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Building tight – ventilating right? How are new air tightness standards affecting indoor air quality in dwellings?

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Abstract

Building more air-tight dwellings is having a deleterious impact on indoor air quality. In a range of recently completed dwellings CO_2 concentrations were measured in occupied bedrooms at unacceptable concentrations (occupied mean peak of 2317 ppm and a time weighted average of 1834 ppm, range 480–4800 ppm). Such high levels confirm that air-tight dwellings with only trickle ventilators as the 'planned' ventilation strategy do not meet the standards demanded by the Building Regulations. Reducing ventilation rates to improve energy efficiency and lower carbon emissions, without providing a planned and effective ventilation strategy is likely to result in a more toxic and hazardous indoor environment, with concurrent and significant negative long-term and insidious impacts on public health. Furthermore, the methodology underpinning the current regulations cannot be considered as creditable. While the complexity around numerical modeling often leads to conclusions based upon simplistic and unrealistic assumptions around all doors in a dwelling being open and trickle ventilators being unobstructed, this paper demonstrates that in 'real life' situations, this is not the case and could lead to significant risks of under ventilation. This is particularly the case when standards and guidance are based upon theoretically modeled scenarios that are not representative of real-life operation. The consequences of this are important in terms of the likely negative impacts on occupant health.

Keywords

Indoor air quality, air tightness, trickle ventilation, health, asthma

Build tight – ventilate right?

In 1992, Perera[1] put forward the concept 'build tight – ventilate right.' This was a proposition that dwellings should be designed and constructed to be as tight as practicable and incorporate a 'planned' ventilation strategy. The paper emphasised that a building cannot be too

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'air-tight', but it can be under ventilated. This approach built on a BRE publication[2] that claimed there was wide acceptance that a whole house ventilation rate of 0.5 ach^{-1} – supplemented by mechanical air extraction during cooking and bathing – was sufficient to dilute indoor pollutant concentrations and suppress relative humidity below 70% – a threshold associated with condensation and mould growth. The current recommendations for trickle vent free opening area (12,000 mm^2 for apartments with a minimum of 11,000 mm^2 where an average of 11,000 mm^2 is provided per room), as recommended in clause 3.14.2 of the Domestic Technical Handbook, Building Standards (Scotland) Regulations[3] are derived from a 'Review of Guidance of Energy and Environment'[4] conducted by Glasgow Caledonian University, that utilised BREVENT[5] software to calculate the area of trickle ventilators required under various conditions, to produce acceptable indoor air quality (IAQ). BREVENT software considers a dwelling to be a single zone.

The potential impact on health, resulting from increased air tightness, has been highlighted in recent research by Davis and Harvey[6] and Crump et al.,[7] who called for further investigations to ascertain 'healthy' ventilation rates. This was partially addressed in a recent study[8] commissioned by the Scottish Government, 'The effect that increasing air-tightness may have on air quality within dwellings.' In this study, air tightness and air change rates were measured in a mid-terrace dwelling (Garston, Watford) under a variety of conditions and the published report concluded that dwellings built to 5 m^3/m$^{2/}$/h@50 Pa provide air change rates roughly in line with the CIBSE[9] recommendation of 8 l/s per person.

BRE test results

In a mid-terrace dwelling, with an air tightness of 6 m$^{3/}$/m^2/h@50 Pa and standard trickle vents fitted on all windows, ventilation rates were measured at 0.7 to 1.3 ach^{-1} on the upper floor (equating to 37–69 l/s), and 0.4 to 0.6 ach^{-1} on the ground floor (equating to 21–32 l/s). Measurements of CO_2 concentrations (released from a mechanical source) did not provide any cause for concern and settled at circa 1000 ppm in the living room and 600 ppm in bedrooms.

The test protocol had, however, several significant confounding variables that ignored 'real life' conditions. The tests were undertaken with all internal doors wedged open, creating one unified internal air mass of 192 m^3. Such a test method does not produce a realistic scenario, given that, in practice, occupants will tend to keep internal doors closed for reasons of privacy, noise transmission (particularly in bedrooms), thermal comfort and in flatted accommodation will be required to do so for fire safety. Furthermore, the release of CO_2 from a central point does not reflect concentrations and intensity of occupation. All trickle vents were open and there was no occlusion of the vents by blinds or curtains. External wind speeds during the test regime were above average (5 m/s) and would create both positive and negative pressures on the elevations, driving cross and displacement air movement in the unified volume. The test protocol did not examine air quality in discrete room volumes where occupants will spend the majority of their time. The task was therefore to identify a 'tightly' constructed test house where air quality under 'real life' conditions could be measured.

Method

A recently completed 'Passive House' in Pittenweem, Fife (Kingdom Housing Association) shown in Figure 1, was selected and air pressure tests (Figure 2) produced a figure of 1.18 m^3/m^2/h@50 Pa. The 'tightness' of this dwelling was then reverse engineered by fitting tarpaulins to the living and bedroom windows (fixed open) with standard trickle vents incorporated (Figures 3 and 4).

The living room and double bedroom were repeatedly pressure tested with the mechanical heat recovery ventilation (MHRV) system outlets/inlets sealed and disconnected from the

Figure 1. Front elevation of the 'Passivehouse' in Pittenween.

Figure 2. Tarpaulin fitted to the patio doors in the living room.

power supply. By progressively increasing the opening area of an additional vent in the tarpaulin, the target air leakage/infiltration rate of $5\,m^3/m^2/h@50\,Pa$ was achieved. The rooms were then re-occupied and a Graywolf CO_2 monitor placed at seated head height (Figure 5) and programmed to take readings every 60 s. The living room was a combined kitchen/diner with a floor area of $31\,m^2$ and a volume of $75\,m^3$. The bedroom had a floor area of $15\,m^2$ and a total volume of $44\,m^3$. Four data sets were collected over two 24-h occupied periods.

