Ventilation and airtightness: chicken and egg?

Kara Rosemeier (PhD)
Director, Passive House Academy New Zealand

ABSTRACT

A popular narrative suggests that houses have become very airtight – which is why we need mechanical ventilation. The story implies that we have created a problem for ourselves when we fixed the punctures in the building envelope. While well-intentioned, we forgot about implications for the air exchange of buildings!

With this paper, I will attempt to set the record straight. Air leaks do not contribute to indoor air quality goals, and I will outline the reasons why, regardless of the blower door test results, purposeful ventilation persists as a design task.

Long before the advent of blower door testing, poor indoor air quality of buildings has been reported, evidencing a dubious success of the concept of "background ventilation". Air that leaks through cracks and gaps in the building fabric cannot be subtracted from fresh air requirements. Neither its quantity nor its quality can be trusted, and a crucial service such as fresh air provision needs dependable measures.

Air-leaky buildings are not healthy places to dwell for reasons unrelated to fresh air needs: they are less comfortable, noisier, and more prone to mould formation at surfaces and in cavities. When we increase the airtightness of the building envelope, we are addressing the indoor environmental quality issues associated with air-leaky buildings. In doing so, nothing changes for our fresh air needs. Good indoor air quality is no coincidence – we need to design for outcomes that are predictable and measurable.

INTRODUCTION

It is intuitive to believe that the holes in the fabric of our houses are providing much-needed fresh air. Yet this is likening our houses to a rubber dinghy – if we perforate the tubes, we know it will deflate, as very little fresh air will flow back through the holes. Instead of letting air in, the breaches will make the boat unfit for its intended purpose.

In the following paper, I will spell out why gaps in the building envelope should be perceived similarly to punctures in the inflatable. To this end I will locate indoor air quality and humidity issues in a historic context before discussing ventilation needs, and eventually arriving at empirical research data for a reality check.

Air-leaky buildings are less comfortable, noisier, and more prone to mould formation at surfaces and in cavities than very airtight buildings. There are good reasons to increase the airtightness of buildings, and the purported trade-off between healthy indoor conditions and energy-efficiency lacks substantiation, in fact. I am hoping to demonstrate that, as counterintuitive as it may seem, airtightness should rather be viewed as a supporting factor in our quest for good indoor air quality than a reason to worry.

As historic data are only available for residential premises, and the concern for moisture build-up and poor indoor air quality is most pronounced there, the following considerations will focus on the residential situation.

Is poor indoor air quality a novel problem?

Prior to the 19th century, the importance of clean air was not generally understood, as breathing was seen as necessary only to cool the heart. Yet, even by 1714 in a classic piece on fireplace design, Nicholas Gauger exclaimed that insufficient ventilation is responsible for a range of afflictions.[1] He was ahead of his time. The understanding of indoor air quality as a contributor to frequent health epidemics grew after the year 1800. This led to soul-searching in many European countries, with official inquiries and scientific initiatives trying to get the situation under control. At a House of Commons Select Committee in 1835 England, George Birkbeck testified that he never encountered a building that was well warmed and ventilated. Asked whether he attributed the lack of performance to the "want of practical knowledge on the subject", he replied:

> *"I do; heating and ventilation, especially the latter, seldom entering into the mind of the builder when he projects his building; he begins as if he did not know that ventilation could be necessary; he trusts to the doors and windows, to neither of which belongs the business of ventilation. The doors admit the occupants to the chambers; the windows the light; and apertures ought to be introduced to admit air for ventilation as regularly as the other openings."*[2]

A few years later in Germany, eminent academic Max von Pettenkofer suggested that natural ventilation may not be suited to deal with the apparent problem of poor indoor air quality:

"A further reason to insist on clean air in apartments is the knowledge that bad air is the source of many chronic ills, and that it certainly plays a part in the evils that plague the nation: scrofula, tubercles, etc. Thus, where the natural ventilation is insufficient to prevent an increase of the carbonic acid content of the air in our living and bedrooms below 1 per million, artificial ventilation has to be employed."[3]
(Translation K. Rosemeier)

In Sweden, contemporary researcher Elias Heyman agreed that natural ventilation cannot be relied upon for the provision of clean indoor air.[4]

Still, long before the airtightness of buildings went on the agenda, another 19th century German researcher lamented the poor indoor air quality (IAQ) of residential premises:

"At every turn, one still encounters rooms and entire buildings in conditions in which no one is able to feel comfortable. Numerous tenement blocks, whose poor ventilation already makes itself noticeable to the olfactory nerves of the passers-by, are not among the healthiest facilities by far."[5]
(Translation K. Rosemeier)

