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The suitability of demand-controlled sensor based ventilation systems in retrofit dwellings - a longitudinal study.

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THE SUITABILITY OF SENSOR-BASED DEMAND CONTROLLED VENTILATION SYSTEMS IN RETROFIT DWELLINGS - A LONGITUDINAL STUDY

A fabric-first approach to dwelling retrofit results in increased airtightness, therefore there is an obligation to ensure that the upgrades do not lead to poor indoor air quality (IAQ) resulting from inadequate ventilation. The sensor-based demand-controlled ventilation (SBDCV) under review seeks to provide fresh air for breathing and to dilute and exhaust pollutants and odours. This system modulates the ventilation rate over time based on relative humidity levels and/or presence detection and considers that the level of ventilation provided is sufficient to control the concentration of all other indoor air pollutants, including those that are not a result of human occupancy. This research takes the form of a longitudinal study that follows a structured approach to monitor the levels of relative humidity, radon, and volatile organic compounds within participating dwellings (n=7) so that the relationship between the variables can be explored. This paper demonstrates that SBDCV systems are insufficient to ensure the removal of non-occupancy related pollutants. This could have significant health and wellbeing impacts for occupants. The findings of the paper have implications for the policy framework.

Keywords: Dwelling Retrofit, Demand Controlled Ventilation, Relative Humidity, Radon, Volatile Organic Compounds.

INTRODUCTION

Ireland’s Climate Action Plan (CAP) 2021 (Department of Communications, Climate Action & Environment, 2021) details a roadmap of measures that align with the European Union’s ambition to achieve a net-zero target carbon emissions by 2050 (European Union, 2019). It seeks to play a key role in delivering energy efficiency in Ireland and follows a Europe wide approach to reduce energy consumption in a building sector that represents 40% of total energy usage. Accordingly, most European countries have similar retrofit strategies that focus on the reduction of regulated energy. In this context, Ireland has introduced the National Retrofitting Scheme (NRS) (Sustainable Energy Authority of Ireland, 2022a) which has set an ambitious goal of retrofitting 500,000 existing homes to a Building Energy Rating (BER) of B2 by 2030. This equates to almost 30% of all residential buildings in Ireland (Sustainable Energy Authority of Ireland, 2022c). These dwellings require fabric interventions to reduce their space heating energy demand. Such intervention refers to the performance of the dwelling envelope (floor, external walls, roof) and requires the prioritising of insulation and airtightness prior to the addition of technology improvements, as heating demand cannot be radically reduced without a suitable designed thermal envelope (Dequaire, 2012).

The precursor to the NRS was the Deep Retrofit Pilot Programme, which was introduced in 2017 and managed by the Sustainable Energy Authority of Ireland

(SEAI). A fabric first approach to dwelling retrofit was promoted, with all participating dwellings achieving a Building Energy Rating (BER) of A1-A3 and an airtightness of ≤ 5 m3/hr/m2 (Sustainable Energy Authority of Ireland, 2022b). The programme investigated the challenges and opportunities presented by deep retrofit in Ireland with the outcomes used to inform the approach to large scale retrofit, culminating in the introduction of the NRS.

83% of the mechanical ventilation systems installed as part of the 2017 Deep Retrofit Pilot Programme were Mechanical Extract Ventilation (MEV) or Demand Controlled Ventilation (DCV) systems (Sustainable Energy Authority of Ireland, 2022b). The purpose of this research study is to assess the suitability of sensor-based demand-controlled ventilation (SBDCV) systems within the dwellings under review, as little consensus exists in respect to the most important indoor pollutants that should be considered when choosing a ventilation system (Poirier et al., 2021) due to the significant list of pollutants that have been identified to date (Abadie & Wargocki, 2017; Cony Renaud Salis et al., 2017). This research follows a structured approach to monitor the levels of relative humidity, radon, and volatile organic compounds within participating dwellings (n=7). The relationship between the variables is explored so that the relative effectiveness of the ventilation strategy can be ascertained.