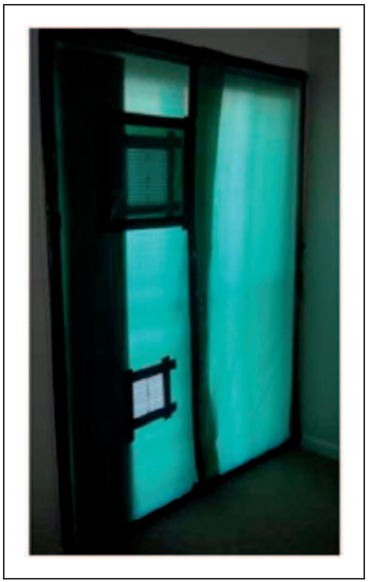


Figure 3. Tarpaulin fitted to the bedroom window.

Figure 4. Tarpaulin fitted to the bedroom window.

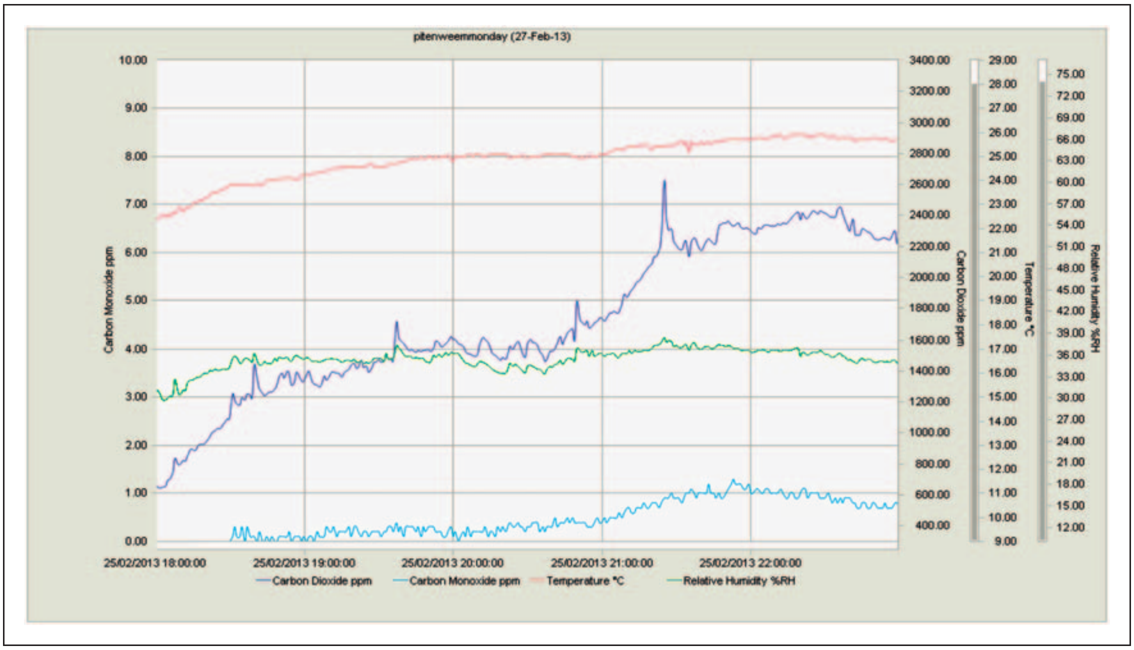
Figure 5. GrayWolf 'Wolfsense' CO_2 monitoring device.

The initial set measured CO_2, temperature and humidity, with the MHRV system disabled throughout the dwelling, between 1800 and 2200 h in the living room and 2300 and 0700 h in the master bedroom. The second two data sets measured the same parameters with the MHRV system re-activated.

Results

Discussion

When the living room door is closed and the 6
room occupied by two adults and three children, CO_2 levels climbed at a rate of 514 ppm/h, peaking at just over 2600 ppm. At this time, the children started retiring to bed with CO_2 concentrations falling slightly and then levelling off at circa 2300 ppm. Readings in the bedroom