Fast forward to 20th century New Zealand, the largest study of IAQ in New Zealand houses focused on homes with gas appliances.[6] Here, the emphasis was on indoor generated oxides of nitrogen and carbon, while formaldehyde and particles were surveyed in most houses as well. Forty-five houses in Auckland, Taupo and Rotorua were investigated for one night. The houses were between one and 90 years old, with most of them being built before 1970. Nitrogen oxides were found elevated in all houses with unflued gas heaters, and concerning levels of carbon monoxide were found in some dwellings. Carbon dioxide levels were high for the whole sample. Formaldehyde concentrations exceeded the referenced World Health Organization's (WHO) recommendation at the time (0.1ppm) in two cases, and the referenced level of concern (0.06 ppm) was breached by a further three measurements. Respirable particulates – it remains unclear which particulate size this refers to – were measured to exceed the quoted WHO level of concern (150 $\mu g/m^3$) in two houses where indoor smoking occurred, while the level of no concern (100 $\mu g/m^3$) was overstepped in three other houses.

My own research found incidences of poor IAQ in all 15 houses without whole-house ventilation and built after the year 2000 (Rosemeier, 2014). The sampled houses were not particularly airtight, with a median n_{50} value of 6.5/h – more detail of this research will emerge in the following sections.

In light of the prevalence of reported poor IAQ long before 1977, when airtightness testing had its debut on the world scene in Sweden,[7] the hypothesis of a causal relationship between increased airtightness and poor IAQ outcomes lacks plausibility.

Are damp houses a recent phenomenon?

Dampness of residential premises is likewise a topic with a long reporting history. A less scientific source from more than 2,000 years ago, the Old Testament, speaks of mouldy houses (Leviticus 14, 34–57) and suggests rather drastic remedies: to take those buildings apart and discard affected materials.

Closer to our timeline, Abel[8] reported from a survey in the Swiss city of Bern in 1896, where 5 per cent of all rooms were found to be damp.

New Zealand research from the 1940s and 1970s[9,10] attests that dampness and mould occurred in a large number of New Zealand houses, although at the time primarily attributed to a lack of insulation. The prevalence of dampness, however, declined significantly from the warmer northern part to the colder southern parts of New Zealand in the 1972 survey, which makes a lack of insulation an unlikely solitary suspect for moisture build-up.

Bastings, in 1947, already explicitly identified insufficient ventilation as a contributing factor, and in a later publication[11] blames the absence of chimneys in all rooms of the "modern" house, and the resulting reliance on leaks, as one cause of the malaise.

In the year 1957 in Germany, Schüle[12] listed 8 per cent of living rooms, 33 per cent of bedrooms and 28 per cent of kitchens out of 733 researched rooms as damp. Still in Germany, but 46 years later, Brasche et al[13] examined 5,530 homes and found 1,827 units to some degree damaged by moisture. Their findings are of particular interest, as about 1,600 of the sampled dwellings employed some form of mechanical ventilation. Homes with mechanical systems in place were found to be significantly less damp. But more strikingly, homes that had properly sealed windows were faring a good deal better than their cousins with no seals in the windows.

Although it remains unclear whether homes with sealed windows also utilised mechanical ventilation systems, the authors refer to research by Künzel[14] and Eicke-Hennig[15] to conclude that leaks are no guarantor for proper air exchange.

Though the presence of window seals is an imperfect indicator for the airtightness of a building, it is often alleged that adding window seals changes a building's ability to manage indoor moisture. Clausnitzer[16] inspected 920 older, uninsulated apartments in the German federal state of Bremen – 26 per cent of these had perceptible mould. For kitchens, he found that the occurrence of seals in windows was indeed in line with a moisture build-up there, but for windows in the other rooms of the apartments the link did not hold.

None of the before-mentioned studies measured the airtightness of the sample buildings. However, given the period in which they were erected, it is a fair assumption that all of them were rather air-leaky. New Zealand houses, for example, were in the 1950s on average 2.5 times leakier than in the early 1990s.[17]

My own research[18] found no correlation between the degree of air-leakiness, a tracer-gas measured air change rate, indoor humidity or indoor pollutant concentration in 15 new homes without mechanical ventilation in New Zealand (see below for more details).

If an airtight building envelope was responsible for poor moisture management of dwellings, historic reports of dampness epidemics were hard to explain. While the airtightness of buildings and their use, for example the integration of laundries and bathrooms, has changed over time, what has not changed is the disregard for proper ventilation of houses.

Ventilation needs

Ventilation quantitative

Recommendations for a health-based-per-person air change rate fall in the area of 7–8 L/s. Only a small fraction of this air will be inhaled. The main reason why we need about 60 times more air than the amount we breathe is the concern for a sufficient dilution of air pollutants. Because air leaks are undetermined in size and distribution, their usefulness for meeting these ventilation needs is entirely random.

