Estimating the Background Ventilation Rates in New-Build UK Dwellings – is $n_{50}/20$ appropriate?

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Abstract

In the UK, a rule of thumb applied to air permeability is commonly employed when estimating background ventilation rates from pressurisation test data. However, this may lead to significant errors in estimating the infiltration rates in UK new-build dwellings, resulting in poor estimation of the dwellings in-use energy and CO_2 emissions, and the adoption of ventilation strategies leading to either unacceptable indoor air quality or unnecessary energy consumption. In this paper, a preliminary investigation into the applicability of the rule of thumb is undertaken. Background ventilation rates in four new-build dwellings in the UK are determined using the tracer-gas decay method and also the pressurisation (blower-door) method coupled with both the conventional $n_{50}/20$ and (in the UK) $q_{50}/20$ rule of thumb, and Sherman's modified rule of thumb, which takes into account other building-related factors. The conventional method over-estimated the air-change rate in two of the dwellings and under-estimated it in the other two dwellings. The modified rule of thumb produced comparable results for two of the dwellings, but significantly underestimated the air-change rate in the other two dwellings. These results suggest that more work needs to be done to devise appropriate climate and building-related correction factors for the UK.

Context

The current trend in the UK, as in many other countries, is towards a requirement for increasing energy-efficiency in new-build dwellings, as part of the drive towards reduced CO_2 emissions from the buildings sector. Regulation has been, and will continue to be, progressively increased in stringency, in order to provide a staged route to zero, or near-zero net CO_2 emissions.[1] At each stage, however, a balance must be struck between targets and aspirations on the one hand, and economic and technical practicalities on the other.

The effort to reduce CO_2 emissions is multi-faceted and must include many factors such as on-site power generation, water and waste management, and behaviour change, but nevertheless in the UK's prevailing climate, the thermal performance of the building fabric remains of paramount importance. Space heating currently accounts for approximately 60% of domestic building energy use.[2]

Broadly speaking, there are two classes of building heat loss: direct fabric losses which can be reduced via enhanced insulation of the plane elements of the building fabric coupled with the minimisation of thermal bridges, and ventilation losses caused by the replacement of heated with unheated air, through either intentional or unintentional means. The drive for increased building thermal performance must address both issues, and in both cases the measurement or reliable estimation of actual *in situ* performance is a vital area of concern, if progress is to be based on evidence, and 'savings' are to be realised in fact rather than merely in theory.

In this paper, we are concerned with the uncontrolled ventilation heat losses of new build UK dwellings. These heat losses can be determined from the background ventilation rate of the dwelling, in conjunction with a range of other parameters, such as the temperature difference between the inside and the outside of the dwelling and dwelling volume. In the UK, a simple rule of thumb is commonly used to estimate the annual background ventilation rate of new dwellings from air permeability data. The aim of this paper is to present the measured background ventilation rates that have been obtained from a small number of new building dwellings in the UK, and compare these to the ventilation rates obtained using the simple rule of thumb method, to determine whether such a rule of thumb is appropriate for new build UK dwellings in this small sample.

Introduction

All dwellings are leaky to some degree. Indeed air exchange with the outside environment is a necessity in order to provide oxygen, dilute atmospheric pollutants and remove excess water vapour. In theory, this function could be performed in a fully controlled way in a perfectly sealed building, but in practice air-exchange is always achieved via a combination of controlled (intentional) and uncontrolled (unintentional) mechanisms. The more air-tight the building, the more important the controlled ventilation strategy.

Traditionally, in the UK, dwellings have been generally very leaky, which is to say that uncontrolled ventilation has been plentiful. This is in keeping with a historical bias towards heating via open coal or wood fires where a good supply of oxygen was required. Indeed, this may be part of the basis of a persistent cultural belief among some sections of the population that dwellings need to be 'aired' by regular opening of windows etc. if indoor air quality is to be maintained. However, modern methods of space-heating, and requirements for increased energy efficiency have led to the need for a new building strategy, often expressed in the form of the popular maxim *"Build Tight, Ventilate Right"*. Thus, uncontrolled unintentional ventilation (infiltration) is reduced, and some form of additional intentional controlled ventilation is introduced in order to make up the deficit and ensure adequate indoor air quality.

However, it is important to be able to understand and reliably estimate the magnitude of uncontrolled infiltration in order to be able to provide appropriate guidelines for regulation, and to ensure that additional controlled ventilation is provided such that the indoor air quality is maintained without excessive energy penalty.

Intentional ventilation may be 'natural' e.g. trickle-vents on windows or designed use of the stack effect, or it may be mechanical, either with or without heat recovery. Whatever strategy is used, the purpose is to ensure that a given minimum air-exchange rate is achieved.