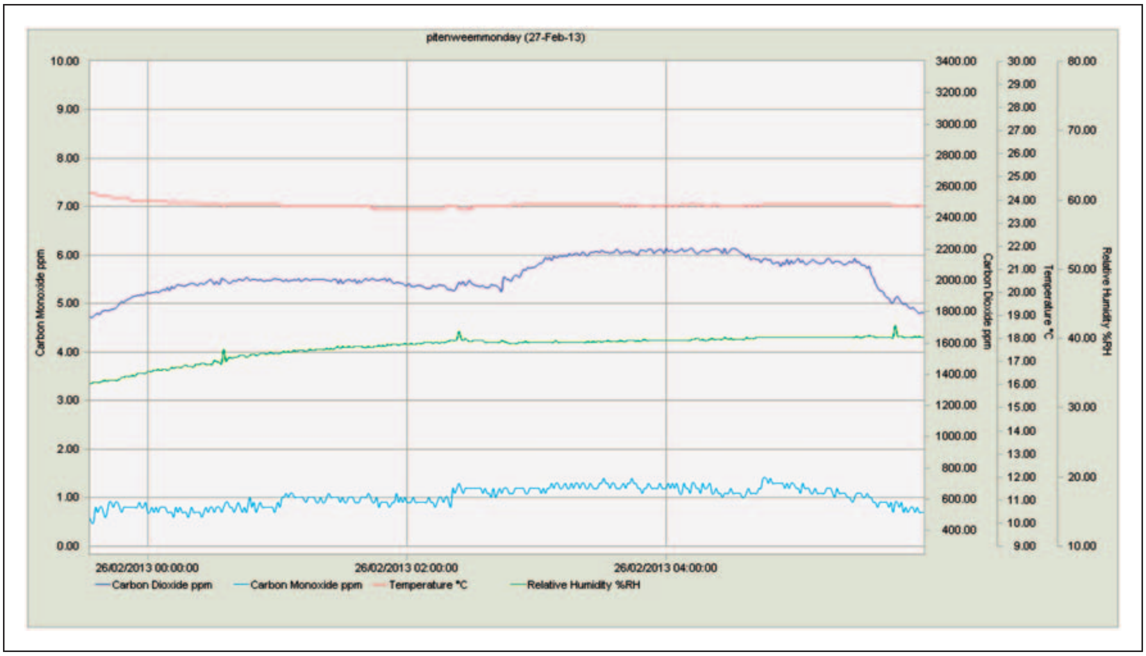


5 **Graph 1.** Living room MHRV disabled.

started at a higher level, possibly due to residual CO_2 from the afternoons occupancy required to fine tune the air infiltration rate, or CO_2 diffusing from the living room. Two adults were, however, able to maintain a level of 2200 ppm for the 8-h overnight sleeping period, well above Pettenkopfer's[10] recognised 1000 ppm threshold. It is also important to note that the room volumes in this dwelling are significantly greater than those found in contemporary 'affordable' housing where living room volumes are typically circa 30 m^3 and bedrooms 28 m^3 (as per Housing For Varying Needs[11] typical layout recommendations assuming 2.4 m floor-to-ceiling height). Under similar occupancy loads, concentrations in smaller volumes are thus likely to be much higher (2.5 times in living rooms and 1.57 in bedrooms). With the MHRV system re-activated, CO_2 levels fell within a range of 910– 280 ppm.

Contemporaneous research

As part of a major post-occupancy evaluation study (POE) funded by the Technology Strategy Board (TSB), the Mackintosh Environmental Architecture Research Unit is monitoring a range of new-build houses ($n = 20$) in five geographical locations. All dwellings are naturally ventilated and represent a range of construction types. Air tightness of these dwellings was measured in the range of 2.88–6.07 with an average of 4.66 $m^3/m^2/h@50\,Pa$ (see Table 1). CO_2 levels in living rooms and bedrooms have now been monitored for over five months. Bedrooms are of particular interest as they tend to have consistent conditions in terms of occupancy, ventilation regime and occupant interaction, with fewer confounding variables.