LITERATURE REVIEW

VENTILATION

Ventilation of homes is necessary to maintain healthy and safe indoor air quality for the occupants. Following significant fabric improvements, there is an obligation to ensure that the upgrades do not lead to poor indoor air quality (IAQ), therefore ensuring the avoidance of negative effects such as inadequate ventilation (Official Journal of the European Union, 2016). Ventilation refers to the process of introducing and distributing outdoor and/or properly treated recycled air into a building or a room (Etheridge & Sandberg, 1996) and is the process by which concentrations of potentially harmful pollutants are diluted and removed from a space (CIBSE, 2006). The ventilation rate is defined as the amount of outdoor air circulated per unit time. Current Irish building regulations require that adequate and effective means of ventilation shall be provided for people in buildings. This is to be achieved by (a) limiting the moisture content of the air within the building so that it does not contribute to condensation and mould growth, and (b) limiting the concentration of harmful pollutants in the air within the building (Department of Housing, Planning and Local Government, 2019) . The presumption within such standards is that the specified minimum rate of ventilation per occupant is adequate for the control of both occupant-generated pollutants and other indoor-generated pollutants (Fisk & De Almeida, 1998). This presumption can lead to IAQ problems as pollutant emission rates from sources other than occupants vary greatly among buildings. This causes potential for building retrofit projects to result in unexpected performance outcomes and/or unintended consequences (Shrubsole et al., 2014). Unfortunately, few large scale studies that utilise data driven methodologies to consider the impact that energy conservation measures have on the internal environment have been carried out, due to the cost prohibitive nature of data collection techniques (Carratt et al., 2020). Those that have (Majcen et al., 2016; Liang et al., 2018) relied on easily accessible data, such as energy bills, which negates the possibility of reporting on anything other than the post works performance of energy-use reduction measures.

INDOOR AIR QUALITY

Multiple studies have shown that levels of indoor pollutants can increase post energy retrofit works. IAQ depends on several factors but is primarily affected by the quality of external air that is introduced through controlled or uncontrolled ventilation channels, bioeffluents that are produced by human occupants and off-gassing from building and construction materials, equipment, furniture, domestic cleaning products and occupant's self-care products (Marć et al., 2018). These factors lead to the existence of pollutants, which can be found at high concentrations in indoor air (Tran et al., 2020), therefore directly affecting IAQ within residential dwellings.

RELATIVE HUMIDITY

Relative humidity (RH) is the ratio of the amount of water vapor in the air to the amount of water vapor air can hold at a specific temperature. Raising the temperature without changing the amount of moisture in the air reduces the RH. The RH goes down because warmer air can hold more moisture than colder air, the opposite occurs when the temperature falls. Pre-retrofit, this posed a significant problem as internal face of uninsulated external walls were susceptible to cooler external temperatures, which subsequently decreased the cross-sectional temperature of the wall, creating a cooler internal surface. This resulted in localised cooling of internal air causing RH levels to rise, inevitably leading to a moisture dump, resulting in condensation and subsequent mould growth. The same cause/effect was true for walls/ceilings, uninsulated floor slabs and single-glazed windows. Post retrofit in the dwellings under review, this poses a much-decreased risk due to the inclusion of a correctly insulated external envelope complete with constant higher internal temperatures.

RADON

Radon is a naturally occurring radioactive gas and has been identified as the second leading cause of lung cancer worldwide after tobacco smoking (World Health Organisation, 2009). Studies have found that energy efficiency measures that increase the airtightness of properties are observed to have an adverse association with indoor radon levels (Pampuri et al., 2018; Yang et al., 2020; Fisk et al., 2020), but that levels can be reduced with appropriate ventilation strategies (Pampuri et al., 2018; Collignan & Powaga, 2019).

