Estimation of the infiltration rate of UK homes with the divide-by-20 rule and its comparison with site measurements.

Alan Vega Pasos[1], Xiaofeng Zheng[1*], Luke Smith[2], Christopher Wood[1]

1. *Building, Energy and Environment Research Group, Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom.*
2. *Build Test Solutions Ltd., 16 St Johns Business Park, Lutterworth LE17 4HB, United Kingdom*

** Corresponding author: xiaofeng.zheng@nottingham.ac.uk*

Abstract

Buildings are responsible for 40% of the global energy usage to which infiltration-caused heat losses are responsible for 30%. Air infiltration is the unintended flow of air through leakage paths and fundamentally determined by the airtightness of a building. In the United Kingdom, building airtightness is conventionally measured through a blower door test and used to predict air infiltration in conjunction with the divided-by-20 rule, which is a rule of thumb that has been adopted by SAP (Standard Assessment Procedure: a UK government's recommended method system for measuring the energy rating of residential dwellings) for the estimation of the infiltration-caused heat losses for dwellings. This paper assesses the representativeness of this rule of thumb by carrying out blower door and tracer gas tests in twenty one dwellings located in the East Midlands Region of the United Kingdom. Results showed that a divide-by-37 rule would be more representative. It was also seen that the air infiltration rate is overestimated by SAP when modifying factors are added. The errors are as high as 500% in some cases. The most affected dwellings were the tighter ones. A revision of the usage of the divide-by-20 rule and the modifying factors is advised.

Keywords:

Airtightness, air infiltration, blower door, air leakage, SAP, divide-by-20

Nomenclature.

Symbol		Unit
A	*Envelope Area*	m^2
b	*Flow exponent*	-
C	*Air flow coefficient*	$m^3h^{-1}Pa^{-b}$
N	*Ratio constant*	-
n	*Air change rate (when at natural conditions also called air infiltration)*	h^{-1}
Q	*Air leakage rate*	m^3h^{-1}
q	*Air permeability*	$m^3h^{-1}m^{-2}$
Δp	*Pressure difference*	*Pa*
δ	*Uncertainty*	
Subscripts		
1	*At natural conditions*	
50	*At 50 Pa of pressure difference*	
UK	*United Kingdom*	
IT	*International*	

1. Introduction

Buildings contribute to a large portion of the global energy consumption. For instance, in the European Union, 40% of the energy usage goes to the building sector [1]. Therefore, the energy efficiency of buildings plays an important role in achieving the global carbon reduction target. Space heating in the building is responsible for 60-70% of the building's overall energy demand [2]. Considering up to one third of the heating is lost through the leaks and craps in the building envelope [3] driven by environment-induced air infiltration, it is essential to understand the amount of energy losses caused by the infiltration as part of the building energy rating process.

Air infiltration (or exfiltration) is the unintended air leakage rate (h^{-1}) in a building, or the flow through leakage pathways driven by the pressure difference induced by the environmental conditions, in particular the outdoor wind and outdoor-indoor temperature difference [4] (or vice versa for exfiltration). Due to being disruptive, time consuming and complex to operate, tracer gas based methods for measuring air infiltration are usually substituted with a measurement of building airtightness, which is then used to estimate the infiltration rate of the test building in conjunction with a leakage-infiltration relationship and sometimes environmental and terrain conditions. Although a number of airtightness testing methods are in existence such as acoustic [5, 6, 7] and unsteady pressurisation technique [8, 9, 10, 11, 12, 13, 14, 15, 16], the blower door is a convenient and reliable means for measuring building airtightness that has been widely adopted as the standard testing method in building regulations and voluntary standards. The measurement of building airtightness has become a regulatory requirement in many countries due to its impact to the building energy efficiency, indoor air quality and building durability. There are a number of leakage-infiltration relationships available, either as a simple leakage/infiltration ratio or leakage-infiltration models [17, 18], which can be used to calculate the corresponding infiltration rate when an airtightness measurement is made to a building.

The leakage/infiltration ratio is the simplest form of the leakage-infiltration relationship that has been used in a number of countries. Although only basic in its consideration of various factors such as conditions related to ambient environment, terrain and shielding, it offers a quick and intuitive means for estimating the infiltration rate. However, the factors related with building design, construction and local climate can have some bearing on this ratio, which may make it unique in countries/regions with very different aforementioned factors. Assessing the representativeness of the divided-by-20 rule has been carried out previously by other researchers [19, 20] and the findings support such speculations. However, validation of these concerns with in-field measurement has been rather limited. As part of large field trial investigations on the relationship between the measured building leakage at various pressure levels and infiltration, this paper extracts the tests performed with the blower door and tracer gas methods across a total of 21 of different dwellings to further evaluate the representativeness of the divide-by-20 rule and implicated energy consumption.

2. UK context

Airtightness is quantified in a number of ways, such as air permeability ($m^3 \cdot h^{-1} \cdot m^{-2}$) or air change rate ($h^{-1}$); both these measurements are usually referenced at a pressure difference of interest. For instance, in the United Kingdom, the air leakage rate is quoted at 50 Pa of pressure difference and normalised by the envelope area to give air permeability at 50 Pa, a guided parameter for the minimal requirement of building airtightness set in the UK building regulation [21].

The pressurisation method, most widely known as "blower door", is a technique which increases the pressure difference of a building by inserting (pressurising) or extracting (depressurising) air into the building using a fan blower. Blower door measures the building airtightness in a range of pressure differences typically from 10 to 60 Pa [22].

The amount of airflow exerted by the fan is related to the established pressure difference to provide the leakage-pressure relationship of the building. Such relationship can be mathematically represented by either a quadratic equation [23, 24, 25] or a power law equation, the latter one is the broadly used and accepted form, as described by eq.(1) [26].

$$Q = C\Delta p^b \quad (1)$$

where:

Q= air leakage rate ($m^3 \cdot h^{-1}$);

C = flow coefficient ($m^3 \cdot h^{-1} \cdot Pa^{-b}$);

Δp = Indoor-outdoor pressure difference (Pa);

b= flow exponent (dimensionless), in the range from 0.5 to 1 (turbulent to laminar flow).