The part of the UK Building Regulations that deals with ventilation issues is Approved Document F (Ventilation), published by DCLG in 2010,[3] together with further minor amendments in 2013 which came into force as of 6th April 2013.[4] This document distinguishes between purpose-provided ventilation (controlled ventilation) and infiltration (uncontrolled ventilation), and sets out the key aim that a ventilation system should *"under normal conditions, be capable of limiting the accumulation of moisture, which could lead to mould growth, and pollutants originating within a building which would otherwise become a hazard to the health of the people in the building".* [4 p.13]

Ventilation Strategies

In practice, compliance with Approved Document F means that there are two options for new-build dwellings. If the air permeability (volume of air infiltration in a given time per unit of external envelope area) is expected to be less than $5m^3/h.m^2$ at 50Pa pressure difference (e.g. in the case of some new-build or refurbishment projects), then purpose-provided ventilation (ppv) must cover the entire ventilation rate requirement (as per the standard rates in litres per second listed in the document for various dwelling types). If, on the other hand, the air permeability is expected to be greater than $5m^3/h.m^2$ at 50Pa, then an infiltration rate of 0.15 air changes per hour is assumed, and ppv must cover the remainder of the requirement. Clearly this is rather rough and ready, and is based upon design expectations (which may or may not be met).

Part L of the Building Regulations also requires that a sample of homes on all new developments should be pressure tested for air-leakage.[5] In this edition of the Regulations, the required sample consists of 3 tests of each dwelling type, or 50% of all instances of that dwelling type, whichever is less. Dwellings are then deemed to comply if they achieve an air permeability of less than or equal to 10 $m^3/h.m^2$ at 50Pa and the DER (Dwelling Emission Rate) and DFEE (Dwelling Fabric Energy Efficiency) calculated using the measured air permeability is not worse than the TER (Target Emission Rate) and TFEE (Target Fabric Energy Efficiency). On sites where two or fewer dwellings are to be constructed, an alternative to pressure testing is available.

In order to meet the whole dwelling ventilation rates recommended for a given house type in the Building Regulations, a number of different ventilation strategies are possible. For new-build dwellings, four possibilities are listed:

1. Background ventilators (e.g. window trickle-ventilators) and intermittent extract fans.
2. Passive Stack Ventilation.
3. Continuous mechanical extract.

4. Continuous mechanical supply and extract with heat recovery.

These strategies are described in detail in Part F of the regulations, together with guidance on design for compliance, and on test methods. Testing and commissioning is required in all cases for mechanical ventilation systems. Procedures for measuring air flow rates and for commissioning mechanical ventilation systems are contained within the Domestic Ventilation Compliance Guide published by DCLG.[6]

It is clear that regulation is based upon some assumptions about background ventilation rates, informed by a degree of testing. However, measurement of background ventilation (infiltration) rates is by no means straightforward, as infiltration varies with time, and can be driven by factors such as pressure differentials, air movement, and temperature as well as being affected by the detailed distribution of the air leakage pathways within the dwelling.[7] If the methods used to estimate infiltration rates are subject to significant inaccuracies, there is a risk that new build dwellings may be either under-ventilated (at risk of poor air quality and overheating), or conversely, they may be fitted with unnecessary or over-specified ventilation systems, in compliance with UK regulations, and may suffer from unnecessarily high energy bills and poor levels of thermal comfort.

Measurement of Background Ventilation Rates

The most widely used technique for measuring the air permeability of a dwelling involves undertaking a fan pressurisation test using a blower door.[8] This technique is commonly used as it is relatively quick and non-invasive and is a basis for guidelines and legislation in a number of countries. In the UK, the test procedure to be adopted for compliance purposes is described within ATTMA Technical Standard L1,[9] and depends upon measurement of the flow of air through a door-mounted fan together with the resultant pressure difference created within the building. Intentional ventilation pathways such as extract ducts are blocked during testing. The relationship between pressure and flow is assumed to take the form of a power law, from which the air permeability of the dwelling can be derived. Measurements are taken at a series of pressure values in the approximate range 20-70Pa, with the final value calculated at 50Pa in the UK (in other countries different pressure differentials are used). Thus air permeability values are generally quoted as $m^3/h.m^2$ at 50Pa (q_{50}), or converted to an air-change rate (ACH) at the same pressure difference (n_{50}), using the internal volume of the building. In the UK, measurements for compliance purposes can be undertaken under pressurisation only, or depressurisation only, and both results are deemed to be equally valid. However, in UK dwellings, a systematic difference is often observed between pressurisation and depressurisation results, and this difference can be significant. CIBSE claim that it is common for the difference between the pressurisation and the depressurisation results to be more than 10%.[10] Stephen, on the other hand, suggests that the results can differ by as much as 20%.[11] These variations in measured air permeability could make the difference between a dwelling complying with a particular airtightness standard or not. The difference between the results can be ascribed to the fact that all of the air leakage paths occurring within a dwelling will have particular aerodynamic characteristics that are dependent upon the direction in which the air is flowing. In addition, various elements of the building fabric, such as windows and doors, can either be pushed tight against their seals or pushed off, depending upon whether the dwelling is being pressurised or depressurised. Therefore, in the UK, as the majority of windows are outward opening, it is likely that more favourable results could be achieved by depressurising rather than pressurising the dwelling. An alternative and more robust approach that can be used to demonstrate compliance is to undertake both a pressurisation and a depressurisation test and quote the average of the two values obtained. By undertaking both sets of measurements and averaging the results, any aerodynamic effects cancel one another out and no preference is given to one direction of air flow. However, this approach is rarely adopted in practice, due to the increase in testing time that is required and the resultant increase in the costs of the test.