If we were to dimension a hole in our building envelope large enough to meet our ventilation requirements on a calm day, we would be looking at an opening the size of a small window. But in contrast to a window that seals well, we cannot regulate the airflow through leaks, adapt to changing wind speeds, and exclude nuisances such as noise and insects from the indoor environment.

Additionally, during times when outdoor temperatures vary significantly from the desired indoor temperature, a large hole in the thermal envelope induces significant discomfort and heat loss or gain. Moreover, because wind is the main driver for air exchange in low-rise buildings in milder climates, our hole would have to move in the facade with the prevailing wind for good effect. Depending on the distribution of leaks with respect to the direction of the wind and the height at which they occur, leaks may actually predominantly induce exfiltration of air, with the potential of damaging the structure via offloading moisture on cold surfaces on its way to the ambient.

Calling the airflow through leaks "background ventilation" is therefore a misnomer, as it does not deliver a reliable baseline for a needed air change rate. And whole-house air change rates are only half the story. I can have a very well-ventilated laundry, and therefore a high overall air change rate for my dwelling, and still have insufficient fresh air delivered to my bedroom. Fresh air in adequate amounts needs to get to the breathing zone where people dwell – leaks cannot guarantee this.

But do air leaks at least prevent us from suffocating indoors? About 11m³ of air are inhaled per person per day to extract the 20 per cent of oxygen contained in it in our lungs. However, we are exhaling 15 per cent oxygen with every breath as well, so we can recycle these 11m³ a couple of times. In a home with 100m² floor area and an average clear height of 2.4m and considering we recycle the air at least once; one person could survive 43 days without any air exchange in a completely airtight building. This would of course also mean never to leave the house during this time. The chances of suffocating in our homes are therefore rather slim, and no reason to perforate our building enclosures.

Quality problems with air that leaks through the building envelope

When air leaks through the building envelope, not only the quantity of it, but also its quality is questionable. It is likely that air which trickles into our homes picks up pollutants and fibres en route. In addition, the outdoor air may not be pristine to begin with, and filtration of air coming in through leaks is imperfect at best (refer Figure 1).

To help with diluting pollutants, fresh air needs to be of significantly better quality than the stale air in the enclosure. There is no point in exchanging polluted air for polluted air. This is another reason why infiltration air cannot be relied upon for meeting ventilation needs.

It has to be noted here that most of the issues associated with leaks in the building envelope pertain to intentional holes such as windows, doors and trickle vents in the same way. Noise, smells,

