Building Performance Evaluation of a Retrofitted Passivhaus Dwelling in Scotland

Key Findings

GRÁINNE MCGILL[1], TIM SHARPE[2]

[1]Mackintosh Environmental Architecture Research Unit, Glasgow School of Art, Scotland

ABSTRACT: It is estimated that 80% of the 2050 building stock already exists and given targets of an 80% reduction of greenhouse gas emissions by 2050, there is a clear need to develop and evaluate retrofitting strategies that reduce energy consumption whilst achieving resilient and healthy indoor environments. This paper presents the results of a building performance evaluation of a retrofitted, Passivhaus certified dwelling in the Orkney Islands (Scotland) during the heating season. The study involved testing of the Mechanical Ventilation with Heat Recovery (MVHR) system, sound assessments, U-Value measurements, energy monitoring, a thermographic survey and indoor environmental monitoring over a three week period. The dwelling had sought to address some ventilation issues identified in other projects by the inclusion of carbon dioxide sensors as part of the MVHR control strategy. The thermal performance of the building envelope and sound level measurements of the MVHR system satisfied the Passivhaus minimum requirements, with acceptable indoor environmental quality observed throughout the monitoring period. However, the results highlighted concerns regarding energy and noise of the MVHR system in boost mode and identified some thermal weaknesses at window seals, and maintenance of the MVHR system in a social housing context. The findings of this study can be used to highlight potential problems and good practice, with the aim of reducing the gap between design intentions and measured performance in future retrofit projects.

Keywords: retrofit, building performance, Passivhaus, Scotland, indoor environmental

INTRODUCTION

The context of this work is the increasingly stringent energy requirements in buildings to meet the targets set out in the Climate Change Act (2008), specifically at least an 80% reduction in carbon emissions by 2050. A particular problem concerns the need to address the retrofit of existing buildings as it is estimated that 80% of the 2050 stock already exists (King, 2013). Passivhaus is a well-regarded low energy building standard in Europe that is gaining traction in the UK, but the need to establish actual performance of homes constructed to the standard, particularly for retrofitted projects and in varying climates, is critical. The Case Study dwelling was certified to the European one standard Passivhaus model, which sets out the following performance targets (PHI, 2015): i) Specific Heating Demand: ≤15 kWh/m^2.yr, ii) Specific Cooling Demand: ≤15 kWh/m^2.yr, iii) Specific Heating Load: ≤10 w/m^2, iv) Specific Primary Energy Demand: ≤120 kWh/m^2.yr, and v) Air Changes Per Hour: ≤0.6 @n50.

METHODOLOGY

The Case Study is a one-bed bungalow (40m^2 area), located in the Island of Orkney (Scotland) and retrofitted to the Passivhaus standard. The project was initiated to assess the actual energy performance and indoor environmental quality of the Passivhaus dwelling over a typical heating season, and identify any shortcomings if present. The L-shaped dwelling was originally a disused boiler house, with construction work completed in the summer of 2013. The project is the most northerly Certified Passivhaus in the UK, and the smallest inhabited Passivhaus in the Northern Hemisphere. The design intent was to preserve the existing protective exterior and insulate internally, with a glazed entrance porch facing south. Solar water heating is supplemented by a small heat pump and an MVHR system provides continuous ventilation, with a CO^2 sensor to boost the ventilation rate when required.

Figure 1: Front façade of Case Study dwelling

The Building Performance Evaluation was conducted over a four week period, from the 5th February to the 5th March 2015. The measurement procedure consisted of both short term testing and longer term monitoring, including the following: i) U-value testing (*Eltek SG44 HB transmitter*) ii) indoor environmental monitoring *(Eltek IAQ monitor)*, iii) external monitoring *(Tinytag, Gemini Data loggers)*, iv) a thermographic survey *(FLIR thermacam B360)*, v) sound measurements *(Pulsar Real Time Analyzer Model 30)*, vi) room survey, vii) MVHR testing *(Observator air volume flow meter)*, and viii) electrical sub-monitoring *(Eltek kWh transmitter)*. The dwelling was occupied by one person during the measurement period.