The air permeability figure or air leakage rate that is obtained from pressurisation testing however, does not represent a real background ventilation rate, since under normal conditions the internal/external pressure differential will be far less than 50Pa and is typically around 3 to 6 Pa.[12] Furthermore, the blower-door test is a single measurement, whereas background ventilation varies with pressure, temperature and wind conditions, and so is most usefully quoted as an annual average figure. The air leakage rate can be approximated to the natural annual average background ventilation rate by simply dividing the air change rate at 50Pa (n_{50}) by 20. This empirical procedure is commonly known as the n_{50}/20 *'rule of thumb'*. However, much controversy surrounds this rule of thumb. Its origin is usually attributed to Kronvall and Persily (cited by Sherman in 1987),[13] who simply observed that much of the existing data approximated to this rule, though it was understood at the time that this observation was underpinned by no particular theoretical or physical model. In the US, the divisor was originally applied to air changes per hour, rather than permeability in $m^3/h.m^2$, thus taking better account of the dwelling geometry. Further work by Sherman used the LBL (Lawrence Berkeley Laboratory) infiltration model to partially validate the rule for large low-accuracy datasets, and also led to a number of modifications, resulting in the application of correction factors for parameters such as climate, building height, shielding and the types of holes, cracks and joints present.[13]

Mapping of the climate correction factor for North America was presented, as well as tables allowing correction factors to be estimated for the other parameters. This method can lead to effective divisors which can vary from less than 10 up to about 40 in extreme cases, though values of around 20 are common. Thus, the modified rule reduces to the simple rule in many cases, but in other cases can lead to values of estimated annual air permeability under normal conditions which are significantly different from those resulting from the simple $n_{50}/20$ rule. More recent work by Turner and Sherman uses a sophisticated infiltration model for various locations in the USA, including detailed weather data as well as building form data to calculate an effective value for the divisor, which varies across the different climate conditions to be found over North America and Canada.[14] The UK represents a much smaller geographical area, and may perhaps be expected to constitute a single climate zone; however it is not necessarily the case that 20 is the optimum divisor for this zone.

In the UK, the simple $n_{50}/20$ divisor has been applied to air permeability ($q_{50}/20$), rather than air leakage, to calculate an average annual infiltration rate for a dwelling. This calculation is contained within the Government's Standard Assessment Procedure (SAP),[15] which forms an integral part of Part L of the Building Regulations. The consequence of applying this divisor to air permeability, rather than air leakage, is that it favours those dwellings with a high surface to volume ratio. In other words, for dwellings of similar volume and similar overall levels of airtightness, a much lower infiltration rate is attributed to narrower, taller dwellings than to a more nearly cubic building. In addition, there is also no attempt with the regulatory guidance to include factors such as climate, sheltering, or building configuration, when estimating the infiltration rate from the air permeability. It is therefore not known whether the $n_{50}/20$ divisor is appropriate for new building UK dwellings or not.

An alternative method of determining the background ventilation rate is to adopt the tracer gas method. The method involves introducing an inert gas into the building and then observing how the gas behaves as air leaks both into and out of the building. Typical tracer gases include nitrous oxide, sulphur hexafluoride, various perfluoro tracers (PFTs) and carbon dioxide. Tracer gas testing is somewhat less convenient than pressurisation testing, but has the advantage that it is conducted at near-zero pressure differentials, thus approaching normal conditions more closely. The American Society for Testing and Materials (ASTM) standard for tracer gas methods identifies three approaches: concentration decay, constant injection and constant concentration.[16] Of these, concentration decay is the simplest, and therefore the most commonly used. A suitable tracer gas (e.g. CO_2) is introduced into the dwelling and distributed as homogeneously as possible. The decay in concentration as the gas is diluted via infiltration is monitored, and the results fitted to an exponential decay curve, where the exponent indicates the background ventilation rate. While this method provides a better representation of real conditions, it may also be more sensitive to seasonal variations in infiltration rates.[17] Roulet and Foradini discuss the decay method in some detail, including the calculation of air-change rates from CO_2 concentration data.[18]

Experimental Details

In this study we compare the background ventilation results obtained using both the pressurisation testing method (using the $n_{50}/20$ rule of thumb or its modifications) and the CO_2 decay method described within Roulet and Foradini,[18] in order to obtain a limited and preliminary indication of whether the SAP is likely to be justified in using the $n_{50}/20$ rule of thumb to determine a reasonable estimate of the infiltration rate for new-build dwellings in the UK. Recent work undertaken by Keig, Hyde and McGill on four existing solid walled UK dwellings indicated that the $n_{50}/20$ divisor overestimated the natural ventilation rates of all of the houses tested by a considerable margin .[19]

The pressurisation tests and tracer gas measurements were undertaken on four new build case study dwellings in total, all of which were built to comply with Part L1A 2006 or better. All of the case studies were new build dwellings that were tested immediately following practical completion and prior to initial occupation. Details of the individual case study dwellings are contained within Table 1.

All of the tracer gas measurements formed a mandatory component of a number of Technology Strategy Board Building Performance Evaluation Programme Phase 1: Post Construction and Initial Occupation studies.[20]

	Dwelling 1	**Dwelling 2**	**Dwelling 3**	**Dwelling 4**
Form	Semi-detached	Semi-detached	Semi-detached	Detached bungalow
No. of storeys	2	2	2	1
Total floor area (m^2)	93	93	90	160
Envelope area (m^2)	240	240	250	451
Volume (m^3)	240	240	268	385
Main construction type	Full-fill masonry cavity	Full-fill masonry cavity	Thin joint masonry cavity	Timber frame filled with Hemcrete and then clad externally either in softwood or a lime-based render.
No. of bedrooms	3	3	3	4

Table 1: Details of the case study dwellings.