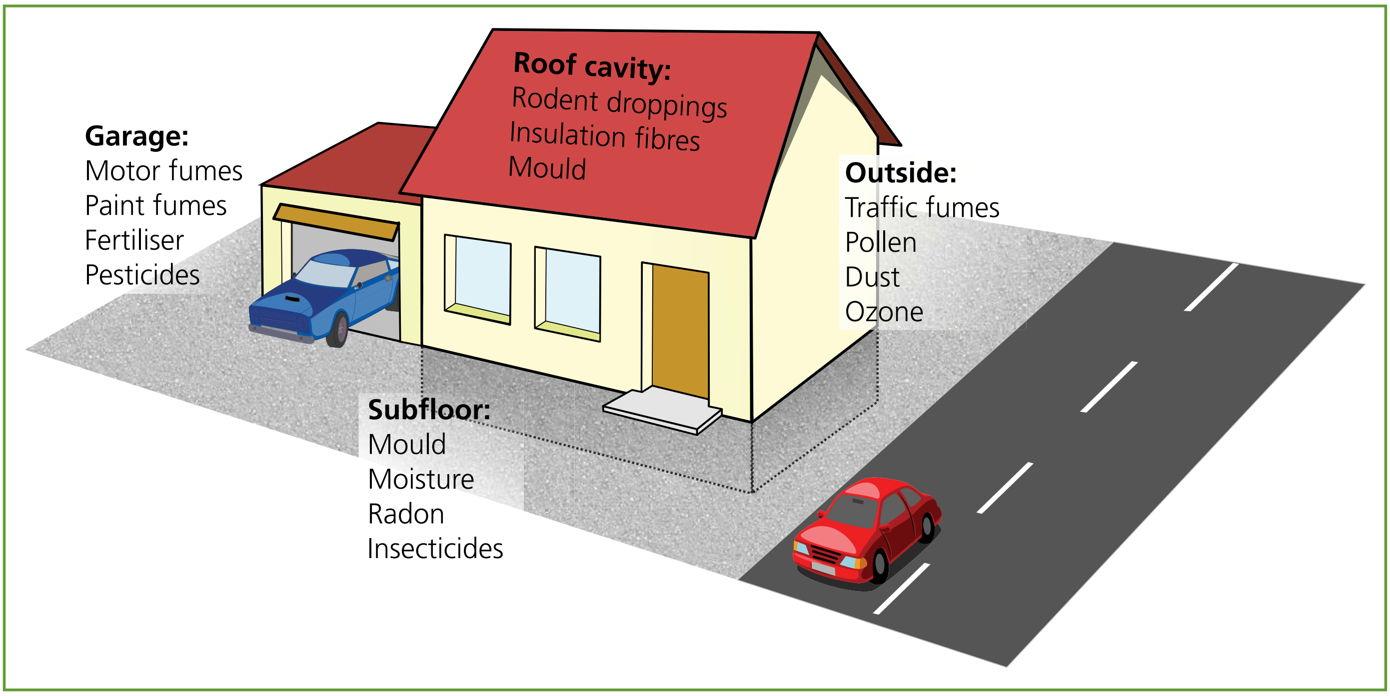

Figure 1. Air leaking through the building fabric may pick up contaminants on its way, or transfer them from the outside.

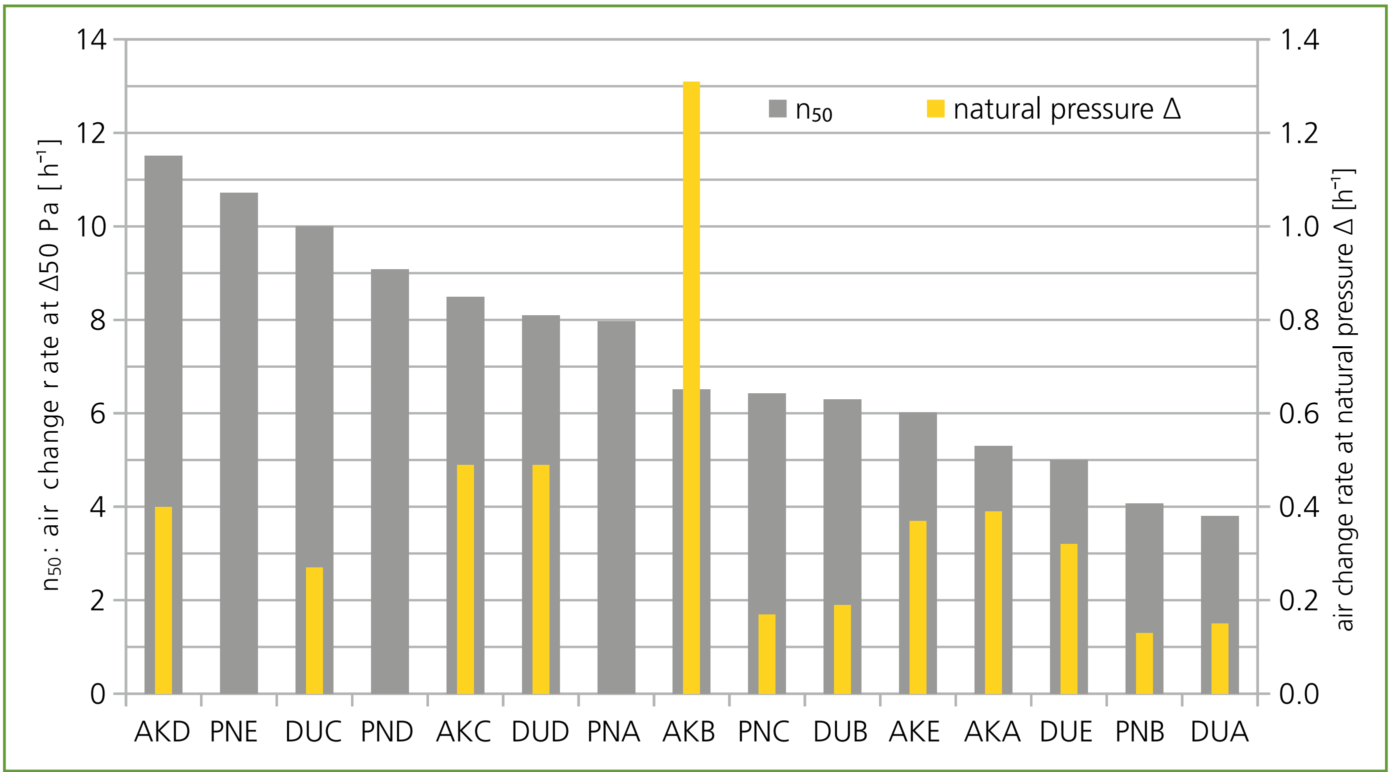

Figure 2. Air change rates at 50Pa and average natural pressure differential; air change rate data for houses PNE, PND and PNA were not available.

outdoor pollutants, insects – not to mention larger animals – can enter the indoor environment with every ventilation event, and heating energy cannot be recovered during the air exchange.

Many people will trade warmth for poor indoor air quality in winter.[19] Moreover, the dependence on wind persists, and mixing of air is entirely random, which makes it impossible to predict required opening times with any accuracy.