Indoor environmental monitoring equipment (recording at 5 minute intervals) was set-up at breathing height in the open plan living room/kitchen, bedroom, bathroom and utility room and remained in place over the monitoring period. U-value testing of the north facing bedroom wall and roof section was carried out, with simultaneous monitoring of external conditions, in accordance with ISO 9869:1994. Short term sound assessments were carried out with the MVHR system on normal, boost and off, at various locations (with windows and doors closed). Internal and external thermographic surveys were undertaken to identify air leakage paths, continuity and performance of insulation and condensation risk or water damage, in accordance with BSRIA 39-2011. Testing of airflow rates and heat recovery efficiency of the MVHR unit was achieved using a flow meter and thermistors to monitor air temperature at supply, extract, exhaust and inlet ducts at the MVHR unit.

RESULTS

U-Value testing

Results from the U-Value testing (within 5% accepted error by ISO9869: 1994) are presented in Table 1.

Table 1: U-Value results

Element	Measured W/m^2K	Designed W/m^2K	Passivhaus W/m^2K
Bedroom wall (N)	0.08	0.064	≤0.15
Bedroom roof (N)	0.11	0.098	≤0.15

The measured values were poorer than the designed values, however they satisfy the Passivhaus recommended criteria for walls, floors and roofs of ≤0.15 W/m2K, and therefore demonstrate excellent thermal performance of the building envelope.

Indoor environmental monitoring

As illustrated in Figure 2, carbon dioxide (CO_2) levels in the open plan living room and kitchen, bedroom and utility room rarely exceeded 1,000 ppm (recommended maximum level) during the monitoring period. Occupancy levels increased from the 5th-6th of February as a result of monitoring work, which explains the higher levels during this time.

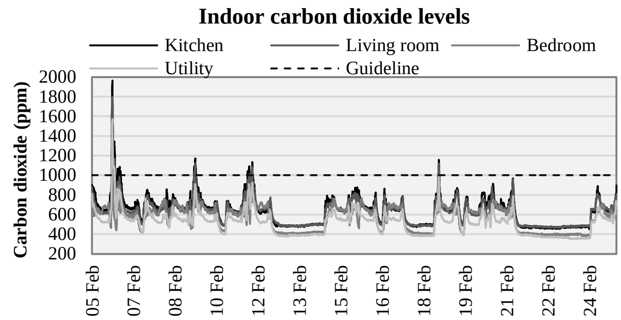

Figure 2: Indoor carbon dioxide levels

It is interesting to note that fluctuations of CO_2 during the monitoring period were similar in each of the monitored rooms, which suggests significant air movement between these spaces possibly due to the opening of internal doors. This was most notable for the living room/kitchen and bedroom spaces, with levels in general lower in the utility room. The MVHR system included a CO_2 sensor in the bedroom, which was programmed to boost the MVHR system when high levels of CO_2 are detected (e.g. >1,000 ppm). However, monitored CO_2 levels exceeded 1,000 ppm only during the initial site visit under increased occupancy conditions, ranging from 381- 1127 ppm, therefore the performance of the sensor could not be observed.

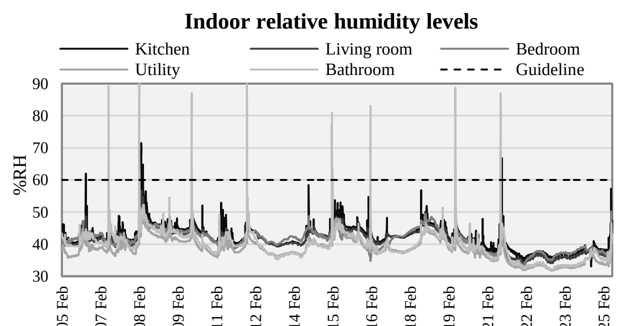

Figure 3: Indoor relative humidity levels

Relative humidity levels exceeded 60% in the bathroom and kitchen for short periods of time during the monitoring period (Figure 3), most likely as a result of cooking and/or use of the shower. In general, levels remained within the recommended limits (30-60%), with average levels of 38- 42%.