Then the air permeability at 50 Pa (q_{50}) can be obtained by normalising the air leakage rate at 50 Pa (Q_{50}) using the eq. (2)

$$q_{50} = Q_{50}/A \quad (2)$$

Where, A is the envelope area of the building, m^2.

The air leakage rate quoted at 50 Pa and the pressurisation of a building does not represent the air leakage rate occurring at natural conditions since it regularly occurs at a pressure difference lower than 10 Pa [27, 28]. A high pressure difference is used to shadow the effects of wind and buoyancy, but is subject to uncertainty when a low pressure result is required due to the error caused by extrapolation [27].

From here, there are different ways to predict the infiltration rate, examples of these are the air infiltration predicting models [17] which vary in their complexity; or, the airtightness infiltration ratio (equation 3) which represents a simple way to predict air infiltration.

$$Q_{50}/Q_1 = N \quad (3)$$

where:

Q_{50} = air leakage rate at 50 pa (m^3h^{-1},);

Q_1 = air infiltration flow rate (m^3h^{-1},);

N = ratio constant (dimensionless).

After a study carried out in the United States [29, 30], it was determined that a representative value of N is 20. Q_{50} and Q_1 were substituted by n_{50} and n_1 respectively; the first term describes the air leakage rate occurring at 50 Pa, measured by the steady pressurisation method; the latter term refers to the air infiltration rate. This study created the divide-by-20 rule of thumb (equation 4).

$$n_{50}/20 = n_1 \quad (4)$$

In the United Kingdom equation 4 was adopted by the government as the way to predict the infiltration rate. This is stated in the Standard Assessment Procedure [31], which is the UK nationally recognised procedure for obtaining the energy rating of a dwelling. The use of this ratio has already been questioned due to its simplicity [29, 19, 20].

Although n_{50} was used in the original American study, in the United Kingdom, the divide-by-20 rule is applied to q_{50} ($m^3 \cdot h^{-1} \cdot m^{-2}$) instead to calculate the infiltration rate, as described by eq.(5). This change implies the assumption that all dwellings have a volume/envelope area ratio close to 1, which might be justifiable considering the fact that the majority of UK dwellings are houses. Finally, SAP modifies the predicted infiltration value by wind and shelter factors.

$$q_{50}/20 = n_1 \quad (5)$$

3. Measurement of air infiltration: Tracer gas methods

Predicting the air infiltration rate through the use of models is widespread and typically the default approach used when designing and evaluating buildings. There are however existing means to measure it directly with the most common technique being by tracer gas means. There are many variants, however the most widely known are the tracer gas constant concentration method, tracer gas constant injection method, and the tracer gas concentration decay method. The first two, are relatively more accurate [32], however, they need costly and sophisticated equipment. The tracer gas concentration decay method is the most widely practised due to its simplicity and low cost.

The tracer gas concentration decay method has been standardised to measure the air infiltration at natural conditions [33, 34]. In order to obtain a correct test, a suitable gas must be used, for example SF_6, N_2O, C_2H_6, CH_4, CFC, H_2, He and CO_2, where CO_2 is probably the most widely adopted due to its low cost, availability and it is safe to use [35, 36]. The tracer gas is distributed throughout the test space and mixed well using fans to achieve a satisfactory uniformity; the decay of the gas concentration is then monitored with a series of calibrated sensors evenly placed around the test environment. The natural logarithm of the decay is related with time on a regression and the infiltration rate is given by the slope of the linear best fit of the relationship. In order to satisfy the standard, the duration of the decay depends on the airtightness of the house, the estimated testing duration for a house with a given airtightness level is listed in Table 1.

Table 1. Examples of minimum durations between the initial and final samples for the concentration decay method. From [33].

Air leakage rate (h^{-1})	Minimum duration of test (h)
0.25	4
0.5	2
1	1
2	0.5
4	0.25

4. Methodology

4.1. Test dwellings

From January to October 2018, 21 different houses were tested in the East Midlands of the United Kingdom. It was intended to test as many different houses as possible in terms of building type, building age, construction method, etc. Figure 1 shows photos of 12 dwellings of the 21 tested dwellings with the typical building form. A brief description of each dwelling is given in Table 2. Table 2 also includes the test number, date when the tests were performed, volume and envelope area. It is interesting to notice that the volume to envelope area ratio for all the dwellings is close to 1, this means that dwellings volume and envelope area are similar; 16 out of 21 dwellings have a ratio between 0.9 - 1.10. The dwelling type, from mid-terrace to detached houses; shielding conditions, from no shielding to heavily shielded houses, as defined by Sherman [37]; terrain conditions, from rural to urbanised areas; and; the shielded façades depending on the orientation of the dwelling are also listed. Party walls in terraced or semi-detached dwellings are considered permeable and therefore, considered in the envelope area calculations. Furthermore, in dwellings where the attic is conditioned, it is considered in the volume and envelope area of the dwelling.

This project is part of a large field study which aimed to investigate how airtightness test results at different pressure levels correlate with each other and the corresponding infiltration measurements using different technologies in a range of dwellings in the United Kingdom. Among over 100 tested dwellings, twenty one were tested for infiltration using the tracer gas decay method. Tested at different times of the year, and the houses were also subject to a good range of wind and temperature conditions.

Dwelling 2 Dwelling 3 Dwelling 6
Dwelling 10 Dwelling 11 Dwelling 12
Dwelling 13 Dwelling 14 Dwelling 15
Dwelling 16 Dwelling 17 Dwelling19

Figure 1. Sample of the 21 dwellings tested, illustrating their overall diversity.

Table 2. Description of test dwellings.

