characteristics of the demonstration projects are presented in Table 1.

Table 1. Dwelling projects' characteristics

Project	Typology	No.	Location	Ventilation
F1	Flat	5	South East	MVHR
H3	Terraced	8	East Midlands	MVHR
F4	Flat	2	South East	MVHR
H5	Detached	1	London	MVHR
F7	Flat	3	South West	MVHR
H8	Detached	2	Wales	MVHR
H9	Semi-detached	2	Yorkshire&Humber	MVHR
H10	Detached	1	Scotland	MVHR
F12	Flat	2	South West	MVHR
H14	Semi-detached	2	Northern Ireland	MVHR
H15	Semi-detached	1	Scotland	MVHR
H16	Detached	1	London	MVHR
H17	Detached	4	Scotland	MVHR
H20	Terraced/semi-detached	4	East Midlands	MVHR
F2	Flat	2	London	Mechanical Extract Vent (MEV)
H6	Terraced	2	Scotland	Intermittent extract fan
H11	Semi-detached	4	Scotland	Passive stack/intermittent extract
F11	Flat	4	Scotland	MEV / intermittent extract
H13	Terraced	3	South east	Mechanical Extract Vent (MEV)
H15	Semi-detached	2	Scotland	Intermittent extract
F18	Flat	1	Wales	Exhaust Air Heat Pump
H18	Semi-detached	1	Wales	Exhaust Air Heat Pump
H19	Terraced	2	Scotland	MEV / intermittent extract
F19	Flat	1	Scotland	Passive stack

3 RESULTS AND DISCUSSION

Ventilation performance

Overall, living room CO_2 levels above 1,000 ppm were found in 65% of dwellings during winter (February), 66% of dwellings during spring (April) and 50% of dwellings during summer (August). In comparison, in the main bedroom, CO_2 levels peaked above 1,000 ppm in 85% of dwellings during winter and spring, and 78% of dwellings during summer. The findings suggest insufficient ventilation, particularly in the bedroom environment.

Measured CO_2 levels were noticeably lower in homes with MVHR systems, as illustrated in Figure 1. The difference is stronger when comparing peak CO_2 levels in living rooms and bedrooms. For instance, in February, 11% of living rooms in MVHR homes exceeded 1,500 ppm, compared to 93% of living rooms in Non-MVHR homes. While CO_2 levels were generally highest in February and April months, it is interesting to note the high prevalence of Non-MVHR dwellings (87%) exceeding 1,000 ppm during August.

Also of interest in MVHR dwellings is, despite higher mean levels of CO_2 during February and April, the percentage of living rooms and bedrooms exceeding 1,500 ppm was greatest during the month of August (see Figures 1 and 2). This could be a consequence of MVHR systems being deactivated by occupants during summer, possibly due to overheating concerns as evidenced by Grandclément et al. (2015), or due to perceived costs of operation.