Indoor temperatures remained within comfortable levels during the monitoring period, as illustrated in Figure 4. The utility room was typically two degrees warmer than the rest of the home, principally as a result of incidental gains from white goods in this space, illustrating the potential impacts of such gains. The bedroom was the coolest, with temperatures peaking at 22.3°C. Small peaks in temperature can be observed in the kitchen space, most likely as a result of heat generated from cooking activities. During seemingly unoccupied periods, indoor temperatures did not drop significantly; however heating may still have been used (e.g. controlled by thermostat).

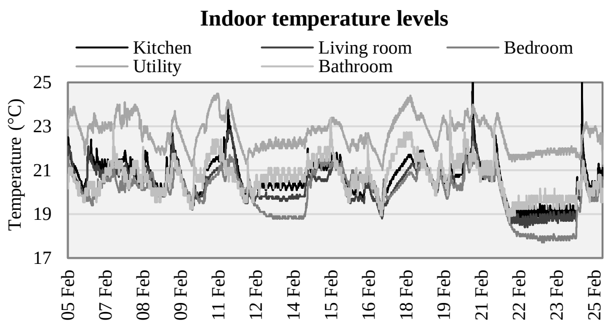

Figure 4: Indoor temperature levels

MVHR testing- air flow rates

Prior to the monitoring of airflow rates, filters were checked and a minor build-up of flies and dust was found. The results from the flow rate measurements are presented in Table 2. To ensure accuracy of the results, three measurements were taken at each location. Measurements of extract rates in the kitchen could not be conducted with the available equipment, because of the size of the vent and the close proximity of the cupboard. Specifically, the hood of the air flow meter was not large enough to form a tight seal around the vent. Similarly, a larger hood would have been of no use given the location of the cupboard. This raises questions regarding the accuracy of the initial commissioning.

The airflow measurements found low measured supply rates to the living room and bedroom under trickle and boost mode, compared to the designed rates. For instance, an airflow rate of 4.5 l/s was measured in the living room on trickle, compared to the design value of 7.4 l/s. After discussion with the Housing Association, it was found that supply grills to the living room and bedroom were removed for air tightness testing which is likely to have affected the commissioning. Measured extract rates in the bathroom and utility under trickle and boost mode exceeded the designed airflow rates.

In addition, although airflow rates from the kitchen extract grille could not be measured, it is clear that the MVHR system was not balanced (i.e. the volume of supply and extract air are not identical). Measured extract rates exceeded supply rates, even with the kitchen extract excluded. This may result in increased running costs, increased deterioration of the fan units and/or problems with de-pressurisation.

Table 2: MVHR flow rates (l/s)

	Measured		Designed		Commissioned	
	Trickle	*Boost*	*Trickle*	*Boost*	*Trickle*	*Boost*
Extract						
Kitchen	------------		5.8	13.0	6.3	14.0
Bathroom	5.3	11.7	3.6	8.0	3.6	8.3
Utility	5.1	10.9	3.6	8.0	3.6	8.3
Total: l/s	10.4	22.6	13.0	29.0	13.5	31.0
Total*: m^3/h	37.4	81.4	46.8	104.4	48.6	111.6
Supply						
Living	4.5	8.3	7.4	16.4	7.8	17.9
Bedroom	4.9	8.7	5.6	12.6	5.7	13.1
Total: l/s	9.4	17	13.0	29.0	13.5	31.0
Total: m^3/h	33.8	61.2	46.8	104.4	48.6	1116

**Excluding kitchen*

Sound assessment

Average sound levels in the open plan kitchen, bedroom and bathroom with the MVHR on normal mode remained below the Passivhaus recommended maximum level of 25 dB(A). Similarly, in the utility (where the MVHR unit is located), mean sound levels from the MVHR system remained below the recommended 35 dB(A) with the system on normal mode (trickle). Care was taken to reduce noise interferences, however peaks were still observed. For this reason, analysis of minimum levels may be more appropriate, as these are more likely to relate to background sound levels from the MVHR unit.