Field research findings

To test the relationship between air leaks, air change rates and pollutant concentration, 15 homes built after the year 2000 without whole-house mechanical ventilation were investigated in three locations in New Zealand. The air leakage rates were established with a blower door test, while the air change rates were assessed using the perfluorocarbon tracer method over three weeks at natural pressure differences.

Quite obviously, the columns for air leakage and air change rates in Figure 2 are ill correlated. Making a prediction about the air change rate from the air leakiness of the building envelope seems therefore a stretch.

A range of indoor air contaminant concentrations were measured over the course of a week. While recommended thresholds for all contaminants were exceeded occasionally, most prominently, CO_2 concentrations were crossing the 1,000-ppm threshold regularly, and reached, in one extreme, an almost tenfold peak (Figures 3 and 4).

To contrast the results of one of the sample houses with a building that is of similar size and location, yet significantly more airtight and employing a balanced ventilation system with heat recovery, CO_2 measurements were undertaken simultaneously.

Looking at the curves in Figure 4, it becomes clear that the ventilation mode rather than the degree of air-leakiness is crucial for IAQ outcomes. This is further corroborated by research on airtight (n_{50} from 0.29-3.33 h^{-1}) new houses with

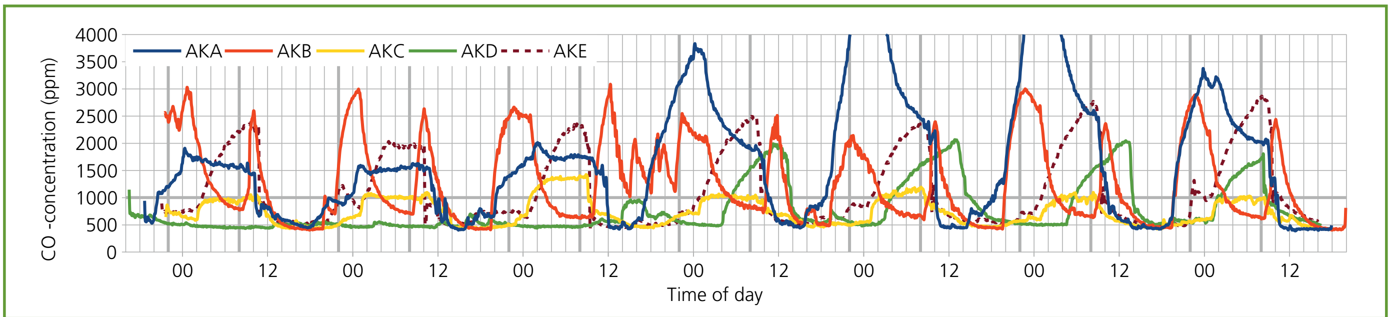

Figure 3. Run of CO_2 concentrations of the bedrooms in five homes in Auckland over a week in winter.