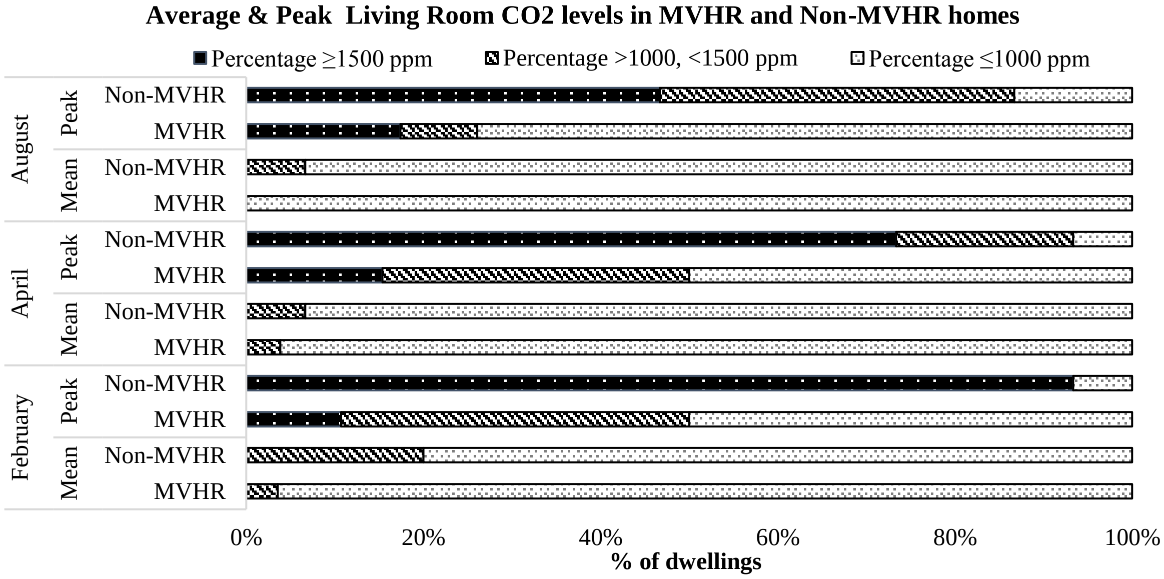

Figure 1. Living room carbon dioxide levels in MVHR and Non-MVHR dwellings

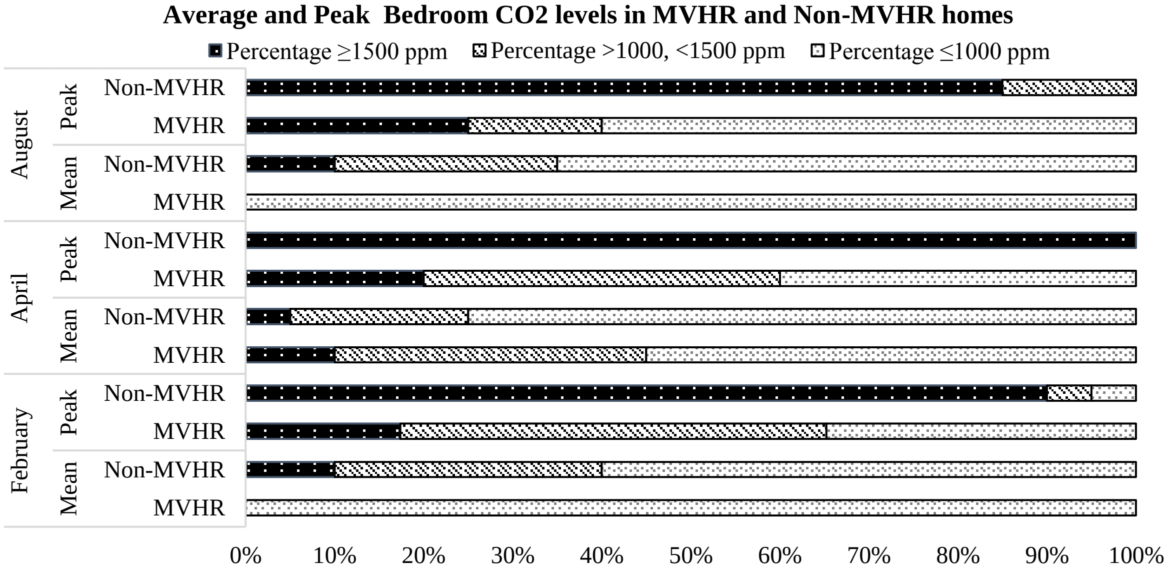

Figure 2. Bedroom carbon dioxide levels in MVHR and Non-MVHR dwellings

Hygrothermal conditions

High moisture levels can have a negative impact on building structures and occupant health and comfort, as they can lead to surface and interstitial condensation, mould growth and proliferation of House Dust Mites (HDMs) indoors (May and Sanders, 2017). Recent evidence suggests that moisture problems may be changing and/or exacerbated in some areas due to higher levels of airtightness and insulation, which may reduce the rate of removal of indoor generated moisture from cooking or cleaning activities (Vardoulakis et al. 2015; Kotol et al. 2014). In this study, measured relative humidity (RH) levels were generally low. Overall, RH levels were highest during August, with 39% of living rooms exceeding 60% RH. CIBSE (2015) recommend a maximum threshold of 60% RH to limit the growth of HDMs indoors.

It is apparent from Figure 3 that, while higher peak levels of relative humidity were observed in Non-MVHR dwellings during February and August, mean levels were consistently higher in homes with MVHR systems. This finding is contrary to previous studies which suggest mechanical heat recovery ventilation systems may provide some control against HDMs due to its ability to reduce humidity levels indoors (Warner et al., 2000; Eick and Richardson, 2011).