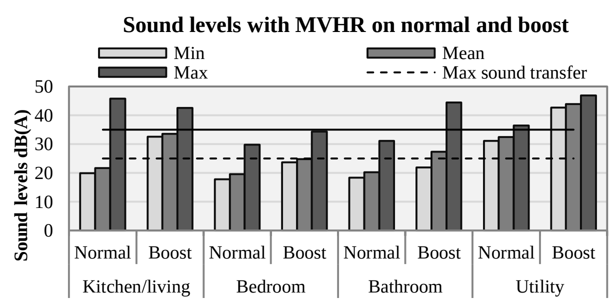

Figure 5: Sound levels (MVHR on normal and boost)

MVHR thermal efficiency & electrical consumption

The heat recovery efficiency of the MVHR system was calculated from 06.02.15 to the 24.02.15. This allowed for 'in-use' efficiencies to be determined, taking into account changes to operating conditions over the monitoring period. The heat recovery efficiency was calculated for the supply air side, following procedures described in BS EN 308:1997: $\eta t = (t22 - t21) / (t11 - t21)$

Where:

ηt = temperature ratio / thermal efficiency (%)
t22 = Supply air temperature (°C)
t21 = Inlet temperature (°C)
t11 = Extract air temperature (°C)

Using this method, the calculated average heat recovery efficiency was 98.9% over the monitoring period, which seems extremely high compared to the designed heat recovery efficiency of 75%. There are a number of factors that may have influenced the results leading to an overestimation of efficiency. Specifically, the measured imbalance of the air flow rates, possible heat generated from the fans, air leakages and/or inadequate insulation of the ducts. In addition, comparison of outside and inlet air temperatures found a significant temperature gain (average of 3 degrees) from ambient air to the heat exchanger. Possible explanations include inadequate insulation of intake duct run, recirculation of exhaust air as intake air, or operation of the frost protection heater.

Figure 6 shows the duct temperatures and electricity consumption of the MVHR system under different conditions. When the boost mode was turned on, the energy consumption of the MVHR system increased to 0.005kWh/5 min, which reduced to 0.002kWh/5 min when the system was in trickle mode. From 18:05 to 18:30 the MVHR system was turned off and the exhaust duct temperature increased. Similarly, supply and extract duct temperatures dropped marginally when the MVHR system was off.

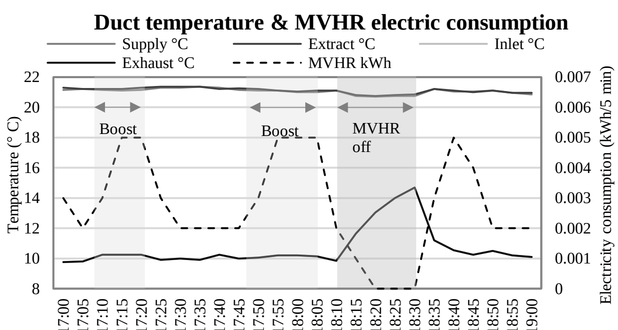

Figure 6: Duct temperature & MVHR electricity consumption

The baseline electrical consumption of the MVHR system on trickle mode (0.002kWh at 5 minute intervals) works out at approximately 24 watts. If the MVHR system was providing whole house trickle ventilation rates as per designed, this equates to an electrical efficiency of 0.513 Wh/m^3 (24/46.8 m^3/h). The Passivhaus standard requires an electrical efficiency of ≤0.45 Wh/m3, therefore even if the ventilation was providing the specified ventilation rate; it would not meet the Passivhaus criteria. In practice, the measured supply ventilation rate (33.84 m^3/h) corresponds to an electrical efficiency of 0.70 Wh/m^3. It should be noted however that the MVHR system was not balanced, and as the kitchen extract flow rate could not be determined, overall airflow rates could not be calculated.