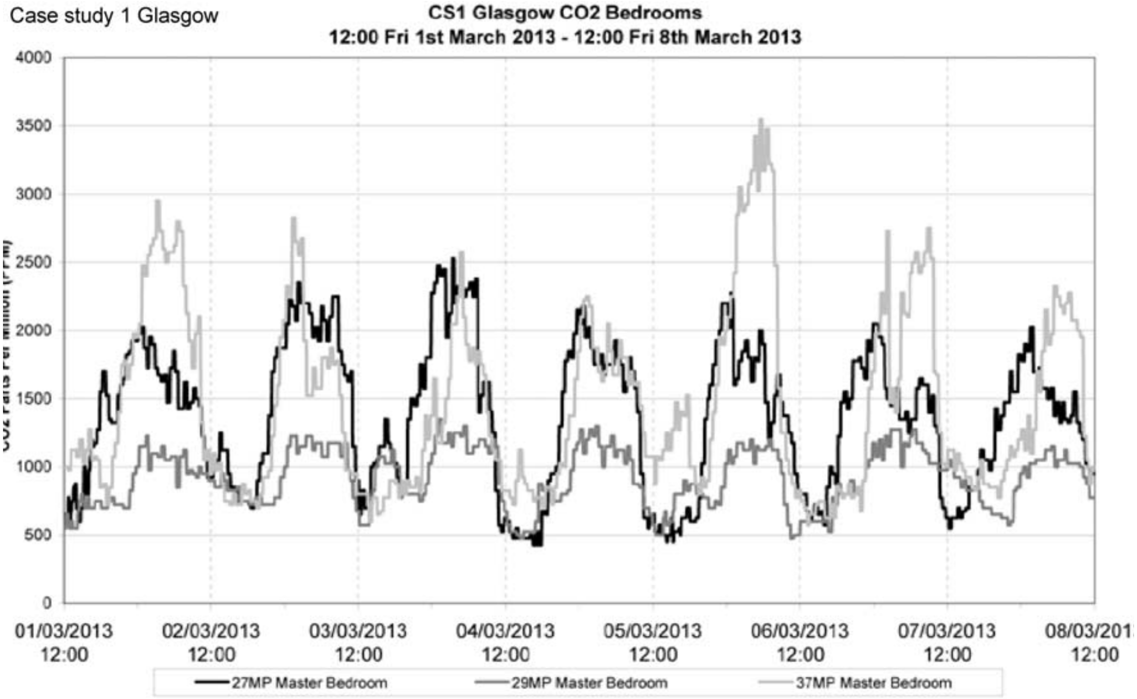


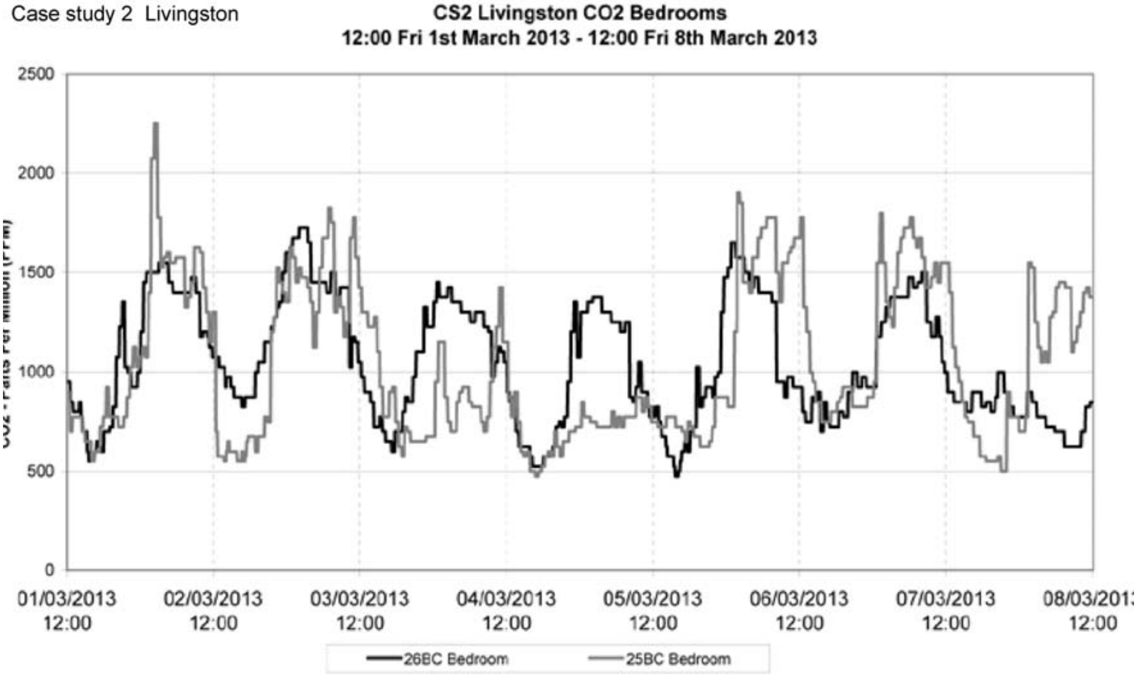
Graph 2. Bedroom MHRV disabled.

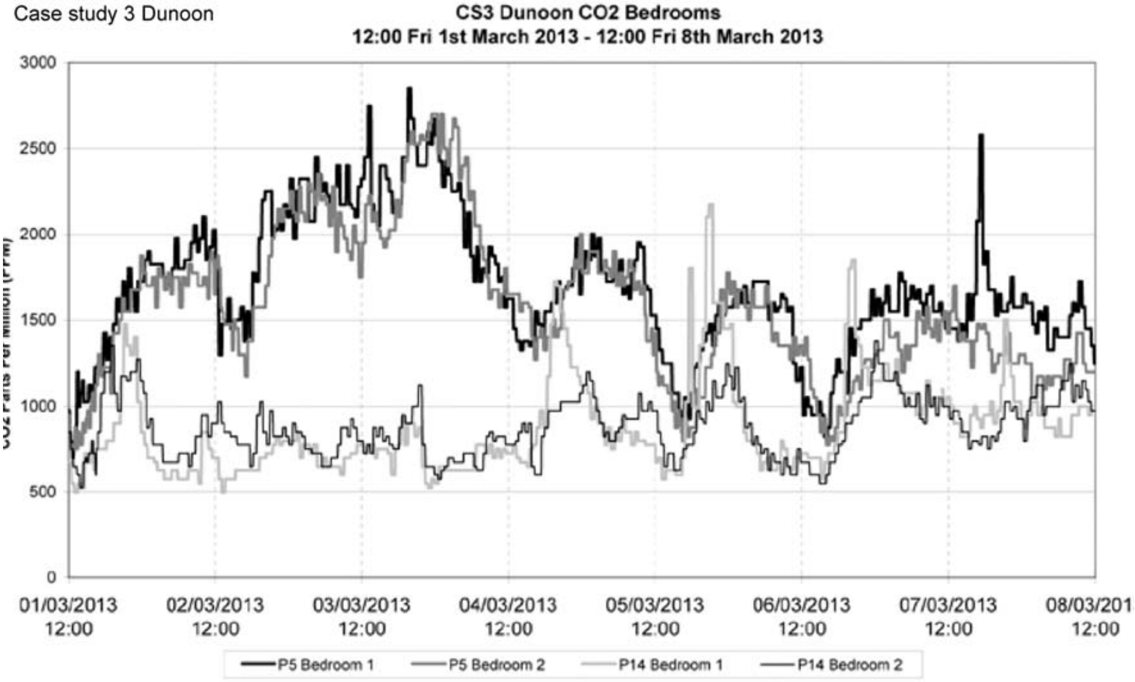
Table 1. New–build house monitoring summary.