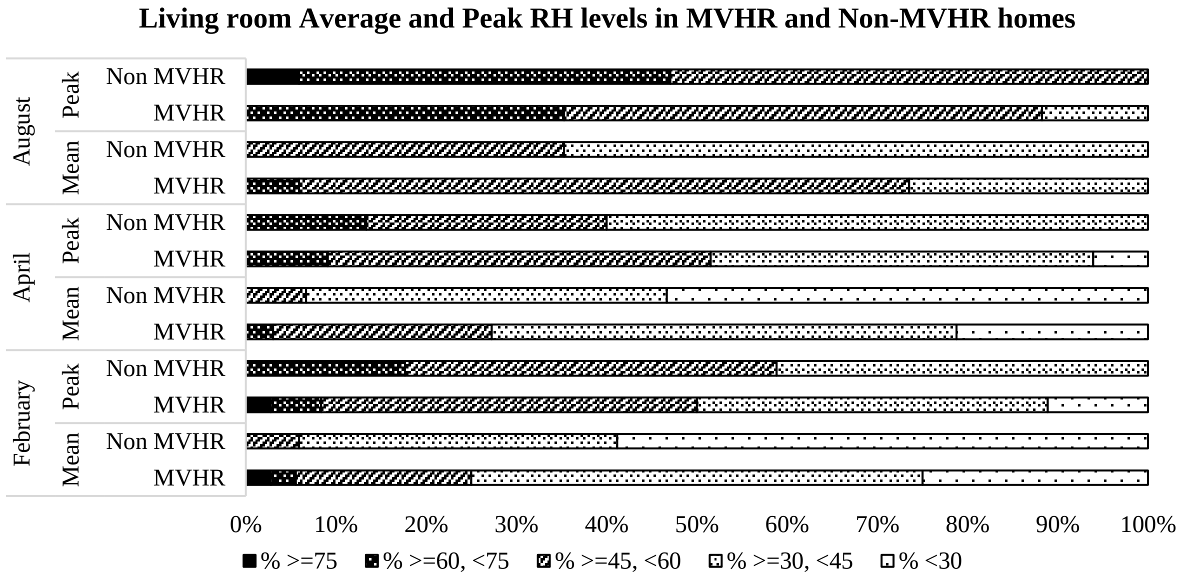

Figure 3. Living room relative humidity levels in MVHR and Non-MVHR dwellings

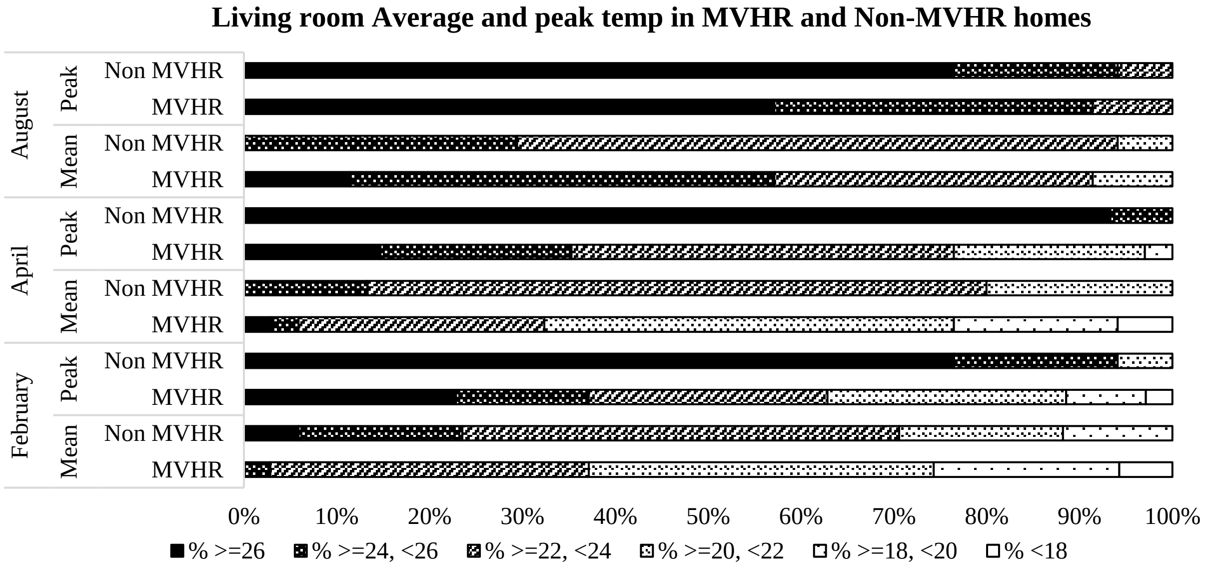

Figure 4. Living room temperatures in MVHR and Non-MVHR dwellings

Public Health England (PHE, 2015) recommend a minimum home temperature threshold of 18°C in winter for health. Overall, 4% of dwellings recorded average temperatures below 18°c during February and April months. Homes with MVHR systems were on average colder during winter and spring seasons (see Figure 4), which may be explained by higher levels of ventilation (evidenced by lower CO_2 levels) in these homes. During August however, average temperatures were higher in MVHR homes, possibly due to the lack of a summer by-pass mode in some of these dwellings.

Stability of indoor conditions

One of the most striking results to emerge from the data comparison was the significant difference between the monthly range of humidity and temperature levels in MVHR and Non-MVHR dwellings. Specifically, homes with MVHR systems were shown to have significantly lower range of humidity during February, April and August months ($P< .001$). Figure 5 illustrates the range of living room humidity levels in MVHR and Non-MVHR homes during February.

Table 2. Living room temperature levels (°C)

		Living room		Bedroom	
		MVHR	Non-MVHR	MVHR	Non-MVHR
Average temperature	February	21.1	22.8	20.3	21.6