VOLATILE ORGANIC COMPOUNDS

VOC's are gases emitted from certain solids and liquids and include a variety of chemicals, concentrations of which are consistently higher indoors than outdoors (US EPA, 2014). VOC's have known adverse effects on human health and comfort, ranging from mild irritation to acute toxicity and carcinogenicity (Sundell, 2004). The thermal retrofit of dwellings has been associated with elevated indoor levels of VOC's (Yang et al., 2020; Kempton et al., 2022). Demand-controlled ventilation (DCV) systems that do not supply airflow continuously but are controlled by humidity sensors to save energy can pose potential problems for exposure to VOC's in rooms that are unoccupied for periods of time (De Jonge et al., 2019). Such increases can be diminished by the use of low emitting materials (Du et al., 2019) or increased ventilation rates (Hernandez et al., 2020). Notably, it has been demonstrated that while increasing outdoor air ventilation rates does reduce the indoor concentrations of VOC's with indoor sources, the actual reductions in concentrations can differ significantly from those calculated with the assumption of a constant indoor emission rate (Offermann & Marcham, 2016) due to the impact of environmental factors on compound specific emission rates.

SENSOR BASED DEMAND CONTROLLED VENTILATION

SBDCV systems modulate the ventilation rate (VR) the rate over time based on the signals from indoor air pollutant or occupancy sensors (Fisk & De Almeida, 1998). The VR of the SBDCV system under review is modulated by increasing/decreasing levels of RH in habitable rooms with wet rooms/bathrooms/utility and kitchens also activated by presence detection. The concept is simple. The centrally located fan extracts at a constant 8 litres per second (l/s). Humidity controlled air inlets are fitted in all habitable rooms with air extract units fitted in wet rooms/bathrooms/utility and kitchens. Increases in RH result in the expansion of a polyamide strip within the air inlet, which is used to activate one or more shutters, thereby adjusting the passage of the air according to the ambient RH. The higher the humidity in the room, the wider the shutters open, resulting in greater inflows of air. Likewise, a humidity-controlled strip and/or presence detector allow shutters within air extract units to open in wet rooms/bathrooms/utility and kitchens, resulting in the removal of stale moist air from these zones. The negative pressure that is realised by the removal of this air is equalised through inflow from the habitable room air inlets. Greater amounts of air flows into the rooms where RH is highest as the aperture created by the opened shutters (8 l/s min – 16 l/s max) within the humidity-controlled air inlets will be larger than those rooms where RH readings are lower. Internal doors are fitted with a minimum of 10mm airgap, between the bottom of the door leaf and the internal surface finish, to facilitate such air flow. No significant pollutant filters exist on the supply air side, therefore whilst outdoor air ventilation dilutes internally generated airborne pollutants, it can also introduce outdoor pollutants to the indoor environment.

The SBDCV system is identical in each dwelling under review. All systems were commissioned upon install, however no requirement currently exists (in the Republic of Ireland) for ventilation systems to be serviced annually.

MATERIALS AND METHODS

DEVICES

Airthings Wave Plus loggers were utilised for data collection. New, factory calibrated devices were used for the duration of this research study. Data was collected wirelessly at 5-minute intervals, 24 hours per day in all monitored rooms (2 locations per dwelling: master bedroom and main utilised living area) for a seven-month period.

DWELLING TYPOLOGY

This study was limited to dwellings that participated in the Deep Retrofit Pilot Scheme. All participant dwellings were retrofit during the lifetime of this scheme. Each dwelling was initially assessed on an individual basis so that a BER of A and an airtightness of ≤ 5 m3/hr/m2 would be achieved post retrofit works. This was facilitated by the production of a designed post-works BER during the application process (Sustainable Energy Authority of Ireland, 2022b). Table 1.0 details the retrofit measures that were applied to each property. It is notable that a fabric first approach (Table 2) was utilised to ensure that each dwelling met minimum required standards in respect to insulation and airtightness prior to the introduction of technologies such as heat pump and ventilation systems. The minimisation of thermal bridging and uncontrolled ventilation channels permit the efficient operation of these systems.