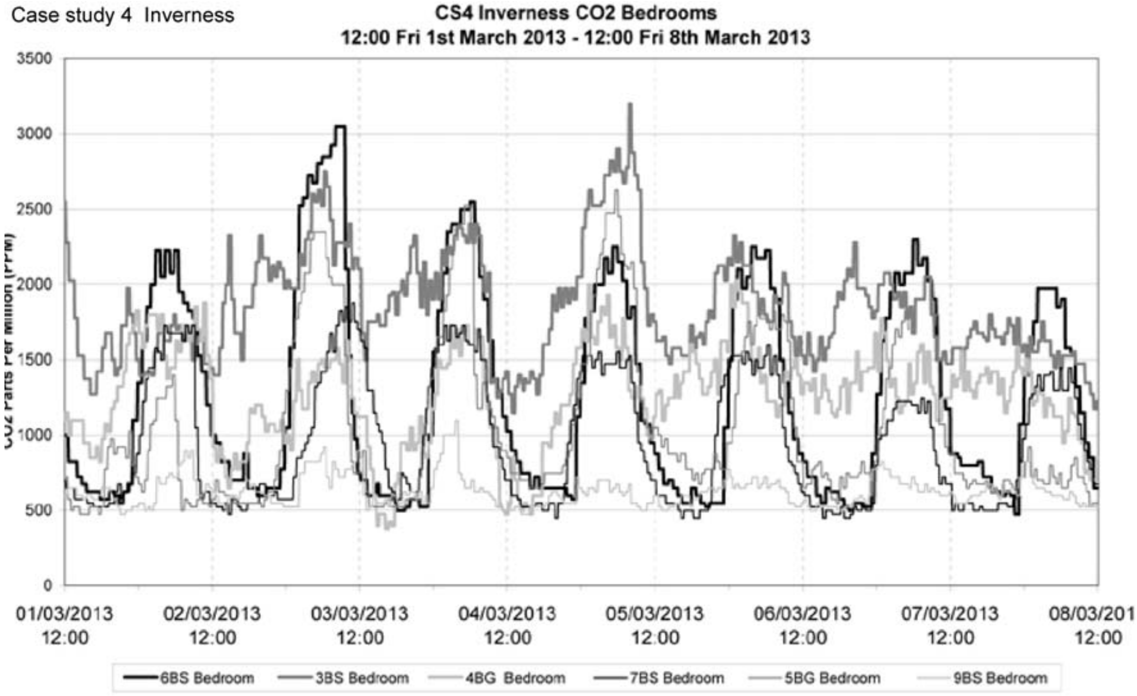
Monitored site	Building standards	Air permeability ($m^3/(hr.m^2)$ @ 50 Pa)	Construction type	Type	Built form	Number of bedrooms	Number of bedrooms monitored	Floor area (m^2)	Room volume (m^3)	Trickle vents
27MP	2010	4.25	Timber Frame	House	Mid-terrace	2	1	12.62	31.23	Yes
29MP	2010	2.88	Masonry	Flat	Flat – ground floor	2	1	13.15	31.50	Yes
37MP	2010	4.98	Timber Frame	House	End-terrace	2	1	12.54	30.34	Yes
26BC	2009	3.71	Timber Frame	House	Mid-terrace	3	1	TBA	TBA	Yes
25BC	2009	3.73	Timber Frame	House	End-terrace	3	1	TBA	TBA	Yes
P5 B1	2010	4.04	Closed Panel Timber System	House	Semi-detached	3	2	11.83	30.77	Yes
P5 B2	2010	4.04	Closed Panel Timber System	House	Semi-detached	3	2	14.22	45.50	Yes
P14 B1	2010	4.29	Closed Panel Timber System	House	Semi-detached	3	2	11.83	30.77	Yes
P14 B2	2010	4.29	Closed Panel Timber System	House	Semi-detached	3	2	14.22	45.50	Yes
3BS	2009	3.82	Timber Frame	House	End-terrace	3	2	11.17	28.08	Yes
6BS	2009	5.71	Timber Frame/Masonry thermal mass	Flat	Flat – ground floor	2	1	9.71	23.30	Yes
7BS	2009	4.53	Timber Frame/Masonry thermal mass	Flat	Flat – ground floor	2	1	9.11	21.86	Yes
4BG	2009	5.82	Timber Frame	House	Semi-detached	3	2	10.63	28.70	Yes
5BG	2009	6.07	Timber Frame	House	Semi-detached	3	2	10.63	28.70	Yes
9BS	2009	5.93	Timber Cassette (Pre-fabricated)	Flat	Flat – ground floor	1	1	11.80	28.32	Yes
MF22	2010	TBA	Timber Frame	Flat	Flat – ground floor	2	1	10.85	26.04	Yes
SF02	2010	TBA	Timber Frame	Flat	Flat – ground floor	1	1	9.00	21.60	Yes
SF17	2010	TBA	Timber Frame	Flat	Flat – mid floor	1	1	11.26	27.00	Yes
SF32	2010	TBA	Timber Frame	Flat	Flat – top floor	1	1	9.00	21.60	Yes
MF03	2010	TBA	Timber Frame	Flat	Flat – ground floor	2	1	14.64	35.14	Yes