The electrical consumption data of the MVHR system made it possible to estimate the percentage of time on each operation mode (Table 3). The boost mode in the MVHR system was activated for approximately 5% of the total monitoring period (06.02.15 to 24.02.15), which equates to 21.6 hours out of a total of 432 hours. The MVHR system was turned off for a short period of time during the sound measurements only (06.02.15).

Table 3: % time MVHR off, trickle and boost

% of time MVHR off (0.000kWh)	% of time on trickle (>0, ≤0.002kWh)	% of time on boost (>0.002kWh)
0.06%	95.42%	4.52%

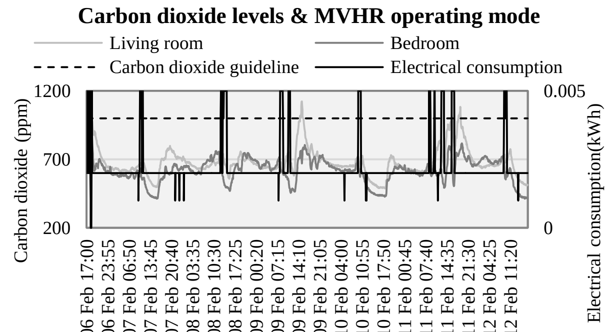

Figure 7: CO_2 levels and MVHR electrical consumption

The relationship between CO_2 levels and operating mode of the MHVR system over the first week of monitoring is outlined in Figure 7. The electrical consumption of the MVHR unit on boost was 0.005 kWh (over each 5 minute monitoring period), therefore it is suggested that the peaks in electrical consumption in the graph are most likely related to the use of the boost mode function. The kWh transmitters provide an average reading over a 5 minute period, and because of that the readings are not instantaneous. However there is a clear relationship between the use of the boost mode function (based on 0.005 kWh peaks) and subsequent reduction of CO_2 levels. As mentioned previously, CO_2 levels in the bedroom exceeded 1,000 ppm only during the initial site visit with 5 people present in the dwelling; therefore the performance of the CO_2 sensor at boosting the MVHR system could not be determined. The boost mode function was typically activated first thing in the morning or during lunch time, which suggests its use was most likely related to showering or cooking activities. The data shows frequent use of the boost mode function (at least once a day), which should help to improve the quality of indoor air in the home.

Risk of surface condensation

The risk of condensation was calculated using the following formula: $f_{Rsi} = (T_{si}-T_o) / (T_i-T_o)$

Where:
f_{Rsi} = Temperature factor
T_{si} = Internal surface temperature
T_o = External ambient temperature
T_i = Internal ambient temperature

The critical temperature factor for avoiding mould growth in dwellings is 0.75. This calculation has been used to assess the thermograms for condensation risk and/or mould growth. It should be noted however that indoor temperature levels during the time of the thermographic survey may not be representative of typical indoor conditions in the dwelling; therefore lower indoor surface temperatures (and greater risk of condensation) may exist at other times. Please see Table 4 for areas of surface condensation risk, identified using the formula described in BRE IP 17-01.