Dwelling	Date of test	Form	Main construction type	Type	Building age	Ventilation	Volume (m^3)	Envelope Area (m^2)	Volume/ Env.Area Ratio
1	25/04/2018	Detached	Cavity	Existing	1950-1966	PIV*	278	269	1.03
2	22/05/2018	Semi-Detached	Solid	Existing	1996-2002	Passive stack	264	252	1.05
3	06/06/2018	Detached	Stone	Existing	Before 1900	Natural	272	296	0.92
4	03/08/2018	Detached	Timber frame	Existing	2003-2006	MVHR*	188	227	0.83
5	16/08/2018	Detached	Solid	Retrofit	1976-1982	Natural	478	435	1.10
6	22/08/2018	Semi-Detached	Solid	Existing	1950-1966	Natural	203	210	0.97
7	10/09/2018	Mid-Terrace	Solid	Existing	1900-1929	Natural	222	265	0.84
8	07/06/2018	Semi-Detached	Solid	Existing	1996-2002	Passive stack	264	252	1.05
9	12/07/2018	End-Terrace	Cavity	Existing	1976-1982	Natural	215	224	0.96
10	30/08/2018	End-Terrace	Cavity	Existing	1983-1990	Natural	197	205	0.96
11	24/09/2018	Mid-Terrace	Cavity	Existing	1991-1995	Natural	164	182	0.90
12	27/09/2018	Detached	Cavity	Existing	2003-2006	Natural	153	218	0.70
13	01/10/2018	Semi-Detached	Solid	Existing	1900-1929	Natural	160	176	0.91
14	04/10/2018	Semi-Detached	Solid	Existing	1991-1995	MVHR*	248	269	0.94
15	05/10/2018	Detached	Cavity	Existing	2012 onwards	Natural	281	294	0.96
16	08/10/2018	End-Terrace	Solid	Existing	1991-1995	Natural	143	170	0.84
17	09/10/2018	Semi-Detached	System	New build	2012 onwards	MVHR*	316	304	1.04
18	10/10/2018	Mid-Terrace	Solid	Existing	1930-1949	Natural	251	287	0.87
19	18/10/2018	Detached	Cavity	Existing	1983-1990	Natural	391	387	1.01
20	31/10/2018	Semi-Detached	Solid	Existing	1950-1966	Natural	333	294	1.13
21	18/01/2018	Detached	Cavity	Existing	2003-2006	Natural	285	290	0.98

*MVHR= Mechanical ventilation with heat recovery; PIV: Positive Input Ventilation;

4.2. Equipment and testing protocol

Each dwelling was subject to a pressurisation and a depressurisation test according to the BS EN ISO 9972:2015 standard for fan pressurisation testing [38]. In addition, a tracer gas decay test was carried out in each property according to international standards [34, 33]. The equipment used in the tests is listed in Table 3.

Table 3. Equipment used in the experimental study.

Equipment		
Airtightness	Minneapolis blower door model 4. (BD-4) with DG-1000 pressure gauge ±0.9%	
Tracer Gas	Gas	Carbon Dioxide
	Gas measuring	Sontay CO_2 sensor GS-CO2-1001 accuracy ±30ppm ±5% of scale
Other	Fans	
	Datataker DT85 data logger	
	WindSonic Ultrasonic anemometer	
	Temperature sensors PT100 RTD	

All the tracer gas tests were set up and carried out immediately after the blower door fan tests, this means, all air openings such as windows or (envelope) doors were closed, trickle vents and other purpose provided vents were sealed. This was done in order to provide a direct comparison with the airtightness test, and to only measure the non-intended ventilation rate (air infiltration).

For aforementioned reasons, CO_2 was used for the tracer gas decay testing. A set of temperature sensors and carbon dioxide sensors were evenly distributed throughout the test property and connected to a data logger with a sampling rate of 1 second. To provide a uniform CO_2 distribution in the dwellings, a set of floor fans were placed in each zone of each dwelling. During testing, the target concentration level of CO_2 was set at 5000 ppm, and it was left to decay for a duration longer than that listed in Table 1 wherever possible. Due to limited access in some dwellings, the achieved test duration was slightly shorter in a small number of cases. Figure 2 shows the equipment used for the tracer gas tests. Note that the testing equipment was not suitable for outdoor uses; therefore for infiltration calculation purposes outdoor CO_2 concentration was assumed to be 400 ppm [39].

Figure 2. Equipment utilised for tracer gas decay method tests. Data logger, CO_2 cannisters and thermal zone arrangement with CO_2 sensor, fan and temperature sensor.

In addition, an ultrasonic anemometer was used to record the external wind conditions during tracer gas testing. A temperature sensor was set next to the anemometer. Both were also connected to the data logger at a sampling rate of 1 second.

In each zone, a temperature sensor was placed next to the CO_2 sensor to obtain a time-averaged indoor temperature, and then the measured outdoor temperature is subtracted to give the indoor-outdoor temperature difference (ΔT).

5. Results

The infiltration rates obtained by the tracer gas decay method are only representative of the conditions present during the tests. The air infiltration rate is given as the unit of air changes per hour (n_1, h^{-1}); the blower door tests results are presented in the form of air permeability (q_{50}, $m^3 \cdot h^{-1} \cdot m^{-2}$). To aid comparisons, the air leakage rate at 50 Pa is also presented (n_{50}, h^{-1}).

The air permeability results (q_{50}) were divided-by-20 as per the UK SAP methodology, and compared with measurements of air infiltration rate given by the tracer gas test. Since the divide-by-20 rule of thumb in the USA originally uses n_{50} (rather than q_{50}) a comparison against n_1 is also analysed. Ultimately final thoughts will be given regarding the use of the divide-by-20 rule of thumb employed in SAP.

5. 1. Blower door results

Table 4 shows the mean value from pressurisation and depressurisation blower door tests. Values of q_{50} ($m^3 \cdot h^{-1} \cdot m^{-2}$) and n_{50} (h^{-1}) are included. It is believed that the divide-by-20 rule in the UK uses q_{50} instead of n_{50} because most of UK dwellings have a volume: envelope area ratio close-to 1:1. For the studied dwellings it can be said that this is true for most of the properties; a fairly similar value between q_{50} and n_{50} reflects this.

Table 4. Blower door test results. Mean value from pressurisation and depressurisation.