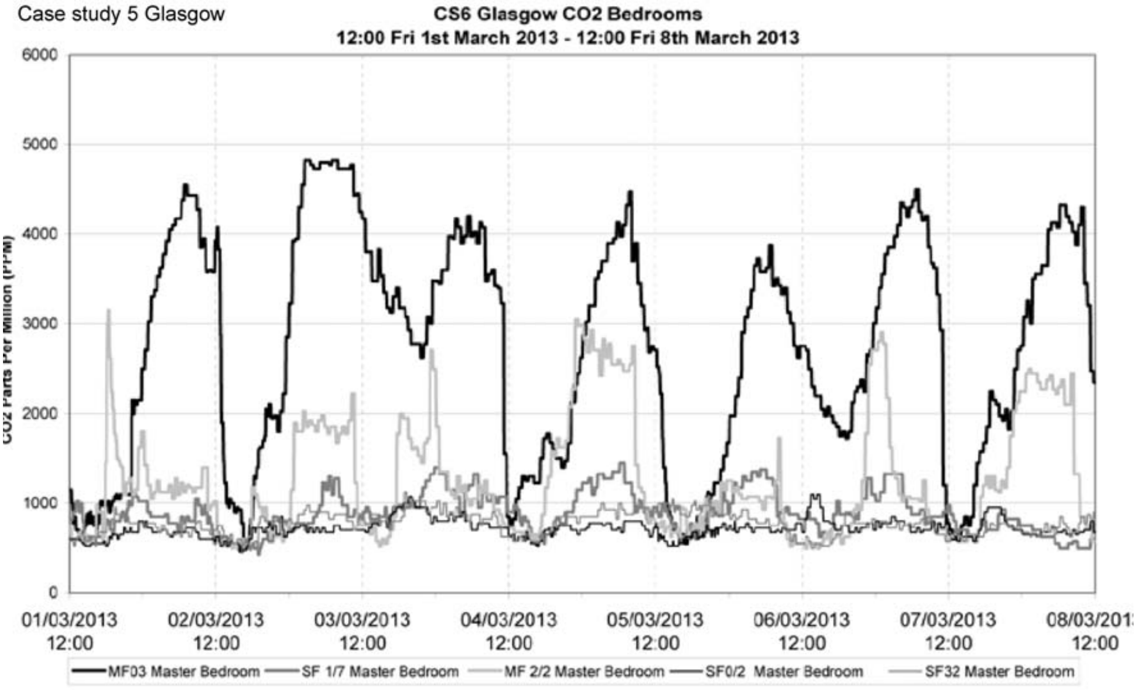
The following graphs show CO_2 profiles in bedrooms for a randomly identified winter week.

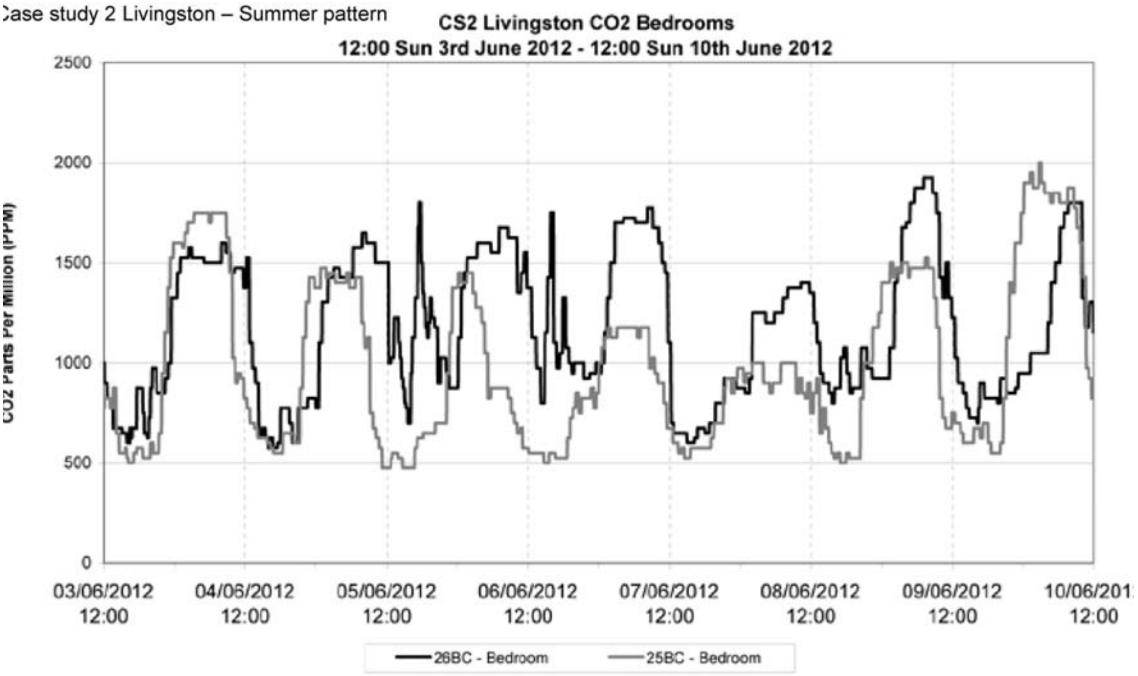

Case study 1 Glasgow
CS1 Glasgow CO2 Bedrooms
12:00 Fri 1st March 2013 - 12:00 Fri 8th March 2013
4000
3500
3000
2500
2000
1500
1000
500
0
01/03/2013 12:00
02/03/2013 12:00
03/03/2013 12:00
04/03/2013 12:00
05/03/2013 12:00
06/03/2013 12:00
07/03/2013 12:00
08/03/201 12:00
27MP Master Bedroom
29MP Master Bedroom
37MP Master Bedroom


Case study 2 Livingston
CS2 Livingston CO2 Bedrooms
12:00 Fri 1st March 2013 - 12:00 Fri 8th March 2013
2500
2000
1500
1000
500
0
01/03/2013 12:00
02/03/2013 12:00
03/03/2013 12:00
04/03/2013 12:00
05/03/2013 12:00
06/03/2013 12:00
07/03/2013 12:00
08/03/201 12:00
26BC Bedroom
25BC Bedroom


Case study 3 Dunoon
CS3 Dunoon CO2 Bedrooms
12:00 Fri 1st March 2013 - 12:00 Fri 8th March 2013
CO2 Parts Per Million (PPM)
3000
2500
2000
1500
1000
500
0
01/03/2013 12:00
02/03/2013 12:00
03/03/2013 12:00
04/03/2013 12:00
05/03/2013 12:00
06/03/2013 12:00
07/03/2013 12:00
08/03/201 12:00
P5 Bedroom 1
P5 Bedroom 2
P14 Bedroom 1
P14 Bedroom 2