***Table 1:** Participant Dwellings - Retrofit Measures*

ID	Replacement of external doors and windows Y/N	Type of external wall insulation used IWI - Internal wall insulation FFCB - Full fill cavity bead EWI - External wall insulation N - None	Replacement of roof / attic level insulation Y/N	Floor insulation Y/N	Ventilation system	Heat Pump Y/N
1	Y	IWI	Y	Y	DCV	Y
2	Y	FFCB	Y	N	DCV	Y
3	Y	EWI	Y	Y	DCV	Y
4	Y	FFCB + IWI	Y	N	DCV	Y
5	N	N	Y	N	DCV	Y
6	N	N	Y	N	DCV	Y
7	Y	FFCB + IWI	Y	N	DCV	Y

***Table 2:** Participant Dwellings - Listed Improvements*

ID	pre-retrofit BER	pre-retrofit energy use - kWh/m2/yr	post-retrofit BER	post-retrofit energy use - kWh/m2/yr	pre-retrofit airtightness test result - m3/hr/m2	post-retrofit airtightness test result - m3/hr/m2
1	E1	304.11	A2	33.59	16.262	4.87
2	G	470.93	A3	58.2	15.714	4.53
3	G	862.6	A2	48.13	n/a	3.38
4	G	535.59	A3	59.29	30.99	4.94
5	C3	218.48	A3	70.97	7.585	4.52
6	B3	125.95	A3	64.39	n/a	2.18
7	C2	193.12	A3	55.93	n/a	4.91

RESULTS AND DISCUSSION

The SBDCV system under review considers that the level of ventilation provided (once compliant with Part F of the building regulations) is sufficient to control the concentration of all indoor air pollutants, including those that are not produced as a result of human occupancy. To explore this position, the data from the monitored variables were tested for linearity, by way of bivariate correlations. The purpose of this type of statistical analysis is to find out whether changes in one variable produce changes in another, by assessing the association that exists between them. Pearson’s r is used to assess the linear relationship that may exist, whilst Spearman’s rho is used where the relationship may be non-linear (sometimes stronger and sometimes weaker) depending on the data. The dataset is significant with > 65000 measurements of each variable (per room, per dwelling) over the monitored period. VOC’s and radon were assessed individually in respect to RH levels, as RH is the catalyst that triggers the SBDCV system. A correlation between variables would indicate that as one variable changes in value, the other variable tends to change in a specific direction. In respect to the SBDCV system, it is expected that increases in RH would trigger greater air inflow into the habitable rooms that would lead to reductions in RH and all other indoor pollutants. Table 3 details the findings of these tests, demonstrating a weak to no correlation between the variables in each dwelling (the designation “A” refers to the main utilised living area in each dwelling, “B” refers to the main bedroom). These findings suggest that the SBDCV system as installed, is unable to adequately control indoor air pollutants that are not related to human occupancy within retrofit dwellings.

***Table 3:** Correlation Coefficients*

Dwelling ID	**Relative Humidity v Volatile Organic Compounds**				**Relative Humidity v Radon**			
	Pearson Correlation	P-Value	Spearman Correlation Coefficient	P-Value	Pearson Correlation	P-Value	Spearman Correlation Coefficient	P-Value
1A	0.001	0.725	0.044	<.001	0.274	0.000	0.219	0.000
2A	0.174	0.000	0.204	0.000	-0.156	0.000	-0.103	<.001
3A	0.299	0.000	0.239	0.000	-0.013	0.001	-0.120	<.001
4A	0.095	<.001	0.145	<.001	0.009	0.179	-0.023	<.001
5A	0.147	<.001	0.161	0.000	0.066	<.001	0.063	<.001
6A	0.147	<.001	0.177	0.000	-0.300	0.000	-0.296	0.000
7A	0.133	<.001	0.190	0.000	0.205	0.000	0.202	0.000
1B	0.016	<.001	0.008	0.043	-0.298	0.000	-0.329	0.000
2B	0.008	0.034	0.050	<.001	0.030	<.001	0.010	0.010
3B	0.172	0.000	0.138	<.001	0.128	<.001	0.202	0.000
4B	0.169	<.001	0.231	<.001	-0.369	0.000	-0.420	0.000
5B	0.101	<.001	0.095	<.001	-0.045	<.001	-0.013	0.002
6B	0.177	0.000	0.254	0.000	0.004	0.332	-0.032	<.001
7B	0.111	<.001	0.149	<.001	-0.214	0.000	-0.151	<.001