Dwelling	Air change rate @50 Pa (n_{50}) h^{-1}	Air Permeability @50 Pa (q_{50}) $m^3 \cdot h^{-1} \cdot m^{-2}$
1	7.62	7.88
2	5.76	6.03
3	8.59	7.90
4	5.31	4.40
5	3.51	3.86
6	7.86	7.60
7	8.61	7.22
8	5.77	6.04
9	7.10	6.81
10	10.45	10.04
11	9.73	8.77
12	8.33	5.85
13	14.97	13.61
14	5.07	4.68
15	5.58	5.33
16	13.27	11.16
17	4.13	4.29
18	11.34	9.92
19	13.29	13.43
20	12.24	13.87
21	7.73	7.60

The data set shows the test dwellings have a range of airtightness levels, from relatively tight properties (dwellings 4, 5, 14 and 17) to leaky houses whose air permeability do not meet the minimal requirement set in the UK regulations (dwellings 10, 13, 16, 19 and 20). The average air permeability of the 21 dwellings is 7.92 $m^3 \cdot h^{-1} \cdot m^{-2}$.

5. 2. Tracer gas results

Figure 2 shows a typical decay curve of the average concentration measured from the sensors. In accordance with the international standard [33], a least squares regression has to be performed between the natural logarithm of the concentration and the time. The best linear fit is produced, and, the slope of the equation represents the air infiltration rate of the building. In Figure 3 and Figure 4, dwelling 12 was used as an example to illustrate how a tracer gas test analysis is made. Figure 4 shows the time against natural logarithm of the concentration regression in dwelling 12; it also shows the equation of the best fit and the r^2 value.

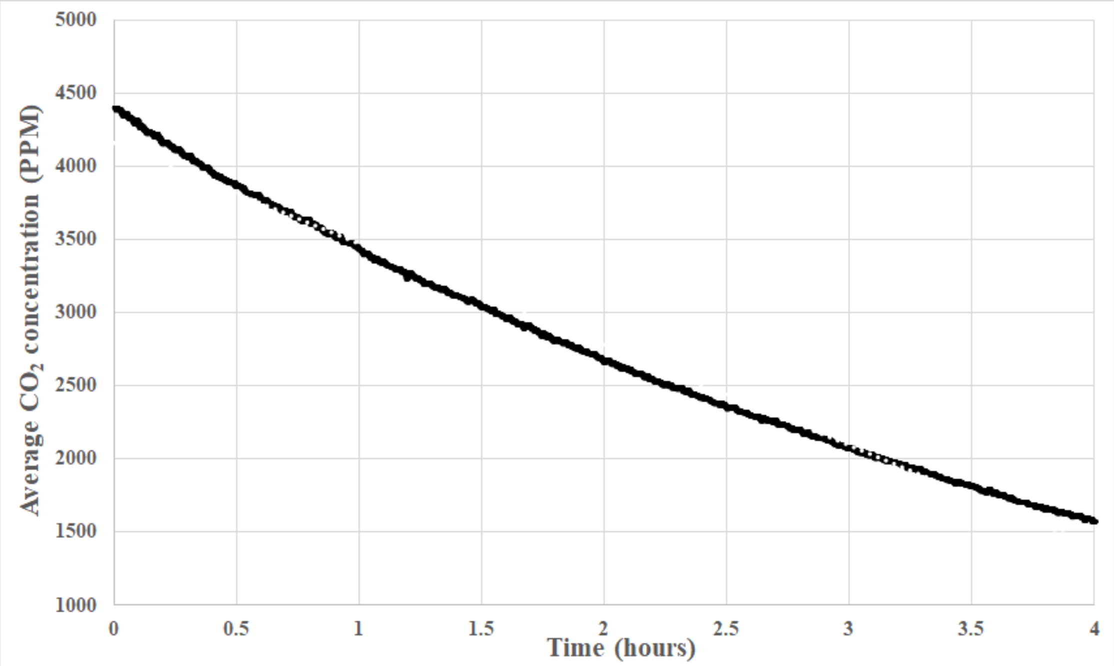

Figure 3. Concentration decay of dwelling 12

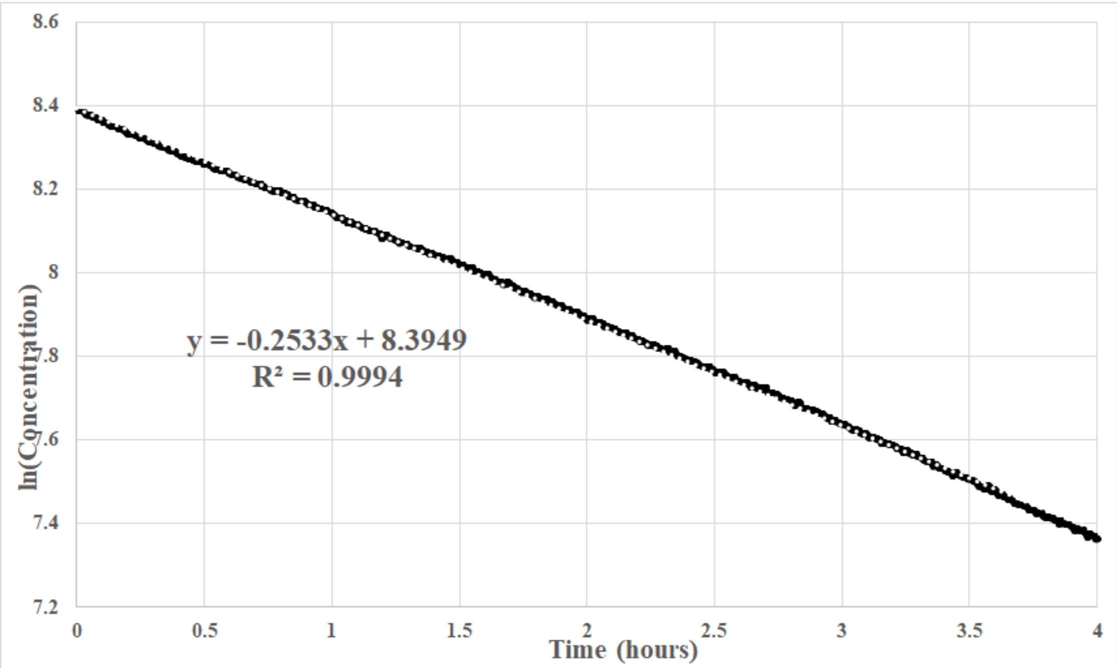

Figure 4. Natural logarithm of the decay of dwelling 12 and best fitting linear equation for the regression.