Case study 4 Inverness
CS4 Inverness CO2 Bedrooms
12:00 Fri 1st March 2013 - 12:00 Fri 8th March 2013
CO2 Parts Per Million (PPM)
3500
3000
2500
2000
1500
1000
500
0
01/03/2013 12:00
02/03/2013 12:00
03/03/2013 12:00
04/03/2013 12:00
05/03/2013 12:00
06/03/2013 12:00
07/03/2013 12:00
08/03/201 12:00
6BS Bedroom
3BS Bedroom
4BG Bedroom
7BS Bedroom
5BG Bedroom
9BS Bedroom


Case study 5 Glasgow
CS6 Glasgow CO2 Bedrooms
12:00 Fri 1st March 2013 - 12:00 Fri 8th March 2013
CO2 Parts Per Million (PPM)
6000
5000
4000
3000
2000
1000
0
01/03/2013 12:00
02/03/2013 12:00
03/03/2013 12:00
04/03/2013 12:00
05/03/2013 12:00
06/03/2013 12:00
07/03/2013 12:00
08/03/201 12:00
MF03 Master Bedroom
SF 1/7 Master Bedroom
MF 2/2 Master Bedroom
SF0/2 Master Bedroom
SF32 Master Bedroom


Case study 2 Livingston – Summer pattern
CS2 Livingston CO2 Bedrooms
12:00 Sun 3rd June 2012 - 12:00 Sun 10th June 2012
CO2 Parts Per Million (PPM)
2500
2000
1500
1000
500
0
03/06/2012 12:00
04/06/2012 12:00
05/06/2012 12:00
06/06/2012 12:00
07/06/2012 12:00
08/06/2012 12:00
09/06/2012 12:00
10/06/201 12:00
26BC - Bedroom
25BC - Bedroom

Seasonality

This data is taken from a week in March and shows a consistent pattern for CO_2 with levels, in the majority of bedrooms, rising well above 1000 ppm during occupied hours. Of particular note are the observations during summer in case study 2 – that has now been monitored for 10 months – where the same pattern exists with little seasonal change, suggesting that bedroom ventilation regimes are habitual rather than adaptive.

Discussion of case studies

Longitudinal observation of CO_2 levels has indicated that these are reaching consistently high levels in bedrooms at night. In some cases, IAQ is less problematic due either to reduced occupancy or more frequent window opening habits. Where windows were kept closed ($n = 12$) CO_2 levels were noticeably higher, with an occupied mean peak of 2317 ppm and an occupied time weighted average of 1834 ppm measured between 11 pm and 7 am (range 480 – 4800 ppm). All bedrooms are characterised by a rapid increase in CO_2 on first occupancy then a levelling out, presumably due to the background ventilation characteristics. Window opening in monitored rooms was recorded using contact sensors. As yet there is limited information available on occupant behaviour such as internal door opening and use or occlusion of controllable trickle vents. Closing bedroom doors is an entirely rational and predictable behaviour, and where this occurs, trickle vents on one window elevation are opening into what is effectively, a 'dead-end.'

Health impacts

In 1991, the House of Commons Select Committee[12] established to investigate indoor air pollution, concluded

> *Overall there appears to be a worryingly large number of health problems connected with indoor pollution which affect a large number of people.*

Carbon dioxide is normally found in 'bad company'. At the outset of the 20th century there were approximately 50 materials used to construct buildings. By the end of the century, Raw[13] claimed that this list had grown to around 55,000, with half of them being synthetic. Compounds found in indoor air may have off-gassed from the building materials, furnishings and fittings, internal processes, cleaning products, with somewhat ironically even air fresheners are implicated in IAQ toxicity. The most common gases found in the indoor environment are carbon dioxide/monoxide, nitrogen and sulphur dioxide, volatile organic compounds, radon, formaldehyde and ozone. The most common suspended particulate matter are asbestos fibres, fibrous particulates (fibreglass or rockwool), bacteria and fungi, tobacco smoke, house dust mite (HDM) allergens, pollen and dust.[14,15] Changes in lifestyle such as indoor clothes drying are in part driven by changes in design and high levels of indoor humidity can have a major impact in terms of stimulating the growth of bacteria, mould fungal spores and HDM allergen generation.[16]

Asthma

In all, 80% of children with asthma are skin-prick sensitive to HDM allergens.[17] Low ventilation rates can produce high relative humidity. HDMs thrive in high humidity[18] and their allergens cause asthma.[19] Asthma prevalence in Britain has risen six-fold in 30 years.[20] There is now a compelling body of evidence that underpins the hypothesis that our dwellings are the single most important independent variable driving the current asthma pandemic. Maintaining internal RH below 60% will inhibit HDM colonisation and proliferation. Two recent studies have shown that it is possible to achieve this by retro-fitting intelligent ventilation strategies.[21,22]

Performance gap

Research have shown that there is a substantial performance gap emerging between the design intentions and measured performance of both new and refurbished buildings in the UK, with some sectors producing more than twice their predicted carbon emissions.[23] In the domestic environment, energy and water use can vary by a factor of 3–14.[24–26] The above case studies support similar outcomes when applied to ventilation rates.