All of the coheating tests, pressurisation tests and tracer gas measurement were undertaken whilst the case study dwellings were unoccupied. Any adjacent dwellings were also unoccupied, and there were no other contiguous spaces which may have contributed CO_2 in addition to that from the outdoor environment. The coheating tests were undertaken in accordance with the Leeds Metropolitan University standard protocol.[21] Two separate pressurisation tests were undertaken on each of the case study dwellings; one immediately prior to and immediately following completion of the coheating test. Two separate tests were undertaken to establish whether the accelerated drying and associated shrinkage that may be caused by the mean elevated temperatures experienced during the coheating test had any impact on airtightness. The mean of the two tests has been used for comparative purposes with the results of the CO_2 tracer gas decay measurements. All of the pressurisation tests were undertaken in accordance with ATTMA Technical Standard L1 under calm conditions using an Energy Conservatory Model 3 Blower Door and a DG700 pressure/flow gauge.[9] The overall uncertainty in the measurements is less than 10%.[22] The coheating test and tracer gas decay measurements were undertaken simultaneously. As a consequence the temperature difference between the inside and outside of the dwelling would have been increased slightly due to the elevated internal temperatures required when undertaking a coheating test. The decay measurements involved releasing a short burst of CO_2 gas (15 minutes in duration) into the living area at the same time each day. The CO_2 was dispersed using a simple CO_2 gas dispersal system. The dispersal system comprised a portable CO_2 canister, a solenoid valve, a digital electronic timer and an outlet tube. To aid mixing of the CO_2 gas within the dwelling, the outlet tube from the CO_2 canister was attached to the outer casing of the air circulation fan located in the living area. CO_2 sensors (Eltek GD47) located in the living area and at least one bedroom were then used to measure the rate of CO_2 decay over time. The measurement range of the sensor is from 0 to 5000 ppm with an accuracy of less than $\pm$(50ppm + 3% of the measured value). Background ventilation rates for the living area and the bedroom were then determined based upon the period of time taken for the CO_2 concentration to decay to the background level. These were calculated in accordance with the method described in Roulet and Forandini.[18] Laboratory measurements have identified that the air change rates calculated using the CO_2 tracer gas decay method have an uncertainty of less than 10%.[23]

Results and Discussion

Pressurisation Test Results

The results of the pressurisation tests are summarised in Table 2. The reasons for the much lower levels of air permeability measured in Dwellings 3 and 4 are likely to be attributable to the fact that these dwellings had an airtightness strategy comprising an airtightness target of 3 $m^3.h^{-1}.m^{-2}$ at 50Pa for Dwelling 3 and 6 $m^3.h^{-1}.m^{-2}$ at 50Pa for Dwelling 4, and the inclusion of pre-completion pressure testing at primary air barrier completion stage. In addition, observations of the build revealed that greater care was taken during their construction. The air leakage data from these tests was also used to calculate the steady state background ventilation rate attributable to the test dwellings.

	Dwelling 1	**Dwelling 2**	**Dwelling 3**	**Dwelling 4**
Mean air permeability **($m^3.h^{-1}.m^{-2}$ at 50Pa)**	8.48	7.73	3.56	5.15
Mean air leakage rate **(h^{-1}at 50Pa)**	8.45	7.71	3.33	4.40

Table 2: Details of the pressurisation test results.

Tracer Gas Measurements

Daily air change rates were calculated for both the living area and the main bedroom in all of the dwellings. In the case of Dwelling 1, tracer gas measurements were made over three separate four-day periods between 6th November and 17th December 2012. In the case of dwelling 2, measurements were made for three consecutive days in December 2012, and in the case of dwelling 3, for only 2 days in March 2013. For dwelling 4, measurements were taken for five days during February 2011 with measurements also being undertaken in a second bedroom.

Figure 1 shows an example of one of the decay curves obtained.