Table 5 presents the results from the tracer gas tests where the air infiltration rate (h^{-1}) given represents only the conditions at the time of testing. The environmental conditions are also presented in order to depict how the two most important air infiltration driving forces (wind and temperature difference) were acting upon the dwellings.

Table 5. Tracer gas tests results.

Dwelling	Date	Infiltration rate n_1 h^{-1}	r^2	Test duration h	Uncertainty $\pm h^{-1}$	wind m/s	ΔT K
1	25/04/2018	0.1484	>0.999	7.32	0.0009	2.736	4.73
2	22/05/2018	0.2093	0.997	9.00	0.0192	1.174	-1.83
3	06/06/2018	0.2080	0.999	5.00	0.0069	0.569	1.13
4	03/08/2018	0.1241	>0.999	8.5	0.0019	1.08	3.69
5	16/08/2018	0.0787	0.998	8.00	0.0036	0.710	3.39
6	22/08/2018	0.3171	0.998	6.67	0.0071	0.930	0.19
7	10/09/2018	0.3512	0.999	4.50	0.0305	0.860	2.87
8	07/06/2018	0.1645	0.997	4.17	0.0020	1.700	0.94
9	12/07/2018	0.1514	0.999	3.00	0.0027	0.510	1.66
10	30/08/2018	0.2344	0.993	6.50	0.0004	0.500	1.64
11	24/09/2018	0.2284	0.998	4.33	0.0026	0.760	3.73
12	27/09/2018	0.2533	0.999	4.00	0.0041	0.910	0.01
13	01/10/2018	0.4192	>0.999	4.17	0.0259	0.67	6.13
14	04/10/2018	0.0849	0.995	3.43	0.0014	0.850	1.30
15	05/10/2018	0.1504	0.996	3.75	0.0033	0.930	1.95
16	08/10/2018	0.5189	>0.999	3.25	0.0111	0.750	4.83
17	09/10/2018	0.0998	0.989	13.5	0.0059	0.350	11.00
18	10/10/2018	0.3594	0.998	2.33	0.0303	1.030	-0.70

19	18/10/2018	0.2928	0.999	3.25	0.0303	0.59	3.91
20	31/10/2018	0.2753	0.991	2.5	0.0171	1.7	3.55
21	01/03/2018	0.3618	0.995	7.64	0.0007	3.830	21.22

It can be seen that the majority of tests were performed with a duration higher than the standard, except for tests 9, 14 and 15 (which should have taken over 4 hours) due to limited access to the dwellings. Nevertheless, in each of these cases the achieved concentration drop was sufficient and therefore they are included in the results. The decay tests provide good results with relatively low uncertainty and all within the limits shown by other authors [32]. It is acknowledged that the use of carbon dioxide as tracer gas introduces uncertainty due to its natural presence in the environment.

The wind measured was an on-site measurement which showed lower values than those ones given in Appendix U from the SAP document [31]. Probably because the measurements taken in this study include the urban-caused turbulence. It is important to remark that the installation of the anemometer during testing depended on the availability of space near the house to obtain the best possible results without compromising the security of the equipment. Fences or other urban barriers might create wind turbulence and this bias is acknowledged. For instance, Figure 5a depicts the location of the anemometer in property 10 where barriers were located; in some properties the anemometer was located in an open space, (Figure 5b). In all cases, the height of the weather station was limited to 2 meters above the ground.

a) b)

Figure 5 a). Example of property where the weather station was blocked by natural obstructions, fences or buildings and; b). Example of property where the weather station was placed in an open space.

5. 3. Air Permeability (air leakage rate) – infiltration ratios.

The standard assessment procedure (SAP) calculates the infiltration rate with the air permeability value (q_{50}) obtained by a steady pressurisation test and dividing it by 20, then modifies it by wind and shelter factors.

In Table 6, the divide-by-20 rule is used to predict the infiltration rate, which is then compared with the measurements of air infiltration. Finally, in the last column a real q_{50}-infiltration ratio is presented.

Table 6. Air permeability (@50 Pa) – infiltration ratios

Dwelling	Air Permeability @50 Pa $m^3 h^{-1} m^{-2}$ q_{50}	$q_{50}/20$	Tracer Gas Measured Infiltration n1 h^{-1}	Error (relative difference)	q_{50}/n_1
1	7.88	0.3938	0.1484	165%	53.07
2	6.03	0.3015	0.2093	44%	28.81
3	7.90	0.3948	0.2080	90%	37.96
4	4.40	0.2200	0.1241	77%	35.46
5	3.86	0.1930	0.0787	145%	49.05
6	7.60	0.3800	0.3171	20%	23.97
7	7.22	0.3608	0.3512	3%	20.54
8	6.04	0.3020	0.1645	84%	36.72
9	6.81	0.3405	0.1514	125%	44.98
10	10.04	0.5020	0.2344	114%	42.83
11	8.77	0.4383	0.2284	92%	38.38
12	5.85	0.2923	0.2533	15%	23.08
13	13.61	0.6805	0.4192	62%	32.47
14	4.68	0.2338	0.0849	175%	55.06
15	5.33	0.2665	0.1504	77%	35.44
16	11.16	0.5580	0.5189	8%	21.51
17	4.29	0.2145	0.0998	115%	42.99
18	9.92	0.4960	0.3594	38%	27.60
19	13.43	0.6713	0.2928	129%	45.85
20	13.87	0.6933	0.2753	152%	50.36
21	7.60	0.3798	0.3618	5%	21.00

It is clear that, in comparison to the measured infiltration rate, a large deviation is created in the estimated infiltration rate by dividing the q_{50} by 20. The use of this ratio overestimates the infiltration rate, this means that systems assume larger heat losses than the ones experienced by a dwelling. Interestingly, results suggest that a much larger value of N (equation 3) is more representative of this sample. However, dwellings 6, 7, 12, 16 and 21 demonstrated that the ratio can be close to 20; these properties represent less than a quarter of the sample. It is important to notice that most of these properties (except number 16) have an air permeability between 5.85 and 7.60 $m^3h^{-1}m^{-2}$ which might indicate that the rule of thumb might be more representative for dwellings with an airtightness that falls in this range. However, considering this sample size is rather small, this should not be treated as a solid conclusion. More tests are required to gain a clearer insight in that regard.