	April	21.3	23.0	20.7	22.3
	August	24.2	23.5	24.1	23.2
Average temperature range	February	4.6	9.1	4.4	6.9
	April	4.8	10.4	4.7	7.4
	August	3.7	7.2	3.9	6.0

The difference between the range of temperatures in MVHR and Non-MVHR homes was also significant (see table 2), with lower ranges identified in MVHR homes ($P< .001$). The results indicate greater stability of indoor hygrothermal conditions in homes with MVHR systems, suggesting that the type of ventilation strategy can play a significant role in regulating humidity and temperature levels in homes. This may be explained by more consistent airflow rates (compared to naturally or mechanical extract ventilated homes), resulting in greater control of indoor climatic conditions.

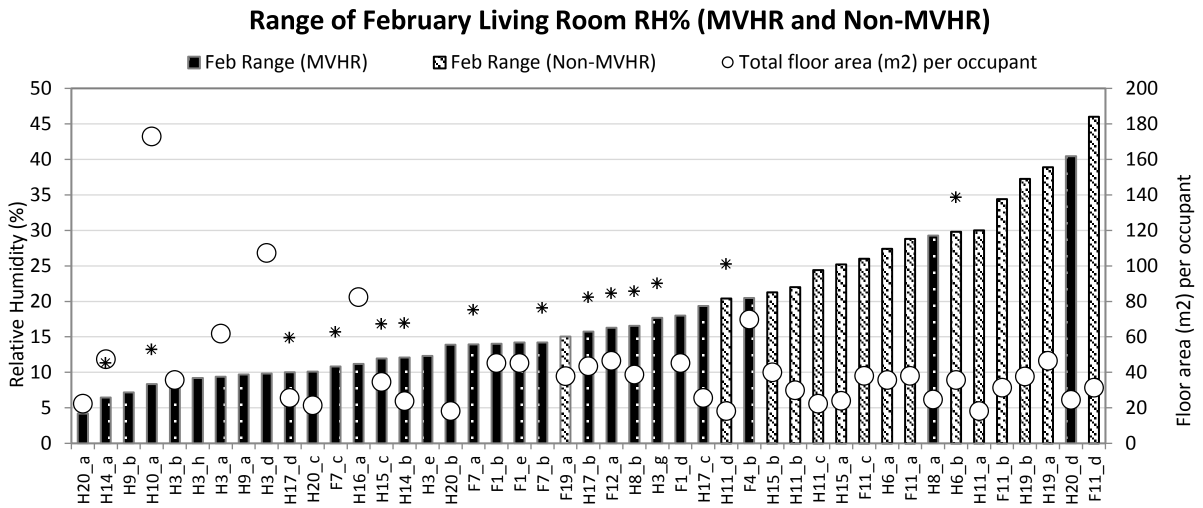

Figure 5. Range of February living room relative humidity levels in MVHR and Non-MVHR homes

These findings are consistent with those of Kalamees and Colleagues (2009), who found that ventilation had a greater effect on the indoor humidity and temperature stability than the properties of the building fabric and materials. Similarly, in a study conducted by Cunningham (1994), fluctuations of room relative humidity levels were found to be proportional to room air-change rates, suggesting building ventilation could potentially be inferred from field psychrometric data only for large studies.

