Evaluation of Indoor Environmental Quality and Thermal Environment in Airtight Energy-Efficient Naturally Ventilated Dwellings

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SUMMARY

Noticeably higher concentrations of gaseous pollutants were measured in bedrooms than living rooms, and in winter than summer, where p-values were found to be of a stringent significance (average $p = 0.008$). $PM_{2.5}$ concentrations were found to be exceeding the WHO 24-h average threshold of 15 µg/m^3 in kitchens for the week-long monitoring time (92% in winter, 51% in summer). High percentages of carbon dioxide concentrations exceeded the WHO guideline in bedrooms during the winter week (mean: 1251 ppm) and summer week (mean: 1028 ppm), with lower percentages in living rooms in comparison (mean in winter: 893 ppm, mean in summer: 735 ppm). TVOC week-long mean values across the bedrooms was 463 ppb in winter and 293 ppb in summer. Temperature and humidity were within limits in general. Air change rate mean values ranged from 0.08 to 0.37 h^{-1} in summer, and from 0.09 to 0.27 h^{-1} in winter, across the monitored bedrooms.

INTRODUCTION

Enhancing building energy efficiency is a global priority that necessitates reducing carbon emissions from the building sector. Since approximately 60-80% of primary energy use is used on space and water heating (SEAI, 2022), energy performance improvements are often achieved by enhancing the thermal and insulation properties of a building to minimise heat loss. However, these strategies may inadvertently lead to a higher risk of overheating, necessitating active cooling systems during warmer months, and thereby increasing energy usage (International Energy Agency (IEA), 2015). In contrast, natural ventilation presents distinct advantages during summer by providing passive cooling opportunities (Schulze & Eicker, 2013), thereby reducing reliance on mechanically driven cooling systems and promoting energy conservation.

Despite the recognised benefits in energy performance associated with increased airtightness, there is a knowledge gap surrounding the ability of natural ventilation to maintain adequate ventilation rates across different seasons. This may result in the accumulation of indoor air pollutants and moisture beyond recommended levels, a concern only further amplified by the impacts of climate change, thereby posing risks to occupants' health and comfort.

This study addresses this knowledge gap by evaluating indoor environmental quality and thermal comfort across nine airtight, energy-efficient naturally-ventilated dwellings in both summer and winter periods.

KEYWORDS

Natural ventilation; Airtightness; Energy Efficiency; IEQ; Sensors

METHODS

The house selection criteria focused on a cohort of semi-detached dwellings (n = 9), which represent 40.7% of the total naturally-ventilated energy-efficient houses in Ireland, with an 'A' Building Energy Rating (BER), denoting a maximum primary energy consumption of up to 75 kWh/m^2 per year, indicative of highly insulated airtight structures; air permeability of 3 to 5 $m^3/h.m^2$ (*Part F: Technical Guidance Document F-Ventilation*, 2019). For a week-long monitoring period, the SidePak AM520 (TSI, Minnesota, USA) was used to measure $PM_{2.5}$ at 1-min interval, while the and the GrayWolf DirectSense II (GrayWolf Sensing Solutions, Ireland) was used to collect measurements of carbon dioxide (CO_2), total volatile organic compounds (TVOC), nitrogen dioxide (NO_2), and carbon monoxide (CO), alongside complementary measurements of temperature and relative humidity levels at 5-min interval. All parameters were analysed based on standardised guidelines. The instrumentations were placed in the main rooms of each house; bedroom, living room, kitchen, collecting over 435,000 datapoints across the monitored houses. Measurements of $PM_{2.5}$ were not taken in the bedrooms due to the absence of direct sources and the low tolerance of occupants for active pumps noise. Apart from $PM_{2.5}$, the parameters of CO_2, Temp, and RH were not measured in the kitchen due to the high variation caused by the cooking activities affecting the levels of these parameters, as the study focuses on the rooms of higher and more consistent occupancy rates.

RESULTS

Generally, the results in Table 1 show higher levels of the monitored parameters in the bedrooms and kitchens than the living rooms. CO_2 concentrations in the bedrooms were higher in the than the living rooms during occupancy times, due to the sleeping time CO_2 accumulation through longer times of occupancy. Same applied to TVOC concentrations, while there are more sources of TVOC in the bedrooms than the living rooms, as the occupants reported. Moreover, the $PM_{2.5}$ concentrations in the kitchens were observed to be consistently higher than the living rooms, while the direct sources of particles were present in the kitchens.

Table 1 – Data Analysis Summary of the Monitored Parameters – Winter and Summer

	Bedrooms (Kitchen for PM2.5)-Winter		**Living Rooms-Winter**	
Parameter	**Mean (s.d.*)**	**Median (25th %ile, 75th %ile)**	**Mean (s.d.)**	**Median (25th %ile, 75th %ile)**
$PM_{2.5}$ (µg/m³)	88 (137)	46 (29, 96)	72 (158)	25 (9, 70)
CO2 (ppm)	1251 (538)	1079 (800, 1620)	839 (260)	782 (658, 961)
TVOC (ppb)	463 (279)	378 (296, 540)	348 (212)	296 (209, 418)
NO2 (µg/m³)	32 (16)	32 (14, 43)	54 (4.2)	56 (50, 58)
CO (mg/m³)	1.4 (0.7)	1.4 (0.7, 1.9)	1.3 (1.6)	1.0 (0.4, 1.6)
Temp (°C)	20.0 (0.97)	19.99 (19.39, 20.65)	19.7 (1.04)	19.7 (19.0, 20.5)
RH (%)	55.3 (5)	55.1 (52, 58)	51.6 (3)	51.4 (48, 53)

	Bedrooms (Kitchens for PM2.5)-Summer		**Living Rooms-Summer**	
Parameter	**Mean (s.d.)**	**Median (25th %ile, 75th %ile)**	**Mean (s.d.)**	**Median (25th %ile, 75th %ile)**
$PM_{2.5}$ (µg/m³)	21 (95)	10 (6, 17)	18 (36)	10 (4, 17)
CO^2 (ppm)	1028 (535)	791 (608, 1436)	735 (175)	701 (605, 823)
TVOC (ppb)	293 (152)	280 (226, 330)	208 (69)	194 (162, 252)
NO_2 (µg/m³)	33 (36)	12 (1.9, 80)	101 (53)	106 (44, 138)
CO (mg/m³)	0.7 (0.4)	0.6 (0.4, 0.9)	0.8 (0.3)	0.9 (0.6, 1.0)
Temp (°C)	23.6 (0.8)	23.6 (23.2, 24.1)	23.0 (0.7)	22.9 (22.5, 23.5)
RH (%)	60.2 (3.2)	60.1 (58.2, 62.1)	58.4 (2.9)	58.2 (56.7, 60.2)

CONCLUSIONS

The natural ventilation's design and operation was concluded to be inefficient to maintain the CO_2 concentrations within acceptable levels during the occupancy time in the bedrooms, and at some points in the living rooms over the monitoring period. Improved ventilation strategies in the bedrooms may participate in bridging the gap between the emission rates of CO_2 and the dilution rates of the existing purpose-provided natural ventilation elements. The design of the monitored energy-efficient dwellings aimed to supply sufficient airflow rates in order to maintain acceptable IEQ levels, nevertheless, this research identified a performance gap between the design aims and the operational performance regarding the effectiveness of natural ventilation.

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