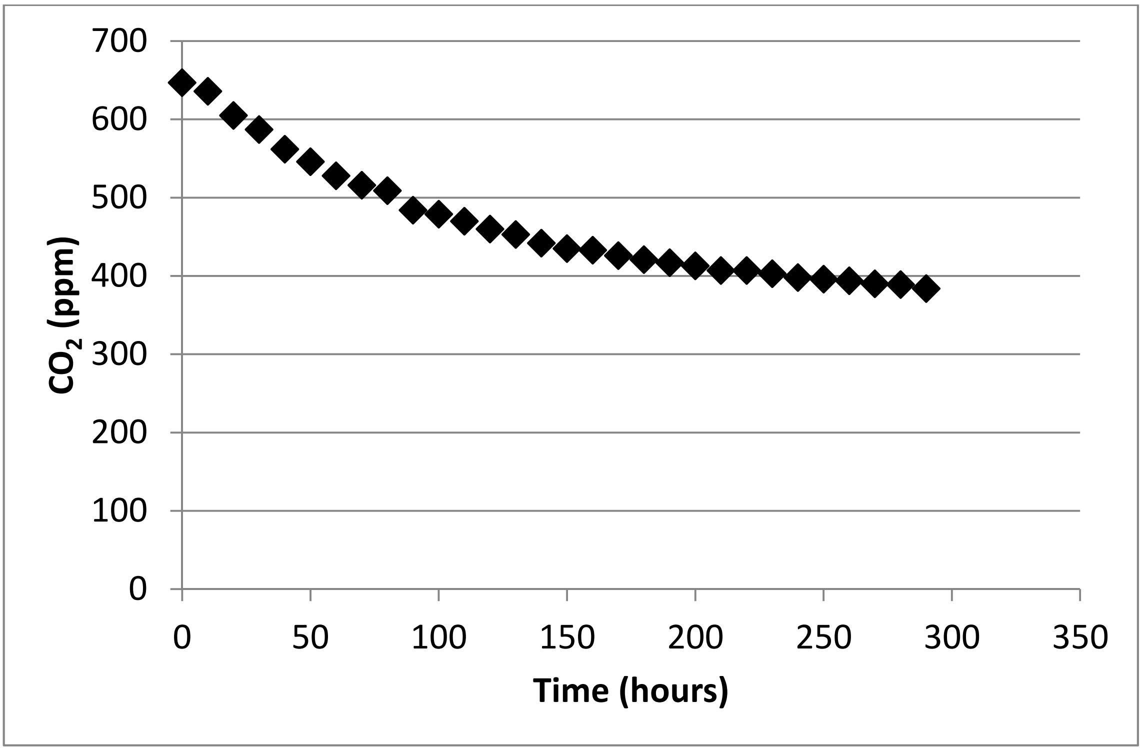

Figure 1: CO_2 decay curve for Dwelling 1 (bedroom) on 8th December 2012

In Tables 3 to 6 below, the calculated air change rates are given for each day, together with the r^2 correlation values obtained from fitting the measurements to a line according to the relationship $\ln[(C-C_{back})/(C_{init}-C_{back})] = at + b$ where C_{back} is the background CO_2 concentration, C_{init} is the initial CO_2 concentration, t is the time (in hours) and a and b are both constants. Some discussion of the tracer gas results is given for each dwelling on a case-by-case basis.

Dwelling 1

	Living area		**Main bedroom**	
	ACH (h^{-1})	**r^2**	**ACH (h^{-1})**	**r^2**
6th Nov 2012	0.31	0.95	0.49	1
7th Nov 2012	0.27	0.96	0.40	0.99
8th Nov 2012	0.32	0.97	0.41	0.99
9th Nov 2012	0.33	0.99	0.41	1
5th Dec 2012	0.26	0.97	0.44	0.99
6th Dec 2012	0.29	0.95	0.41	0.99
7th Dec 2012	0.26	0.95	0.40	0.98
8th Dec 2012	0.25	0.96	0.38	0.99

14th Dec 2012	0.28	0.96	0.41	0.99
15th Dec 2012	0.24	0.95	0.34	0.98
16th Dec 2012	0.35	0.96	0.42	0.99
17th Dec 2012	0.23	0.95	0.33	0.98

Table 3: Summary of tracer gas results for Dwelling 1

The data indicates that there was some variation in the air change rates in each of the rooms where measurements were undertaken over the period of the coheating test, with air change rates in the living area ranging from 0.23 to 0.35 h^{-1} and bedroom 1 ranging from 0.33 to 0.49 h^{-1}. Furthermore, the correlation (r^2) was consistently better in the bedroom than in the living area, though values were reasonably good for both.

Wind speed was also measured during the coheating test period using an on-site weather station. Analysis of the data indicates no particular relationship between the measured air change rate and wind speed.

Dwelling 2

	Living area		**Main bedroom**	
	ACH (h^{-1})	**r^2**	**ACH (h^{-1})**	**r^2**
6th Dec 2012	0.29	0.95	0.41	0.99
7th Dec 2012	0.26	0.95	0.40	0.98

8th Dec 2012	0.25	0.96	0.38	0.99

Table 4: Summary of tracer gas results for *Dwelling* 2

A similar pattern is observed for dwelling 2, which is perhaps not surprising since these dwellings were adjacent to one another and were of identical construction, shape and form (one dwelling was a handed version of the other).

Dwelling 3

	Living area		**Main bedroom**	
	ACH (h^{-1})	**r^2**	**ACH (h^{-1})**	**r^2**
14th Mar 2012	0.17	0.99	0.20	1
20th Mar 2012	0.21	0.97	0.22	1

Table 5: Summary of tracer gas results for Dwelling 3

In this case all r^2 values are good, and variability in ACH (h^{-1}) is fairly low, though confidence in the latter is limited by the fact that only 2 days of data is available. The lower and much less variable air change rate measured in this dwelling, in comparison to dwellings 1 and 2, may be attributable to the fact that an explicit airtightness strategy was adopted, and to the fact that the dwelling is of a different construction type.