Vapour pressure levels

In order to identify any potential risks associated with moisture levels indoors, vapour pressure levels were calculated, using the following equation:

$$e^{o} = 0.6108\, exp\ ((17.27\ \times T)/(T + 273.15))$$
$$e^{a} =\ (RH/100)\ \times\ e^{o}$$

Where:

e^{o} = Saturation Vapour Pressure (kPa)
T = Temperature (° C)
e^{a} = Actual Vapour Pressure (kPa)
RH = Relative Humidity (%)

Table 2. Living room vapour pressure (kPa)

	MVHR (n=31-34)				Non-MVHR (n=15-17)			
	Min VP	Peak VP	Mean VP	Range of VP	Min VP	Peak VP	Mean VP	Range of VP
Feb (mean)	0.64	1.25	0.90	0.61	0.47	1.76	0.88	1.29
Apr (mean)	0.61	1.36	0.95	0.74	0.43	1.82	0.88	1.39
Aug (mean)	1.15	1.92	1.49	0.78	0.82	2.12	1.29	1.30

Table 3. Bedroom vapour pressure (kPa)

	MVHR (n=33-37)				Non-MVHR (n=19-22)			
	Min VP	Peak VP	Mean VP	Range of VP	Min VP	Peak VP	Mean VP	Range of VP
Feb (mean)	0.65	1.29	0.90	0.63	0.52	1.54	0.93	1.02
Apr (mean)	0.61	1.37	0.94	0.76	0.51	1.61	0.94	1.10
Aug (mean)	1.15	1.98	1.49	0.83	0.90	1.98	1.34	1.08

As presented in Tables 2 and 3, there is a clear difference between the peak and range of vapour pressures in MVHR and Non-MVHR homes, corresponding to the results of the previous analysis. Average bedroom and living room vapour pressure levels were generally higher in MVHR homes during August (with notable exceptions), and the range was considerably lower. This supports the previous findings indicating that the use of MVHR systems may help to provide greater level of stability of the indoor climate.

To examine whether higher temperatures observed in thermally efficient homes could be masking moisture problems indoors, the data was plotted against Critical Equilibrium Humidity levels (CEH) and Population Equilibrium Humidity (PEH) (based on a model developed by Crowther et al. (2006), for two common dust mite species: *Dermatophagoides pteronyssinus* and *Dermatophagoides farina*. From the data in Figure 6a and Figure 6b, it can be seen that the thresholds for CEH and PEH were exceeded in one bedroom (H20_c) during February and April. In comparison, vapour pressure levels in August exceeded 7g/kg in the majority of bedrooms monitored, with levels exceeding CEH for *Dermatophagoides pteronyssinus* in 9 dwellings (6x MVHR homes, 3x Non-MVHR homes).

