A Longitudinal Study to Assess Indoor Environmental Quality in Airtight Energy-Efficient Naturally Ventilated Dwellings

Ibrahim Alhindawi*[1], James McGrath[2], Divyanshu Sood[3], James O'Donnell[3], and Miriam Byrne[1]

1 Physics Unit, School of Natural Sciences and the Ryan Institute's Centre for Climate and Air Pollution Studies, University of Galway, Galway, Ireland
**Corresponding author: i.alhindawi1@universityofgalway.ie*

2 Department of Physics, Maynooth University, Maynooth, County Kildare, Ireland

3 School of Mechanical & Materials Engineering and UCD Energy Institute, University College Dublin, Dublin, Ireland

SUMMARY

The global demand to improve the energy performance of buildings has led to greater air tightness and uncertainty in the ability of natural ventilation to maintain adequate indoor environmental quality. A monitoring campaign was carried out to evaluate the long-term indoor environmental quality across a year-long period in energy-efficient Irish dwellings. During the winter months (December, January, February), the mean $PM_{2.5}$ concentration in kitchens was 19 µg/m³, which is 38% higher compared to the summer months (June, July, August), where the mean concentration was 13 µg/m³. The mean $PM_{2.5}$ increased 58% in winter (19 µg/m³) than in summer (12 µg/m³). In bedrooms, the mean CO_2 concentration during winter was 1116 ppm, reflecting a 19% increase over the summer concentration of 919 ppm. In the living room, CO_2 increased 29% in winter from summer. Additionally, radon levels in the dwellings were 52% higher in winter than in summer; however, they remained well below the Irish EPA threshold of 200 Bq/m³. VOC mean values in winter and summer showed similar ranges across the monitored dwellings, referring to the greater impact of occupancy activities than ventilation.

KEYWORDS

Natural ventilation; Airtightness; Energy Efficiency; IEQ; Sensors

INTRODUCTION

While it is globally imperative to conserve energy in buildings and reduce greenhouse gas emissions from the building sector. Poor application of some energy-efficient measures, such as increased airtightness, may induce elevated levels of indoor air pollutants and thermal parameters; this may lead to incompliant levels of indoor environmental quality (International Energy Agency (IEA), 2015). While ventilation is the main mechanism to dilute pollutants and provide the required air change rates, it does not always operate optimally, and natural ventilation, in particular, is dependent on multiple factors. Although natural ventilation may save energy and provide higher air change rates (Schulze & Eicker, 2013), the main drawback is lower ventilation rates and compromise thermal comfort in winter. While it is challenging to conduct long-term indoor environmental quality monitoring using high-grade instruments, low-cost sensors, with the capability for remotely-transmitting information for several parameters, allow a unique opportunity to gather large-scale monitoring data without the traditional constraints (Omidvarborna et al., 2021). This research aims to evaluate indoor environmental quality in semi-detached energy-efficient dwellings for a full year, by deploying remotely-operated low-cost sensors in the main rooms of each dwelling.

METHODS

The criteria for house selection concentrated on a group of nine semi-detached naturally-ventilated, energy-efficient houses in Ireland with an 'A' Building Energy Rating (BER). This rating signifies a maximum primary energy consumption of up to 75 kWh/m² per year, reflecting highly insulated, airtight structures with an air permeability of 3 to 5 m³/h.m² (*Technical Guidance Document F-Ventilation*, 2019). Consumer-grade sensors (Space Pro, Space Plus-Airthings, Oslo, Norway, and Foobot SAT-Airboxlab SA, Luxembourg) were used to map the year-long trends for particulate matter ($PM_{2.5}$, PM_1), carbon dioxide (CO_2), toal volatile organic compounds (TVOC), temperature (temp), relative humidity (RH), and radon (Rn). These devices are installed in the living room, kitchen, and bedroom within each dwelling. Over 20 million datapoints were collected at a 5-min interval for the monitored parameters.

RESULTS

The results in Table 1 show a selection of the data summary for the measurements across the monitored dwellings. In general, the rooms with indoor-generated emission sources showed higher mean values of air pollution concentration across the year. The annual average CO_2 concentrations were higher in the bedrooms than in the living rooms and kitchens, surpassing the World Health Organisation (WHO) guidelines. However, the mean PM concentrations were within similar ranges in all the rooms, surpassing the annual WHO guideline level of 5 µg/m^3. The mean TVOC concentrations were observed to be surpassing 130 ppb ("I.S. EN 16798-1," 2019) in all the monitored rooms. The mean values for temp and RH were within the recommended levels of WHO. The mean $PM_{2.5}$ winter concentration (19 µg/m^3) was 38% higher than in the summer period (13 µg/m^3) across the kitchens. The mean CO_2 winter concentration (1116 ppm) was 19% higher than the summer concentration (919 ppm) across the bedrooms. Radon was observed to be 52% higher in winter than summer yet, it was well below 200 Bq/m^3 (Irish EPA threshold) across the dwellings.