Dwelling 4

	Living area		Main bedroom		Second bedroom		Wind speed (ms^{-1})
	ACH (h^{-1})	r^2	ACH (h^{-1})	r^2	ACH (h^{-1})	r^2	
11th Feb 2011	0.32	1	0.31	1	0.31	1	1.69
12th Feb 2011	0.31	0.99	0.29	1	0.30	1	0.88
13th Feb 2011	0.38	0.99	0.35	1	0.35	1	1.66
19th Feb 2011	0.34	1	0.35	1	0.34	1	1.22
20th Feb 2011	0.37	0.99	0.35	1	0.34	1	0.88

Table 6: Summary of tracer gas results for Dwelling 4

Here there is little variation in air-change per hour results over the five days of data, and this consistency is supported by the excellent correlation (r^2) values. However, in contrast with the case of dwelling 1, the small amount of variation observed did appear to be generally consistent with changes in daily average wind speed. Therefore, this data has also been included in Table 6. Exceptions to the apparent correlation occur on Feb 11th and Feb 20th. These exceptions may be the result of a change in wind direction, but unfortunately wind direction data was not available for this site.

Comparison between Pressurisation Test Results and Tracer Gas Measurements

Table 7 compares the air change rates from pressurisation testing modified by the $n_{50}/20$ rule with the average rates obtained via tracer gas measurements for all 4 dwellings.

Dwelling	n_{50} (Pressure Test)	**$n_{50}/20$**	Average ACH (Tracer Gas) Living Area	Average ACH (Tracer Gas) Main bedroom	Average ACH (Tracer Gas) 2nd bedroom	Average ACH (Tracer Gas) Whole Dwelling
1	8.45	**0.42**	0.28	0.40	-	0.34
2	7.71	**0.39**	0.27	0.40	-	0.33
3	3.33	**0.17**	0.19	0.21	-	0.20
4	4.40	**0.22**	0.34	0.33	0.33	0.33

Table 7: Comparison of air change rates from pressurisation testing and tracer gas measurements.

In the case of dwellings 1 and 2, the majority of the tracer gas decay measurements suggest a lower air-change rate than that approximated using the $n_{50}/20$ rule. There is also a distinct difference between the tracer gas measurements obtained for the living area and those obtained for the bedroom, with the bedroom measurements more closely matching the approximated results obtained from pressurisation testing. This may be due to different ventilation conditions in the two areas, with the more highly ventilated area (main bedroom) having a much greater proportion of air leakage paths than the living area. As the bedroom was located directly above the living area on the same façade of each dwelling, the differences in air change rates measured are not thought to be related to the exposure of the room. A qualitative analysis of the air leakage paths that were identified during the pressurisation tests using a hand-held smoke puffer revealed that the majority of the air leakage paths were concentrated at the intermediate floor/external junction in both dwellings. As two of the four walls in the main bedroom are external walls, this supports the expectation that the main bedroom may have a considerably greater air change rate than other rooms that do not have such junctions.

A closer examination also reveals that the r^2 correlation values obtained from fitting these tracer gas measurements to a line according to equation 1 are somewhat lower for the living area in these two dwellings, indicating slightly less confidence in the ACH figures calculated. Inspection of the raw data for the living area shows some non-linearity in the early part of each test, which is not seen in the bedroom data. This suggests that initial dispersion of the CO_2 tracer gas may not have been sufficiently fast to give accurate results close to the dispersal mechanism. An example is given in Figure 2 below.