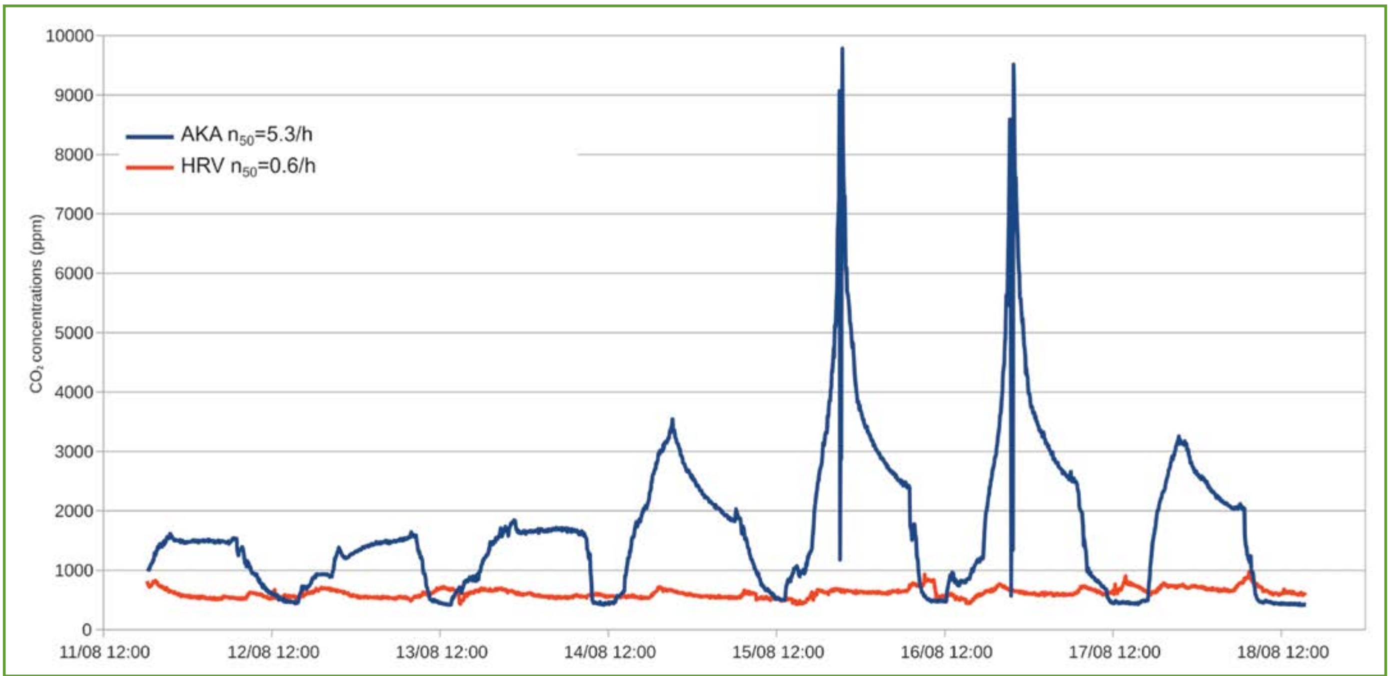

Figure 4. Comparison of CO_2 concentrations in the living rooms of two three-bedroom houses (each with an occupancy of four) in Auckland. AKA bedroom concentrations are displayed in Figure 3.

mechanical heat recovery ventilation systems in France, where indoor air contaminant concentrations were lower than the national average, apart from volatile organic compounds related to new construction, which, however, declined over the time of the testing.[20]

In the sampled houses without whole-house mechanical ventilation in New Zealand, other gaseous air contaminant profiles often followed the CO_2 curves, although were variously offset in magnitude based on usage patterns (such as gas cooking or heating), which confirmed the role of CO_2 concentrations as an indicator for ventilation effectiveness. However, trying to tie the severity of indoor air pollution to the airtightness of

House code	Air-tightness	Air change rate	CO_2 bedrooms	CO_2 living rooms	CO	NO_2	Formalde-hyde	PM_{10}
DUA	1	10	1	1	8	15	3	8
PNB	2	11	11	7	4	12	4	11
DUE	3	6	14	12	10	14	5	12
AKA	4	4	2	2	3	1	6	9
AKE	5	5	7	9	5	6	8	5
DUB	6	9	3	8	13	11	1	14
PNC	7	10	8	6	12	9	15	6
AKB	8	1	4	3	9	2	7	10
PNA	9	—	15	13	15	10	11	1
DUD	10	2	13	10	6	5	9	4
AKC	11	2	12	11	11	7	12	2
PND	12	—	5	5	2	3	10	13
DUC	13	7	6	15	14	13	14	15
PNE	14	—	9	4	7	8	13	3
AKD	15	3	10	14	1	4	2	7

Table 1: Contaminant concentration rankings after airtightness.
For column 1: 1 = most airtight, all other columns: 1 = lowest contaminant concentration.
Note: measured air change rates for PNA PND and PNE were not available.