Figure 1, illustrates the long-term variations in one of the monitored dwellings' bedrooms, demonstrating the wider data distribution in the colder months than the warmer months. The latter observation suggests higher ventilation rates in summer than in winter, caused at least by a higher frequency of window opening in warmer months.

Table 1 – Annual Data Summary of the Monitored Parameters

Parameter	Mean	Median	Min	Max	25th%ile	50th%ile	75th%ile
Bedrooms							
$PM_{2.5}$	14	7	1	783	3	7	15
PM_1	13	7	1	422	3	7	14
CO_2	1037	856	397	3879	585	856	1343
VOC	311	147	24	4715	68	147	385
Temp	21.81	21.77	16.42	27.62	20.80	21.77	22.77
RH	58.3	58.6	32.7	81.6	53.8	58.6	63.3
Living Rooms							
$PM_{2.5}$	15	7	1	627	3	7	18
PM_1	14	7	1	451	3	7	18
CO_2	731	669	400	2723	542	669	850
VOC	210	132	42	3311	74	132	258
Temp	21.87	21.85	16.68	27.65	20.76	21.85	22.86
RH	54.2	54.3	30.4	77.3	49.3	54.3	59.2
Kitchens							
$PM_{2.5}$	16	7	1	895	3	7	19
PM_1	15	7	1	637	3	7	18
CO_2	666	619	400	2350	519	619	762
VOC	201	133	34	3916	76	133	249
Temp	21.60	21.53	16.08	27.38	20.54	21.53	22.71
RH	56.0	56.1	31.0	84.8	51.2	56.1	60.9

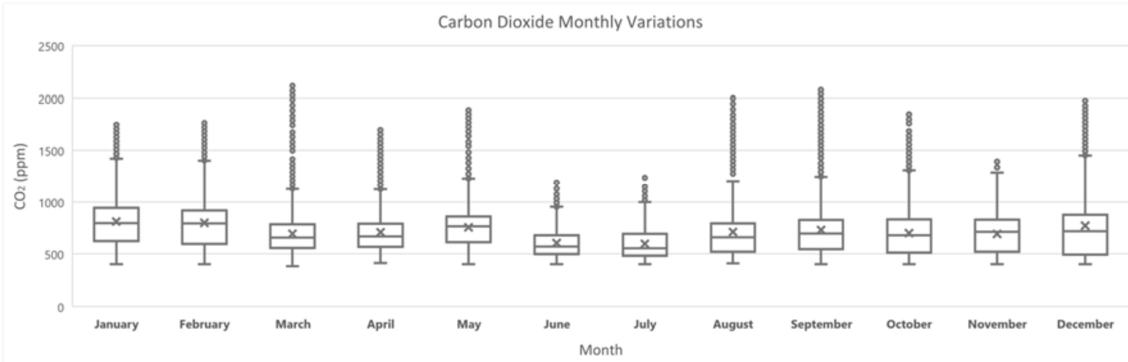

Figure 1: Monthly CO_2 Data Distribution

CONCLUSIONS

This study seeks to assess the indoor environmental quality across a sample of energy-efficient dwellings over the course of an entire year, utilising remotely-operated, low-cost sensors placed in the primary rooms of each dwelling. The use of consumer-grade sensors showed practicality and resilience in terms of measurements and data collection of the long-term data. The longitudinal study provides a large-scale description of the data trends on an annual and a seasonal basis. The levels of the monitored parameters indicated the deficiency of natural ventilation, at least within the current operation strategy, in maintaining acceptable levels of indoor environmental quality. Additionally, seasonal variations suggest an adaptive ventilation strategy in the monitored airtight houses to maintain pace with the deviations of the impacting factors on indoor environmental quality.

ACKNOWLEDGEMENTS

The ALIVE project (19/RDD/537) is funded by the Government of Ireland through the Sustainable Energy Authority of Ireland's Research, Development and Demonstration Funding Programme 2019.

REFERENCES

I.S. EN 16798-1. (2019). In *Method 2 - method using limit values of substance concentration*: The National Standards Authority of Ireland (NSAI).

International Energy Agency (IEA). (2015). *Capturing the Multiple Benefits of Energy Efficiency*. https://www.iea.org/reports/capturing-the-multiple-benefits-of-energy-efficiency

Omidvarborna, H., Kumar, P., Hayward, J., Gupta, M., & Sperandio Nascimento, E. G. (2021). Low-Cost Air Quality Sensing towards Smart Homes. *Atmosphere*, *12*, 453. https://doi.org/10.3390/atmos12040453

Schulze, T., & Eicker, U. (2013). Controlled natural ventilation for energy efficient buildings. *Energy and Buildings*, *56*, 221–232. https://doi.org/10.1016/j.enbuild.2012.07.044

Technical Guidance Document F-Ventilation. (2019). Dublin, Ireland: Minister for Housing, Planning and Local Government under article 7 of the Building Regulations 1997