It is important to notice if only the tightest properties are considered (q_{50} < 5 $m^3h^{-1}m^{-2}$), the error (between measured and predicted) is on average 128%, which is a large error. A possible reason for this is that the rule was created based on tests performend in dwellings with different leakage characteristics under different environmental conditions (than the ones measured in this study). There is a trend to build tighter dwellings, “build tight, ventilate right” (in fact some of the tested dwellings went through a refurbishment which resulted in more airtight envelopes); therefore, it can be said that for these results, tighter buildings incur larger errors when predicting infiltration rates using the divide-by-20 rule of thumb. If a correct use of tight construction and an appropriate accompanying ventilation strategy is desired, a revision on the prediction of infiltration must be considered.

Table 7 presents the statistical figures for the values taken by N if a ratio using q_{50} is to be used to predict the air infiltration rate. Results suggest that a value of N closer to 37 (36.53 exactly), is more representative to predict the infiltration rate. This is almost twice the figure that is originally utilised. It is important to notice that the minimum value taken by N in the sample is larger than 20 as well (20.54).

Table 7. q_{50}/n_1 statistical figures.

	q_{50}/n_1 (N)
average	36.53
min	20.54
max	55.06
std dev	11.02
std error	2.41

In the USA, where it was created, the divide-by-20 rule of thumb uses the value of n_{50} (air leakage rate) instead of q_{50}. A similar analysis is made in Table 8 and Table 9 for the measured values of n_{50}. There is not a notable change compared with the air permeability since most of the houses have a volume-to envelope area ratio close to 1.

These results suggest that the ratios have to be used with care, the British building stock seems to not follow the same rules as the North-American stock. Crucially, the prediction of infiltration rate should, in our view, be done using a range of different ratios or a more accurate infiltration model [17]. This is in line with [19] which suggests that a divide-by-30 rule would be more accurate for the houses the study tested in the Belfast region.

Table 8. Air leakage rate (@50 Pa) – infiltration ratios

Dwelling	ACH @50 Pa n_{50} h^{-1}	$n_{50}/20$	Infiltration n1 h^{-1}	Error	n_{50}/n_1
1	7.62	0.3810	0.1484	157%	51.35
2	5.76	0.2878	0.2093	38%	27.50
3	8.59	0.4296	0.2080	107%	41.31
4	5.31	0.2656	0.1241	114%	42.81
5	3.51	0.1756	0.0787	123%	44.63
6	7.86	0.3931	0.3171	24%	24.79
7	8.61	0.4306	0.3512	23%	24.52
8	5.77	0.2883	0.1645	75%	35.05
9	7.10	0.3548	0.1514	134%	46.86
10	10.45	0.5224	0.2344	123%	44.57
11	9.73	0.4864	0.2284	113%	42.59
12	8.33	0.4164	0.2533	64%	32.88
13	14.97	0.7486	0.4192	79%	35.71
14	5.07	0.2535	0.0849	199%	59.73
15	5.58	0.2788	0.1504	85%	37.08
16	13.27	0.6634	0.5189	28%	25.57
17	4.13	0.2064	0.0998	107%	41.35

18	11.34	0.5671	0.3594	58%	31.56
19	13.29	0.6644	0.2928	127%	45.38
20	12.24	0.6121	0.2753	122%	44.46
21	7.73	0.3865	0.3618	7%	21.37

Table 9. n_{50}/n_1 statistical figures.

	n_{50}/n_1
average	38.15
min	21.37
max	59.73
std dev	9.90
std error	2.16

5. 4. SAP calculated infiltration rates

The procedure to calculate the effective air infiltration rate in dwellings by the Standard Assessment Procedure (SAP), is to divide the air permeability value ($m^3 \cdot h^{-1} \cdot m^{-2}$) by 20 and then modify it by shelter, wind and ventilation factors. Therefore, the divide-by-20 rule is only partially followed in SAP. SAP gives monthly average windspeed depending on the location of the building. Furthermore, SAP considers the shielding depending on the sheltered facades of the dwelling (a semi-detached house will have one sheltered side).

The wind factors are obtained depending on the area where the dwelling is located. In this study all dwellings were located in two regions: East Pennines and Midlands. The wind measured was smaller in magnitude than the one given in SAP. Furthermore, it is important to say that SAP does not include factors to modify the infiltration rate by the temperature difference even when the theory recognizes its importance when wind speed is low [18, 40].

Table 10 shows the air infiltration rates calculated as per SAP after including the modifying factors; two cases are considered, first during the month when the tracer gas test was carried out and, an annual average of the air infiltration rate. SAP uses monthly wind modifying factors. The “during month” columns of Table 10 only use the wind modifying factors from the month of the tracer gas test; the “annual average” columns were calculated using the average of all year wind modifying factors. Dwelling 1 was tested during the month of April; hence, the “during month” calculation was done using the April wind speed for the region (4.4 m/s leading to a correction factor of 1.1 with a sheltering factor of 1) given by SAP in Appendix U [31]. It is important to remark that SAP calculates the infiltration rates depending on the characteristics of the dwellings such as ventilation system. Furthermore, Table 10 includes the values that N would take if a direct leakage – infiltration ratio (or divide-by–N rule) is to be used. Finally, the table mentions the error (difference) of using the air infiltration rates calculated by SAP compared with measurements.