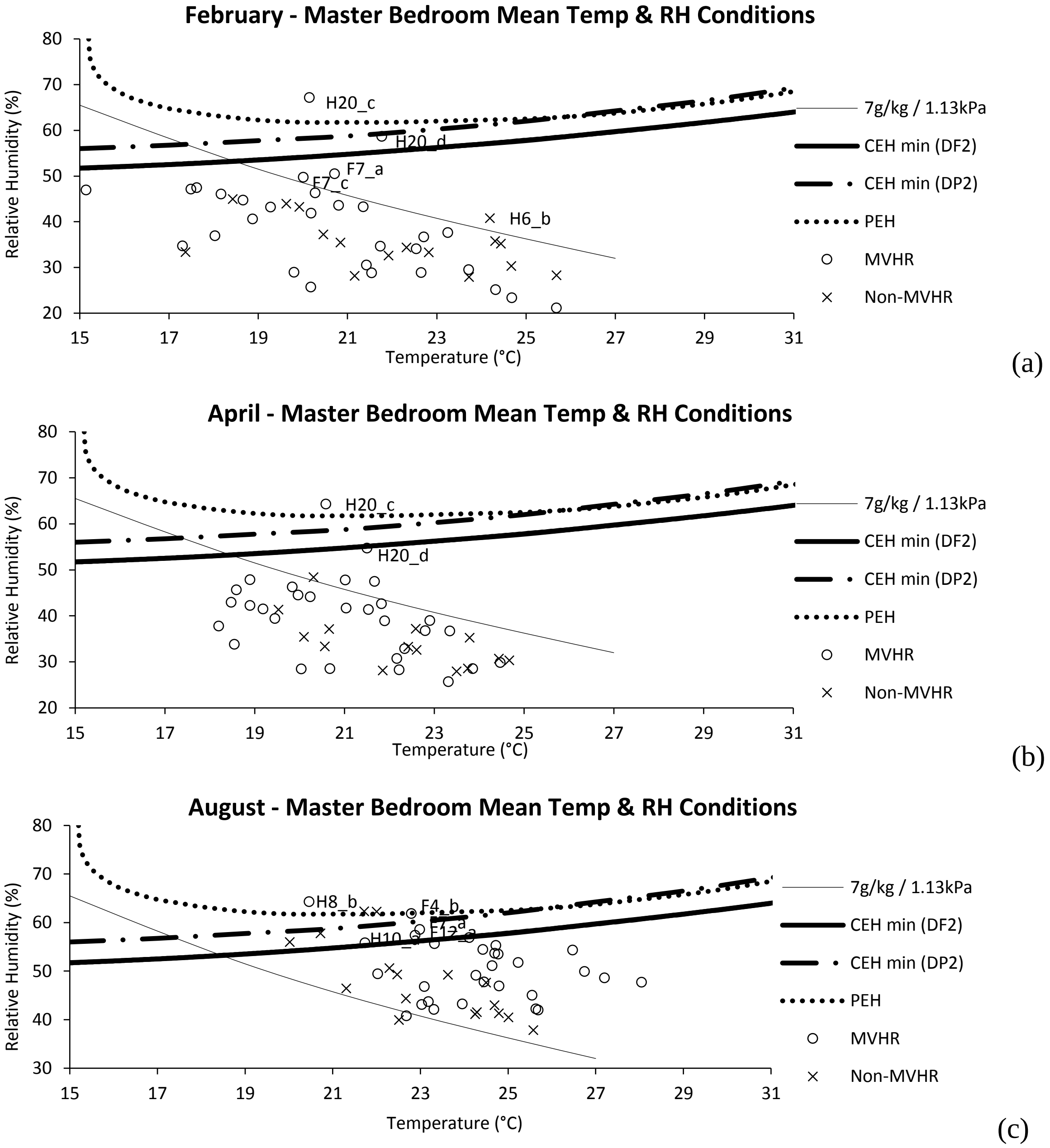

Figure 6. (a) February, (b) April, and (c) August master bedroom mean temperature and relative humidity levels

4 CONCLUSIONS

The study identifies insufficient ventilation levels (evidenced by high CO_2) in the new-build demonstration homes, which is particularly evident in bedrooms. The results suggest homes with MVHR systems were better ventilated, which was most notable during winter (February). The significantly lower range of temperature and relative humidity levels (P=<.001) in homes with MVHR systems indicate greater stability of indoor hygrothermal conditions. The findings imply that MVHR systems may help to control the indoor climate, which may have important consequences on energy performance, thermal comfort, and indoor air quality; particularly the growth of micro-organisms and HDM indoors.

Nevertheless, homes with MVHR systems were found to have consistently higher average indoor relative humidity levels and higher vapour pressure levels compared to Non-MVHR homes, suggesting a greater risk of surface/interstitial condensation and mould growth. Further work is proposed to explore in more detail the impact of ventilation design, through examination of excess moisture in indoor versus outdoor air (absolute humidity) and the presence and nature of microorganisms in MVHR and Non-MVHR homes.

There are a number of limitations to this study; therefore caution must be applied when interpreting these results. Firstly, the analysis of ventilation performance is based on CO_2 levels only and therefore does not consider the impact of other important factors such as room occupancy, CO_2 generation rate, occupant activity level, and building airtightness. Secondly, the sample sizes for MVHR (n=35) and Non-MVHR (n=18) were not equal, which may have affected the results. Thirdly, the impact of occupant behaviour on ventilation performance is not clear, as this was not objectively measured. While the dwellings were not randomly selected and may not be representative of all new build housing stock in the UK, they do represent emerging building standards and the dataset provides one of the largest bodies of comparable case study information on measured indoor environmental conditions in exemplary UK housing. As such, the results provide an interesting insight into the performance of these demonstration homes in practice.

ACKNOWLEDGEMENT
This work was funded by Innovate UK (formerly the Technology Strategy Board).

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