Table 4: Surface condensation risk

Location	T_{si}	T_i	T_e	fR_{si}	fCR_{si}
Bed window	13.8	19.6	8	0.50	0.75
Bed window	15.9	19.6	8	0.68	0.75
Toilet cistern	15.4	20.2	8	0.61	0.75
Toilet base	16.8	20.2	8	0.72	0.75
Bath window	17.2	20.2	8	0.75	0.75
Porch door	13.6	20.6	8	0.44	0.75
LR window	17.4	20.6	8	0.75	0.75
Switchboard	16.5	22.3	8	0.59	0.75
Utility room	16.4	22.3	8	0.59	0.75

Summary of thermography results

The thermal imaging survey found that the integrity of the thermal insulation had not been breached, with very minor thermal transmission through timber studs and roof joists. Lower surface temperatures at corners were evident, which is to be expected due to the greater boundary level resistance in these areas. Significantly lower surface temperatures were observed at window seals in the bedroom, living room and bathroom, which are at risk of surface condensation. The impact of the blinds at limiting cold surface temperatures at the glazing perimeter was apparent, which may help to reduce heat loss during cold, overcast days.

Lower surface temperatures most likely caused by infiltration were observed at the base of the toilet, at the porch door (which was slightly ajar), at the base of the fuse box, and at a pipe penetration point in the utility room. Heat gains were also observed by the fridge and hot water cylinder in the utility room, at appliance plugs, and on the living room wall, which was most likely caused by hot water pipes feeding the radiator.

Electricity consumption

The average daily electricity consumption of the MVHR unit was 0.61 kWh during the winter monitoring period, which was slightly greater than the average daily electrical consumption of the fridge, at 0.48 kWh. Since meter readings at the end of the monitoring period were not available, it was not possible to determine the total electricity consumption in the home. However, the data does provide interesting information on appliance use.

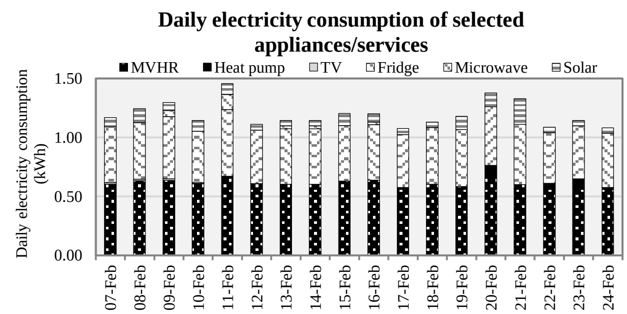

Figure 8: Daily electrical consumption of appliances

Room survey

The measured undercuts for each of the internal doors were as follows: living room- 1.40cm, bedroom- 1.50cm, utility room- 1.50cm. These significantly exceed minimum levels of 5 to 8 mm, as recommended in the Scottish Building Regulations for whole house mechanical ventilation systems. This may explain the significant relationship between CO_2 levels in each room, as identified through the indoor air quality monitoring. The thermostatic control setting on the living room radiator was at 5; the highest setting. However, the bedroom radiator was turned off, which may explain the lower temperatures observed in this room. There is no thermostatic control on the towel radiator in the bathroom. The thermostat was set at 19 degrees Celsius, at the time of the building survey.

DISCUSSION

An assessment of the MVHR system found low supply rates in practice, which failed to meet the design values specified in the Passivhaus Planning Package (PHPP). Despite this, satisfactory indoor environmental conditions were observed. Specifically, CO_2 levels in the open plan living room and kitchen, bedroom, bathroom and utility room rarely exceeded the recommended maximum level of 1,000 ppm. This level is used as an indicator of ventilation, since it is generally accepted that CO_2 keeps 'bad company'. However, the dwelling is occupied by only one adult; therefore sources of CO_2 indoors are limited. Re-commissioning of the MVHR system is recommended, to provide adequate supply rates to the bedroom and living space, and to balance the system by providing an equal amount of supply and extract air flow rates. This should help to ensure adequate ventilation rates to remove moisture and pollutants generated indoors.

Analysis of electrical consumption data of the MVHR system identified regular use of the boost mode function, which should help to reduce moisture build-up and indoor sources of pollutants. Bedroom CO_2 levels remained below the recommended maximum of 1,000 ppm, therefore it was not possible to evaluate the performance of the CO_2 sensor at activating the boost mode (or the subsequent effects of this). Analysis of the sound data however found high levels during the operation of boost mode (>25 dB(A)), which questions the appropriateness of CO_2 sensors in bedrooms, as this may cause disruption to sleep if activated at night.