Table 10. Air infiltration rates (h^{-1}) calculated using SAP, values of N from values calculated, and their error compared to measured values

Dwelling	SAP n_1 during month	SAP n_1 annual average	N SAP month	N SAP annual	ACH, tracer gas	Error SAP month	Error SAP annual average
1	0.5938	0.5938	13.2621	13.2625	0.1484	300%	300%
2	0.5449	0.5470	11.0654	11.0228	0.2093	160%	161%
3	0.5703	0.5943	13.8432	13.2855	0.2080	174%	186%

4	0.5207	0.5293	8.4501	8.3132	0.1241	320%	326%
5	0.5159	0.5225	7.4816	7.3871	0.0787	556%	564%
6	0.5529	0.5747	13.7468	13.2235	0.3171	74%	81%
7	0.5470	0.5569	13.1898	12.9563	0.3512	56%	59%
8	0.5352	0.5472	11.2852	11.0380	0.1645	225%	233%
9	0.5448	0.5600	12.5008	12.1606	0.1514	260%	270%
10	0.5922	0.6304	16.9524	15.9528	0.2344	153%	169%
11	0.5531	0.5656	15.8464	15.4965	0.2284	142%	148%
12	0.5327	0.5404	10.9725	10.8164	0.2533	110%	113%
13	0.7289	0.7397	18.6709	18.4003	0.4192	74%	76%
14	0.7289	0.7330	6.4135	6.3780	0.0849	759%	763%
15	0.5320	0.5336	10.0179	9.9891	0.1504	254%	255%
16	0.6202	0.6260	17.9937	17.8285	0.5189	20%	21%
17	0.6850	0.6883	6.2628	6.2328	0.0998	586%	590%
18	0.6027	0.6075	16.4592	16.3289	0.3594	68%	69%
19	0.7033	0.7130	19.0880	18.8279	0.2928	140%	144%
20	0.6856	0.6944	20.2244	19.9662	0.2753	149%	152%
21	0.6173	0.5873	12.3070	12.9357	0.3618	71%	62%

It can be seen that SAP overestimates the infiltration rate of all test houses, this can be translated as a step backwards in the energy efficiency due to the oversizing of heating and ventilation equipment. Such overestimation by SAP is more obvious in more airtight dwellings, the error compared to the measured values is greater than 500% in some cases. The authors suggest urgent revisions are made to the correction factors and the divide-by-20 rule as currently used. Whilst it may be seen as more appropriate to err of the side of caution and act conservatively when estimating infiltration losses, the construction sector is continually advancing toward ever better levels of fabric performance and air tightness. The infiltration estimate plays a vital role in this, impacting both the fabric heat loss rate calculation as well as serving to guide and dictate ventilation strategies. If, as these findings indicate, buildings are already far more air tight than the SAP infiltration and ventilation rate models suggest, there is a very real risk of a mismatch between fabric performance and ventilation with many associated risks in terms of indoor air quality, health and wellbeing.

6. Error analysis

The derivation of leakage-infiltration ratio is based on the measurements of the air leakage results at 50 Pa using the blower door unit and the infiltration rate using the tracer gas decay method. Although the leakage-infiltration ratio used in the UK context is based on the air permeability at 50 Pa (q_{50}), the ratio of the air change rate at 50 Pa (n_{50}) to the infiltration rate is also appraised in order to provide the international context.

The leakage-infiltration ratios based on the q_{50} and n_{50} are given by eq.(6) and eq.(7), respectively.

$$N_{UK} = q_{50}/n_1 \quad (6)$$

$$N_{IT} = n_{50}/n_1 \quad (7)$$

Where the subscripts UK and IT refer to the United Kingdom and international context. Therefore, the errors in deriving N_{uk} and N_{IT} are based on the measurement errors of the combination of q_{50} and n_1, and the combination of n_{50} and n_1, respectively. Both q_{50} and n_{50} are calculated by normalising the air leakage rate at 50 Pa, Q_{50} respectively with the envelope area and volume of the building.

According to the BS EN ISO 9972 [38], the error in obtaining the building parameters is between 3% and 10% and doesn't specify the difference between the envelope area and volume. It is assumed that the measurement errors of both building parameters are the same and therefore the error analysis herein will be only performed to the derivation of N_{uk}. The associated error sources of N_{uk} are summarised and listed in Table 11.

Table 11 Sources of error in obtaining N_{uk}

Source	**Error denotation**	**Error value**
Air leakage rate at 50 Pa, Q_{50} (m^3/h)	δQ_{50}	1.24%-3.77%
Envelope area of the building, A (m^2)	δA	3%-10%
Air infiltration rate, n_1 (h^{-1})	δn_1	0.17%-12.53%

Based on eq.(6), the calculation of N_{uk} can be described by eq.(8) using the error sources listed in Table 11,

$$N_{uk} = Q_{50}/(A \times n_1) \tag{8}$$

Therefore, the error in obtaining the leakage-infiltration ratio based on the air permeability at 50 Pa (q_{50}) can be quantified by eq.(9):

$$\delta N_{uk} = \sqrt{\delta Q_{50}^2 + \delta A^2 + \delta n_1^2} \tag{9}$$

Where, δQ_{50} is determined by the instrumentation error of the blower door unit used in the test, the precision error caused by environmental conditions and manual readings and the model specification error that is used to quantify Q_{50} [28].

The instrumentation error or bias error is given by the manufacturers of the DG-1000 gauge (pressure) used with the blower door. The precision error is calculated by the procedure described in Annex of the ISO 9972 standard [38] which is based on the error by each of the pressure and flow readings in each pressurisation test. Finally, the model error was calculated through the propagation of the error in the procedure given in section 6.2 from the ISO 9972 standard; this approach is based on the uncertainty given by the measuring device, and, how it propagates through the algorithm.