Conclusions

The observed data from ‘real life’ conditions, where dwellings have been built to the prescribed standards for air tightness ($5\,m^3/m^2/h@50\,Pa$) with trickle ventilation as the sole ‘planned’ ventilation strategy, produced CO_2 levels indicative of poor IAQ. When considered as a discrete volume, an occupied apartment will require a substantially greater ventilation rate than can be provided solely by trickle ventilators with a free vent area of 11,000 mm^2. In most dwellings, air infiltration through these vents will be occluded by curtains or blinds and in many cases where vents incorporate controllable flaps, they will remain habitually closed. Whilst it may be argued that elements such as occupants closing vents or occlusion by curtains is out with the remit of statutory regulations, these are nevertheless predictable behaviours which should be taken into account, in the same way that ‘safety factors’ are applied in structural regulations to account for accidental overloading.

In the case studies, 60% of households did not open windows during the heating season. Were this to be consistent across the UK population as a whole, the majority of households residing in non-mechanically ventilated homes are relying solely on trickle ventilation and fabric air infiltration as the effective ‘fail safe’ ventilation regime. Such trickle ventilation has additional difficulties relating to user interaction. Where vents are adjustable they may remain closed year round, for a variety of reasons (draughts, noise or inaccessibility). Where non-adjustable vents are provided, it is common to find that they have been blocked in order to prevent heat loss or reduce the impact of external noise pollution, particularly where dwellings are situated close to traffic. Furthermore, occupants cannot interact with such controls when they are asleep. When considered as a discrete volume, a living room with five occupants will require close to 40 l/s to enter through an area of 12,000 mm^2. This in turn will require an air speed of 3.3 m/s, equivalent to a pressure differential of close to 18 Pa. Where rooms have a window vent in only one elevation, cross-ventilation will not occur. Without a potential exhaust, it is difficult to conceive how an opening area of 12,000 mm^2 could provide anything close to ‘healthy’ ventilation rates.

It appears from these case studies that dwellings built to the new prescribed air tightness standard – that rely solely on trickle ventilators for background ventilation – do not appear to satisfy the requirement of Technical Standard 3.14 that states:

Ventilation should have the capacity to:

- provide outside air to maintain IAQ sufficient for human respiration;
- remove excess water vapour from areas where it is produced in sufficient quantities in order to reduce the likelihood of creating conditions that support the germination and growth of mould, harmful bacteria, pathogens and allergies;
- remove pollutants that are a hazard to health from areas where they are produced in significant quantities.

Reducing ventilation rates to improve energy efficiency and lower carbon emissions without providing a planned and effective ventilation strategy is likely to result in a more toxic and hazardous indoor environment, with concurrent and significant negative long-term and insidious impacts on public health.

Recommendations

Technical Standard 3.14 (Scottish Regs.) should be rigorously enforced with designers and house builders required to demonstrate a planned ventilation strategy that maintains 'healthy' IAQ (below 1000 ppm) in all occupied rooms.

To assist with this the recommendations of the Sullivan Report[27] calling for post occupancy evaluation of dwellings should be implemented. Further building performance evaluation (BPE) of completed buildings is required to establish a clearer picture of actual performance and to provide an epidemiological evidence base for changes in legislation and ventilation design for occupant health.

Reliance on trickle ventilators to provide background ventilation in airtight buildings should be reconsidered, with a greater emphasis placed on the planning and prediction of overall house ventilation strategies, taking into account, either solely or in combination, cross, stack, permanent, displacement and mechanical ventilation.

The Building Regulations that underpin any applied ventilation strategy require to be based on a more robust house model that views occupied rooms as discrete volumes. This will allow for a better understanding of the actual free vent area and distribution required particularly where a room has no facility for cross ventilation. It should also account for room volume, ergonomic occupant control and external influences on operation.

Legislation is required to specify minimum 'safe' levels for indoor air pollutants in the domestic environment. Many countries are developing such standards and several have now brought forward legislation. Although any study that attempts to incorporate the synergistic, additive or antagonistic chemical and biological reactions that may occur in the indoor environment would have to address an unmanageable number of variables, such complexity should not provide an excuse for doing nothing in terms of research, guidance and the development of legally binding standards in respect to individual compounds. These 'proxy' compounds can be used indicatively as measures of IAQ and should be included in performance standards and monitored post completion.

Monitoring or control of actual performance for immediate feedback to occupants or mechanical systems could be achieved by using CO_2 or humidity sensors. This could include a CO_2 monitor installed in the living room (possibly on a standard traffic light warning system) to alert occupants when CO_2 levels exceed 1000 ppm (amber) and 2000 ppm (red). Such an alert may stimulate occupants to open a window for even a short period of time and allow CO_2 levels to partially equalise with ambient air.

Further work is needed to establish more precise relationships between room volume, likely levels of occupancy and ventilation requirements. Although appearing intuitive, assumptions that a smaller openable area is suitable for smaller rooms is not actually the case. An occupied small volume will more rapidly reach unacceptable levels of carbon dioxide and therefore will require a larger vent.

Summary

The above data sets confirm that small, 'tight' modern dwellings are highly likely to present with exceptionally poor IAQ that will, in turn, have an increasingly negative impact on occupant health. At present IAQ is being prejudiced by the drive to reduce carbon emissions. Although a worthy aim, public health should not be compromised in the name of 'energy efficiency.' Making dwellings tighter without insisting on a robust 'planned' ventilation strategy will produce further deleterious effects. The methodology underpinning the current regulations cannot be considered as creditable.

While the complexity around numerical modeling often leads to conclusions based upon simplistic and unrealistic assumptions around all doors in a dwelling being open and trickle ventilators being unobstructed, this paper demonstrates that in 'real life' situations, this is not the case and could lead to significant risks of under ventilation. This is particularly the case when standards and guidance are based upon theoretically modeled scenarios that are not representative of real life operation. The consequences of this are important in terms of the likely negative impacts on occupant health.

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