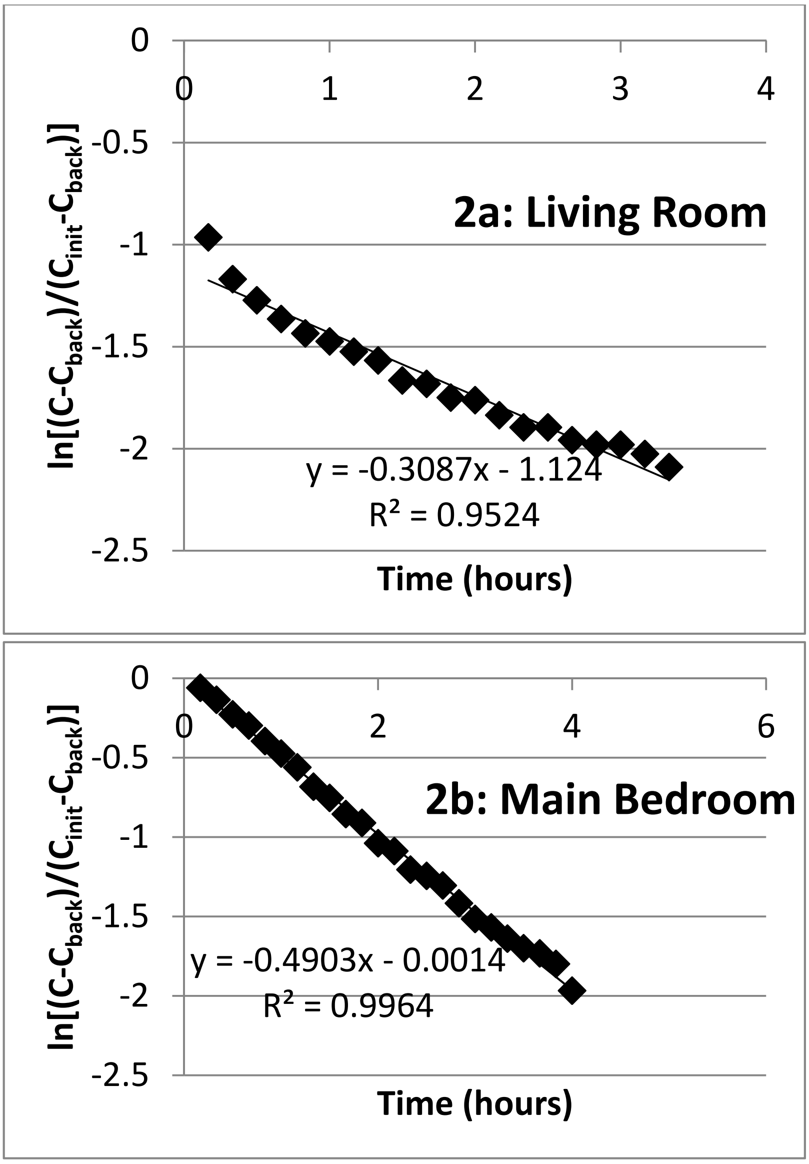

Figure 2: Fitting of tracer gas data for a) Living Room, and b) Main Bedroom, Dwelling 1, November 6th 2012.

In the case of dwelling 3, the tracer gas decay measurements for both rooms were slightly higher than that approximated using the $n_{50}/20$ rule. However, it must be remembered that there were only 2 days of tracer gas measurements in this case.

Dwelling 4 shows very consistent tracer gas measurement results between the three areas (living area, bedroom 1 and bedroom 2). However, all these measurements suggest a significantly higher air-change rate than that suggested by pressurisation testing using the $n_{50}/20$ rule. In this case however, some correlation between ACH rate and wind-speed was observed for the majority of the days. In addition, this building is of a non-standard construction, and may also therefore have different types of holes and cracks present. Finally, while all the other buildings were of 2 storeys, dwelling 4 was only one storey. Since shielding, crack type and building height are all correction factor parameters mentioned by Sherman[13] in his modified 'rule of thumb' model, these factors may account for the greater difference observed between the air change rates measured and those approximated using the $n_{50}/20$ rule.

In order to explore whether some of the observed discrepancy in air leakage rates could be attributed to building related factors such as shielding, crack type and height, the $n_{50}/20$ figures and the tracer gas results have been compared against the air leakage rates estimated using Sherman's modified 'rule of thumb' model[13]. In

Sherman's modified model, the air leakage rate is approximated by dividing the n_{50} value by a correlation factor (*N*), rather than 20. The correlation factor (*N*) is determined from the product of various building-related variables, which include a climate factor (*C*) and correction factors relating to the height (*H*), shielding (*S*) and leakiness (*L*) of the building. As the various climate factors used by Sherman are applicable to North America only, in the absence of any UK specific figures, an assumption has been made. A figure of 20 has been assumed for the UK, which is in the middle of the range of the climate factors developed for North America, which range from 13 to 26. It is also approximately equivalent to the climate factor for Seattle, which has a similar climate to that experienced in London. This figure is also equivalent to the current divisor used in SAP[15].

In terms of the correction factors, as Dwellings 1, 2 and 3 are two storey dwellings, a height correction factor of 0.8 has been used. A figure of 1.0 has been used for Dwelling 4, as this dwelling is single storey. As all of the case study dwellings are neither exposed nor well-sheltered, a shielding factor of 1 has been used for all four dwellings, representing a normal level of sheltering. Finally, in terms of the leakiness factor, a value of 1.4 has been used for all of the dwellings, as the dwellings are new build and no significant areas of air leakage were identified during the pressurisation tests.

Details of the correction factors relating to each of the case study dwellings are contained within Table 8 along with the resulting correlation factor (*N*) and n_{50}/N. Using Sherman's modified model, the air leakage rates obtained for Dwellings 1 and 2 are very close to those measured from the tracer gas decay measurements (see Table 7). However, this is not the case for Dwellings 3 and 4, where the air leakage rate obtained using Sherman's modified model is much lower than the corresponding tracer gas decay measurements, particularly with respect to Dwelling 4 where the air leakage rate is less than half of that obtained from the tracer gas measurements. The reasons for the discrepancies in these results cannot easily be attributed to building related factors and are not known. This suggests that further research needs to be undertaken on the inputs to the modified Sherman model, to ascertain whether it is possible for this model to be applied successfully to dwellings in the UK.

	H	***S***	***L***	***N***	$\mathbf{n_{50}/N}$
Dwelling 1	0.8	1.0	1.4	22.4	0.38
Dwelling 2	0.8	1.0	1.4	22.4	0.34
Dwelling 3	0.8	1.0	1.4	22.4	0.15
Dwelling 4	1.0	1.0	1.4	28	0.16

Table 8: Correction factors, N and n_{50}/N for the case study dwellings.

The pressurisation test results and the tracer gas measurements have also been used to determine a tracer gas dividing factor (ratio between pressurisation test result and measured tracer gas air change rate for the whole dwelling) for each dwelling. As can be seen from Table 8, the tracer gas dividing factor for dwellings 1 and 2 using the air leakage figures is larger than 20, indicating that the n_{50}/20 rule overestimates the air change rate in these dwellings by 25% and 17% respectively. Conversely, the tracer gas dividing factor for dwellings 3 and 4 using the air leakage figure is smaller than 20, indicating that the n_{50}/20 rule underestimates the air change rate in both of these dwellings by 17% and 34% respectively.