In this case, due to the low levels of occupancy and significant mixing of air between rooms, bedroom CO_2 levels are generally low. However in future work, it is important to consider the effect of the boost mode (activated by CO_2 sensors in bedrooms) on sound levels at night, particularly in bedrooms occupied by more than one adult. On one hand, it is important to ensure adequate ventilation rates at night, however if this subsequently causes disruption to sleep, it may result in occupants turning off the MVHR system altogether or trying to find ways to deactivate the sensors.

A significant relationship was observed between the indoor environmental conditions of each room; specifically, CO_2, temperature and relative humidity levels. This may be explained by internal door opening during the measurement period and/or the generous (1.4-1.5 cm) door undercuts measured during the building survey. As such, the dwelling acts as a single volume, which is essential for adequate circulation of air throughout the spaces in MVHR dwellings.

Access to the property was a significant issue, which raises questions regarding the ability to maintain equipment in the property and carry out regular servicing and checks of the MVHR unit. An examination of the filters at the time of the site visit revealed minor build-up of debris/ dirt, however a filter replacement is recommended in the next month or two. The ventilation system manual recommends replacement of the filter every six months at the latest. Furthermore, a filter replacement prompt is programmed to display on the room air control every three months, suggesting a recommended maintenance period of three months. This is likely to be unrealistic in practice, particularly in a social housing context; and suggests that the required maintenance of MVHR systems should be carefully considered in any future projects. This corresponds to the results of previous studies that have highlighted the risk of inadequate maintenance of MVHR systems in a social housing context (McGill et al. 2014; Sullivan et al. 2013).

The thermographic survey found minor thermal transmission at timber studs and roof joists, infiltration at service penetrations and heat loss at seals of the glazing in the bedroom, living room and bathroom. Overall however, the integrity of the thermal insulation had not been breached. The U-Value results support these findings, with excellent thermal performance of the building envelope in practice. Sound measurements revealed that the MVHR system was not noisy in trickle use, and meets the Passivhaus sound criteria for maximum sound transfer in occupied rooms and sound transfer from the MVHR unit under normal mode.

CONCLUSIONS

Overall, an evaluation of the building performance revealed excellent thermal performance of the building envelope, and satisfactory indoor environmental conditions during the monitoring period. Furthermore, the results from the sound measurements and thermal efficiencies of the MVHR system meet the specific criteria set out in the Passivhaus Planning Package. Measurements of airflow rates however revealed an imbalance of the MVHR system and inadequate supply rates in practice. Re-commissioning of the MVHR system therefore is recommended, to provide adequate supply rates and to balance the system. Care is needed with a CO_2 sensor to trigger a boost mode as if this results in unwanted noise, it may have unintended negative consequences such as the system being disabled. Also, since access to the property was an issue, it is recommended to consider carefully the maintenance requirements of MVHR systems at the design stage, in a social housing context.

ACKNOWLEDGEMENTS

The authors would like to thank the Housing Association & building occupant for access to the home.

REFERENCES

1. The Climate Change Act, 2008, Chapter 27, The Stationary Office, London
2. King, D., 2013, Green facelift for concrete buildings, *Ingenia online*, Issue 55, June 2013
3. PHI (The Passivhaus Institute), 2015, http://www.passivhaus.org.uk/standard.jsp?id=18 (accessed 10.12.15)
4. McGill, G., Oyedele, L., Keeffe, G., Keig, P., 2014, Indoor air quality and the suitability of MVHR systems in energy efficient social housing projects: Perceptions of UK building professionals, *International Journal of Sustainable Building Technology and Urban Development,* 5 (4) : 240-249
5. Sullivan, L., Smith, N., Adams, D., Andrews, I., Aston, W., Bromley, K., et al., 2013, Mechanical ventilation with heat recovery in new homes: Final Report, London: Zero Carbon Hub