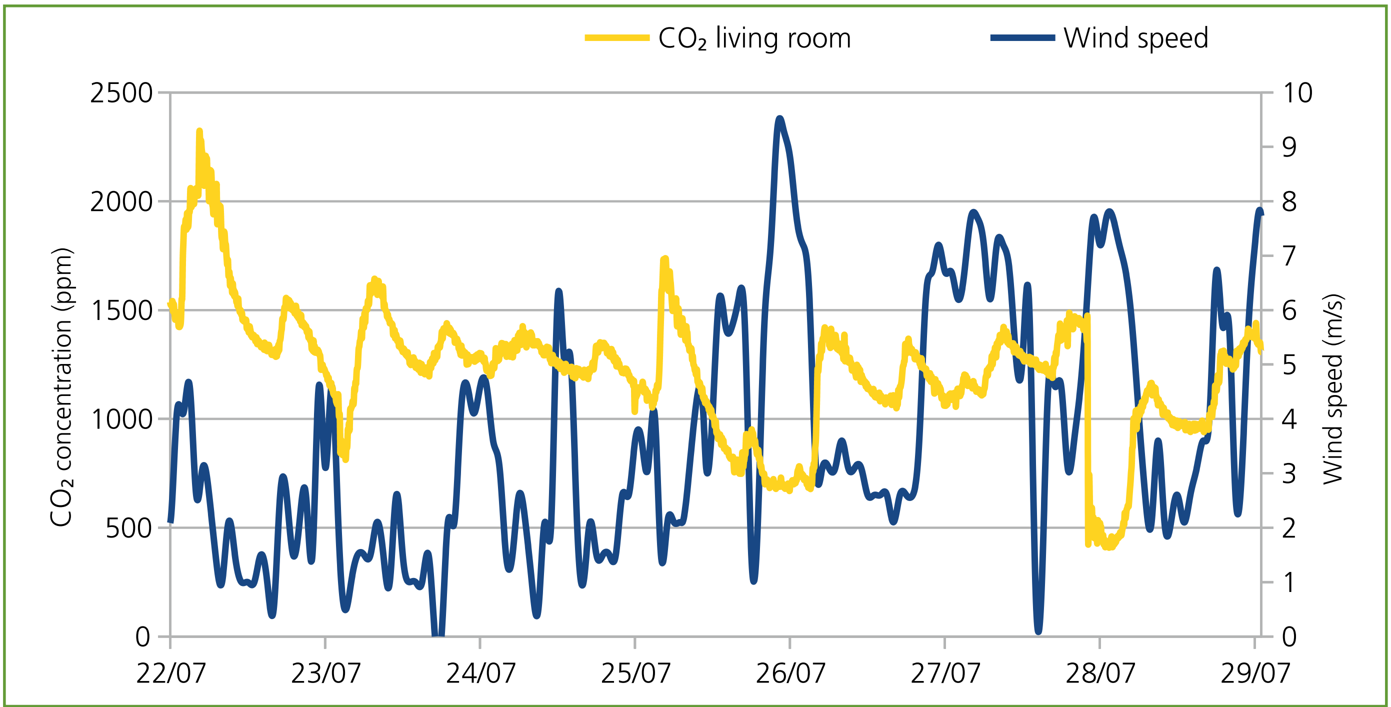

Figure 5. CO_2 concentration and wind speed at closest NIWA data station (#24851), DUA.

the building envelope or whole-house air change rates failed (refer Table 1).

Although there appears to be a relation between airtightness and contaminant concentration rankings for the tightest house, this does not hold for the second and third-tightest house, which have medium to low rankings for contaminant concentrations, and the air-leakiest home (AKD) presented the highest CO and second-highest formaldehyde concentrations.

Taking occupancy into account and looking at litres per second and person as indicators (ranging from 3.8 for DUB to 66.2 for AKB) also does not explain the distribution. Pollutant concentration is still high in the home with a high per person air change rate, while the IAQ of home DUB is not great, but not the worst.

For ventilation effectiveness, neither air leakage nor air change rates are helpful indicators, as success will be established by the degree of mixing in the enclosure, and the extent to which fresh air provision and occupancy are matched.

In an enclosure that relies on holes in the fabric for the provision of fresh air, air changes will largely be determined by the wind (refer Figure 5). The randomness of supply, poor mixing of air and the asynchronicity of fresh air demand and provision are a more probable explanation for the observed outcomes than leakage or whole-house air change rates. The reliance on wind for IAQ outcomes in free-running, low-rise houses was also confirmed in parametric modelling of a reference building in the three locations.

To assess the impact of air-leakiness on the moisture content in the sample houses, temperature and relative humidity were recorded over one week in winter, and the water content in indoor air calculated from averages.

		Average water content in indoor air in g/m³	
House code	n_{50}/h	Bedrooms	Living rooms
DUA	3.8	8.00	7.93
PNB	4.1	8.77	8.13
DUE	5.0	8.25	8.90
AKA	5.3	8.91	8.81
AKE	6.0	9.92	9.53
DUB	6.3	8.25	8.05
PNC	6.4	7.87	7.41
AKB	6.5	9.18	8.98
PNA	8.0	8.78	9.16
DUD	8.1	9.04	8.79
AKC	8.5	7.16	7.14
PND	9.1	7.35	7.64
DUC	10.0	7.22	6.70
PNE	10.7	7.21	6.82
AKD	11.5	8.12	7.97

Table 2: Average water content in indoor air, ordered by increasing air-leakiness of the building envelope.

In the air-leakiest home, AKD, a slightly higher water content in air was recorded than for the three times air-tighter home DUA. Even when locational factors are excluded (houses with identical first letters are in the same location): house DUA is drier than DUD with more than twice the amount of air leaks.

Airtightness of the building envelope does neither predict IAQ nor indoor humidity levels, as it is a poor indicator of ventilation effectiveness.

CONCLUSION

The history of indoor air quality and dampness of dwellings teaches us that conditions in our homes were dire long before houses were anywhere near airtight. Although concerns about a negative impact of mandated airtightness on IAQ have frequently been voiced and occasionally been confirmed with parametric models, negative side effects of an increased level of airtightness fail to manifest in field research, where factors other than airtightness are far more important in determining IAQ outcomes.

There is no benefit of air leaks to compensate for the increased discomfort, cost of conditioning the building or loss of ventilation control they incur. Changing the airtightness of a building is of no consequence for the ventilation requirements. Buildings need a ventilation concept, already requested by Birkbeck in 1835. Leaving the provision of fresh air to chance is not acceptable. We need to know how fresh air gets to where it is needed, when it is needed.