Dwelling	Tracer gas dividing factor (Ratio of pressurisation test result to tracer gas result)	Tracer gas dividing factor, using air permeability figure derived from pressurisation test (as per SAP)
1	24.9	24.9
2	23.4	23.4
3	16.7	17.8
4	13.3	15.6

Table 9: Tracer gas dividing factor for all dwellings.

For comparative purposes, the tracer gas dividing factor has also been calculated based upon the measured air permeability of the dwellings rather than the air leakage rate, as SAP uses air permeability in the rule of thumb (q_{50}/20) rather than air leakage (n_{50}/20). The results contained within Table 9 indicate that the tracer gas dividing figures for dwellings 3 and 4 are higher than those obtained using air leakage, as the measured air permeability for these dwellings was slightly higher than the corresponding air leakage rate. Nevertheless, in these two dwellings, SAP would still tend to underestimate the background ventilation rate. For dwellings 1 and 2, as the air permeability and air leakage rates are the same for these two dwellings, the tracer gas dividing factors are also the same, irrespective of whether air leakage or air permeability is used to calculate the dividing factor. Therefore SAP would over-estimate the background ventilation rate to the same extent as if air leakage figures were used.

Interestingly, the mean of all four results using the air leakage or air permeability values are very similar, being 19.6 and 20.4 respectively. Therefore, if the UK is to be considered as a single climate zone, this suggests that 20 may be a reasonable average divisor to use within SAP. However, many more measurements undertaken on a range of different dwelling types and forms located in various different parts of the UK would be necessary to support this hypothesis. Additional data might also help to indicate whether SAP could be significantly improved by introducing some simple modifications to the average divisor, to account for factors such as building height or site exposure.

Conclusions

Four different new-build dwellings in the UK have been studied, and air-change rates calculated based upon pressurisation test results, tracer gas measurements and the use of Sherman's modified model[13]. Comparison of the results shows that the use of a single divisor of 20 in the $n_{50}/20$ and $q_{50}/20$ rules of thumb leads to significant discrepancies in all dwellings, though the results are distributed around a mean of 19.6 for air leakage and 20.4 for air permeability. Even if various building related factors are taken into account using Sherman's n_{50}/N modified model, significant discrepancies between the air leakage rates and the tracer gas measurements were still obtained for the two of the four dwellings. Consequently, if a single divisor is to be used in the UK, this preliminary work therefore provides no basis for choosing an alternative to 20, though many more measurements would be necessary in order to be confident that this represents an approximate UK mean.

For dwellings 1 and 2, which are adjacent, two-storey semi-detached, traditionally constructed dwellings, the $n_{50}/20$ rule overestimates the air change rate, compared with that obtained from tracer gas measurements, whilst the n_{50}/N rule produces comparable results. Conversely, for dwellings 3 and 4, both of which had an explicit airtightness strategy, the $n_{50}/20$ and the n_{50}/N rule both underestimate the air change rate compared with the tracer gas measurements. Dwelling 3 is also two-storey and traditionally constructed, but is a semi-detached dwelling in a different location from 1 and 2 and of differing construction. The lower and much less variable air change rate measured in this dwelling, in comparison to dwellings 1 and 2, is likely to be attributable to the fact that an explicit airtightness strategy was adopted for this dwelling. Dwelling 4 is a detached bungalow of non-traditional construction where some relationship was observed between wind-speed and air change rate over a 5 day period. However, whilst undertaking this comparison, it should be remembered that the tracer gas measurements are based upon measurements that were undertaken in a limited number of rooms over a very limited period of time and at a slightly elevated internal temperature. Consequently, they may not necessarily be representative of the average annual air leakage rate of the dwellings measured, and may simply be an consequence of the time of year, the differential temperatures experienced and the rooms in which the tracer gas measurements were undertaken.

Dwellings 1 and 2 showed the most marked variation between tracer gas measurements in different areas of the dwelling (living area and bedroom). This is likely to represent a real difference in the ventilation characteristics of the two areas, which is most likely to be attributable to differences in the distribution of the main air leakage points between these two areas of the dwellings. However, it should also be noted that delayed initial dispersal of the tracer gas may also have led to reduced accuracy in the living room measurements (where the tracer gas injection mechanism was located).

Despite the above caveats, it may be noted that all the infiltration rates measured exceeded the SAP assumption of 0.15 h^{-1} (and in fact were more than double this figure in the case of dwellings 1,2 and 4 which had measured air permeability values of >5 $m^3h^{-1}m^{-2}$ at 50Pa). Therefore in these cases, compliance with UK building regulations may result in over-specified ppv systems intended to make up the notional difference between 0.15 h^{-1} and the necessary requirement for the building type.

It is recommended that further research should be undertaken on a much larger sample of dwellings of different construction types and forms, over different periods of the year and in different geographical locations, in order to establish whether:

- The UK mean figure for the divisor in the average annual infiltration estimate is in fact close to 20.
- The divisor currently incorporated within SAP could be improved by introducing some simple UK specific climate and building related correction factors based on factors such as building height, form and site exposure.

- The assumption that the assumed infiltration figure of 0.15 h^{-1} (as per Approved Document F) is appropriate for air permeabilities > $5m^3h^{-1}m^{-2}$ at 50Pa.

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Authors' contributions

All authors contributed equally in the preparation of this manuscript.

Conflict of interest

There was no conflict of interest in relation to the work reported in this paper

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