Figures 1-4 demonstrate the lack of correlation in four of the monitored rooms. Each plot incorporates a line of best fit which graphically demonstrates the lack of relationship between the variables. Figures 1 and 2 plot VOC measurements gathered during the monitoring phase. The Airthings Wave Plus loggers use a metal-oxide based sensor with a sensitive layer that reacts to chemicals by adsorption. This type of sensor reacts to most volatile organic compounds but is not able to differentiate between them. Therefore, it is not possible to consider specific adverse health effects from the measurement data, as each type of VOC has its own specific threshold limit value (TLV). This is defined as the limit a person can be exposed to a certain VOC without experiencing adverse effects. The lack of correlation is a cause for concern, should the levels exceed a compound specific TLV within the indoor environment. Figures 2 and 4 detail radon measurements that are in excess of the national reference level of 200 becquerels per cubic metre (Bq/m3). It is accepted that this level of activity may not exist within all retrofit dwellings but rather is a potential unintended consequence of dwelling retrofit in high radon areas.

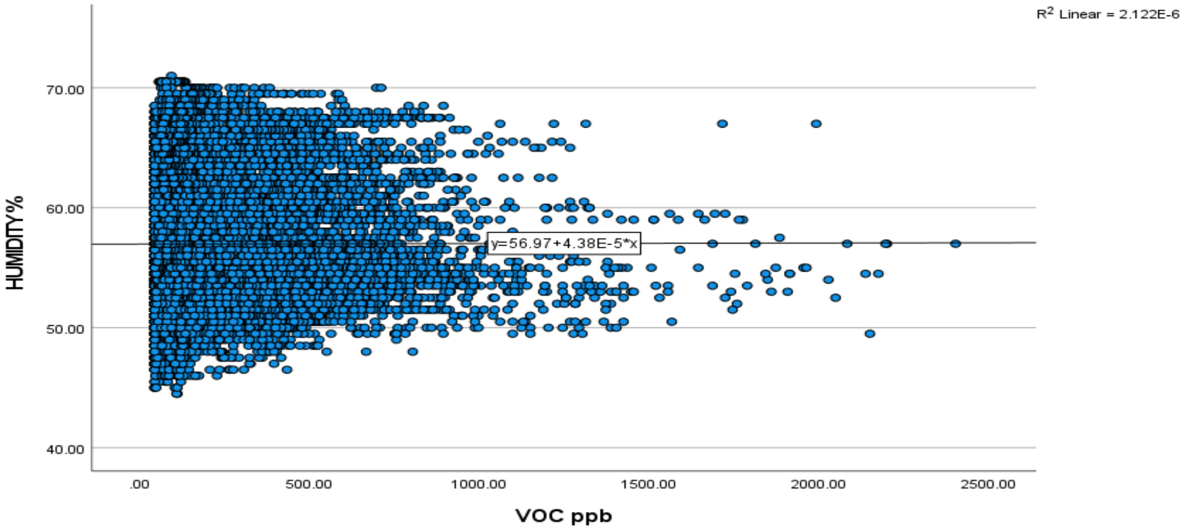

Figure 1: Relative Humidity & VOC Scatter Plot – Dwelling 1A

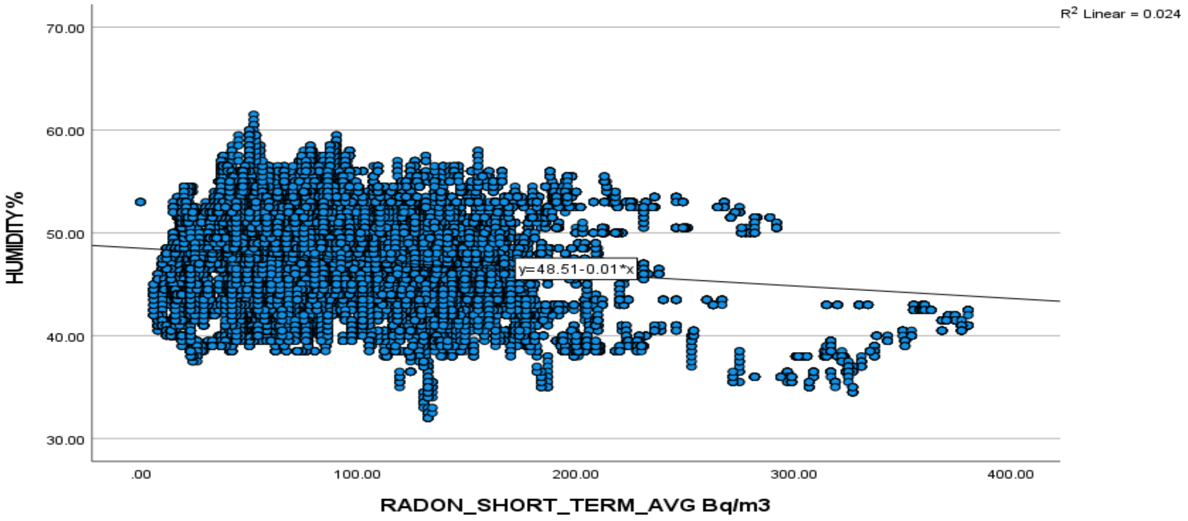

Figure 2: Relative Humidity & Radon Scatter Plot – Dwelling 2A

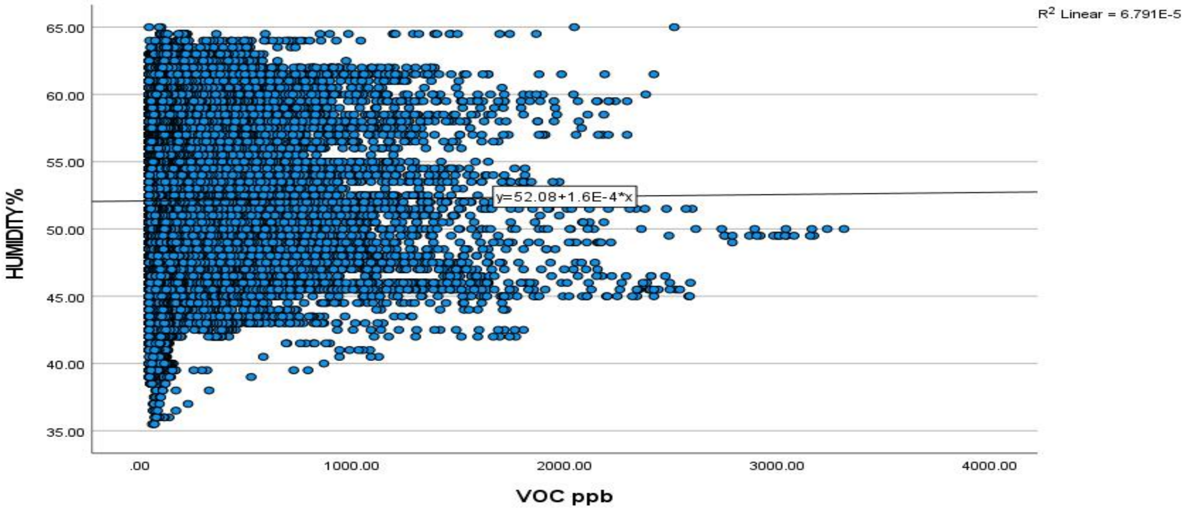

Figure 3: Relative Humidity & VOC Scatter Plot – Dwelling 2B

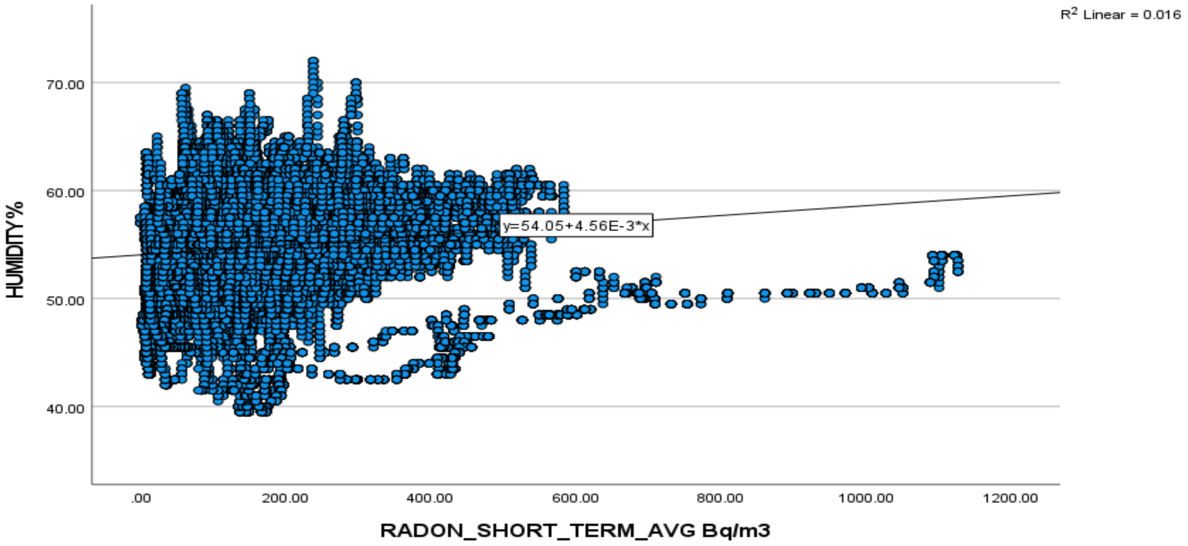

Figure 4: Relative Humidity & Radon Scatter Plot – Dwelling 3B

These results question the suitability of deploying a SBDCV strategy when undertaking large scale dwelling retrofit, due to the significant impact that indoor air pollutants can have on dwelling inhabitants (Borsboom et al., 2016; Logue et al., 2012). It is accepted that the sample size (n=7) is small but countered that the near identical fabric first approach to each retrofit suggest these findings can be extrapolated to apply to all dwellings (including those in other jurisdictions) that fit criteria similar to those listed and achieved in Tables 1 & 2.

CONCLUSIONS

This research has demonstrated that SBDCV systems that are activated by RH and presence detection are not sufficient to control the levels of specific indoor pollutants that are not produced as a direct result of human occupancy patterns, as these pollutants have varying emission rates and do not correlate to the number of occupants in a space. The financial cost associated with dwelling retrofit ensures that retrofit measures become locked-in for a significant period, therefore the ventilation strategy adopted within the dwellings under review has the potential to cause significant health and wellbeing impacts for occupants. It is suggested that balanced mechanical ventilation systems, that incorporate multi-pollutant sensors and an automatic modulating boost capacity, are considered for install within retrofit dwellings. Such systems should also incorporate suitably sized filters for incoming air, to limit the introduction of external pollutants to the internal environment.

We are constructing the future, therefore our approach to indoor air quality is critically important as we seek to retrofit 500,000 existing homes to a BER of B2 by 2030.

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