Yet, once we are employing mechanical forces with this task, avoiding cracks in the building fabric gains importance, as leaking air may well circumvent the designed air paths, lead to short-circuiting, poor mixing of air and suboptimal acoustic outcomes. Moreover, if a heat recovery core is used, the recovery rate will suffer from air bypassing the heat exchanger. While the need for ventilation is unrelated to the level of airtightness of the building envelope, the effectiveness of ventilation hinges on it. So, rather than its raison d'etre, airtightness is a means to achieve good ventilation outcomes. For user acceptance we need to reduce noise, draught and other discomfort associated with mechanically forced ventilation to a minimum. Although this sounds daunting, there are rewards. Only forced ventilation entails the option of filtering and thus improving outdoor air before it enters the indoor environment – unless air is allowed to bypass the filter through leaks in the building envelope.

An airtight building envelope is an ally when good indoor environmental quality is the goal, and we must not fear any negative side effects. But regardless of whether we live in a draughty old villa or a hermetically sealed box, we need to design for adequate ventilation!

ACKNOWLEDGEMENTS

The field research reported here was partially funded by BRANZ from the Building Research Levy.

References

1. Gauger, N. *La mechanique du feu*. (1714).
2. *Report from the select committee (of the House of Commons) on the ventilation of the Houses of Parliament; with minutes of evidence*. (House of Lords, 1835).
3. Pettenkofer, M. J. *Über den Luftwechsel in Wohngebäuden*. (Cotta, 1858).
4. Heyman, E. *Om luften i våra bostäder*. (1881).
5. Haase, F. H. Lüftungsanlagen im Anschlusse an die gebräuchlichen Heizungssysteme. *Polytech*. J. 277, 597–612 (1890).
6. Bettany, B. L., Chauvel, R. B. & Edmunds, C. J. *Domestic indoor air quality: a survey of the impact of gas appliances*. (Domestic indoor air quality: a survey of the impact of gas appliances, 1993).
7. Sherman, M. The Use of Blower-Door Data. *Indoor Air* 5, 215–224 (1995).
8. Abel, R. *Die Entwicklung der Gesundheitstechnik während der letzten 50 Jahre und ihre Einwirkungen auf die Gesundheitsverhältnisse in Deutschland*. 50, (1927).
9. Bastings, L. Dampness and mould in modern houses. *N. Z. J. Sci. Technol. B Gen. Sect*. 28, 195–227 (1947).
10. Trethowen, H. A. *Dampness in housing*. (Building Research Association of New Zealand, 1972).
11. Bastings, L. *Handbook on the insulation and heating of buildings: with special reference to dwellings*. (New Zealand Department of Scientific and Industrial Research, 1958).
12. Schüle, W. *Feuchtigkeitsschäden in Wohnungen*. (Forschungsgemeinschaft Bauen und Wohnen, 1957).
13. Brasche, S., Heinz, E., Hartmann, T., Richter, W. & Bischof, W. Vorkommen, Ursachen und gesundheitliche Aspekte von Feuchteschäden in Wohnungen. *Bundesgesundheitsblatt - Gesundheitsforschung - Gesundheitsschutz* 46, 683–693 (2003).
14. Künzel, H. Lüftung in Wohnungen. *FBW-Bl*. 1982, (1982).
15. Eicke-Henning, W. Wohnungslüftung, Feuchte und Schimmel in Wohnungen- ein neues Problem? *Gesundheitsingenieur* 121, 69–81 (2000).
16. Clausnitzer, K.-D. *Vermeiden Gasetagenheizungen Schimmelpilze?* (Bremer Energie Institut, 2006).
17. McNeil, S. et al. *Trends in Airtightness of New Zealand Homes*. in (2011).
18. Rosemeier, K. *Healthy and affordable housing in New Zealand: the role of ventilation*. (The University of Auckland, 2014).
19. Bruce-Konuah, A. Window use in single person offices: do occupants control personal ventilation to provide adequate IAQ? in *Proceedings – Healthy Buildings 2012* (Queensland University of Technology, 2012).
20. Derbez, M. et al. Indoor air quality and comfort in seven newly built, energy-efficient houses in France. *Build. Environ*. 72, 173–187 (2014).

ABOUT THE AUTHOR

Kara Rosemeier leads the Passive House Academy New Zealand and teaches building science in Auckland. She has been the director of an engineering consultancy, advised federal and state governments in Germany on matters of building energy efficiency, supported private clients on Passive Houses design, and supervised hundreds of retrofit projects. She is a board member of the Passive House Institute New Zealand (PHINZ) and chair of Air Permeability Testing New Zealand (APTNZ). Email her at rosemeier@phanz.ac.nz