Figure 6 shows the leakage-infiltration ratio of all the test dwellings with the error bands. The boxes in Figure 6 represent the lowest uncertainty range, when δA=3%; and the lines represent the highest uncertainty when δA=10%. For example, in dwelling one the calculated N is 53.07, the range of values that N can take when δA=3% is between 51.3 and 54.8; on the other hand when δA=10% N can be between 47.7 and 58.4.

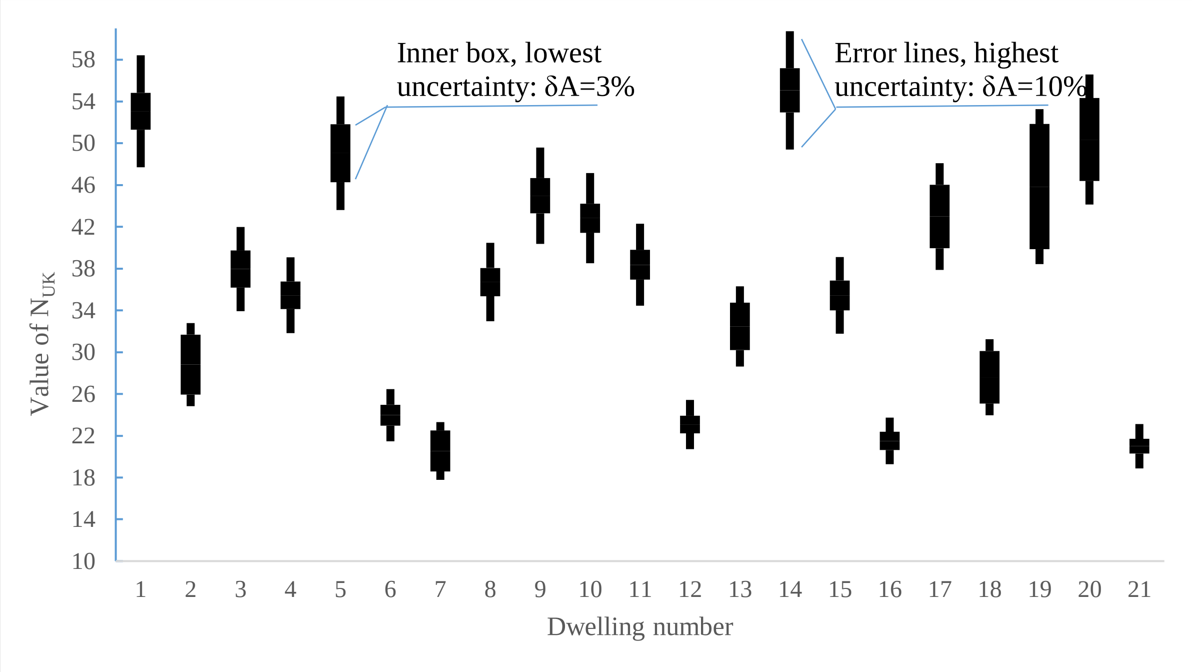

Figure 6 N_{uk} of all testing dwellings with their uncertainties, boxes representing the best case scenario for $\delta A=3\%$ and, lines representing the worst case scenario $\delta A=10\%$.

It is important to remark that each uncertainty is for each dwelling and depends on the uncertainty of each measurement. On average, the calculation of the uncertainty in q_{50} was 1.81% and as mentioned in Table 11, the range of the uncertainty in this parameter is from 1.24% to 3.77% which is small, especially when compared to the one given in the calculation of the uncertainty in n_1; overall 14 dwellings had their Q_{50} uncertainty under 2%. Dwelling 19 has a large uncertainty mainly due to a large uncertainty in the calculation of air infiltration (n_1); on the other hand, dwelling 10 presents a small uncertainty due to a low uncertainty in n_1. Finally, the uncertainty in the measurement of the envelope area is fixed, in this case set as 3 to 10%. This particularly remarks the importance of having a good measurement of the envelope area (or volume if n_{50} is used) of the dwelling; an inaccurate value of envelope area leads to the calculation of an inaccurate N.

The previous analysis implies that despite the uncertainties in each factor (Q_{50}, n_1 and A) most of the values in the range of N are higher than 20 used in the divide-by-20 rule. Only 3 dwellings include 20 in the range within the uncertainty. In conclusion, a higher value for N represents better the sample reported in this study.

According to the ISO 9972, the measurement uncertainty of blower door test is ±10% under calm conditions and ±20% under windy conditions. Considering the calculation of N_{uk} is arrived from the aforementioned multiple measurements, the probability of N_{uk} of each dwelling lying within ±20% of the average $\overline{N_{uk}}$ is evaluated. Such assumption might be crude and have the tendency of being conservative considering N_{uk} is affected by a range of factors, but it gives us a benchmark estimate so a better understanding can be obtained.

The value of N of twelve dwellings would fall in a range of $\overline{N_{uk}}$ ±20% (37±20%) when considering the ranges of uncertainty calculated for each N, which represents 57% of the test dwellings. However, the overall probability in this sample of an infiltration being correctly predicted using $\overline{N_{uk}}$ ±20% is only 41% (When using the worst case scenario of δA=10%). When using the original divide-by-20 ±20% rule the probability of correctly predicting infiltration is 20%. If δA=3% is considered, the probability of predicting correctly are 42% for the new $\overline{N_{uk}}$ ±20% and 22% for the original divide-by-20 rule ±20%, respectively. In both cases the ratio proposed in this study is more accurate than the divide-by-20 rule; nevertheless, in both cases the accuracy is low.

These results indicate that it is possible that a divide-by-20 rule is accurate for some very specific cases, as Johnston [20] has previously mentioned. However, other studies have showed that a higher N value is more representative in the UK context, such as the one proposed by Keig (divide-by-30), and the average N value reported herein (37). This study followed a similar approach as the one taken by Keig [19]; however, the starting concentration in the tracer gas tests by Keig was lower (between 1700 and 3300 ppm) than the ones used in this study (above 4000 ppm). The Johnston [20] study considered multiple tests in each of the 4 dwellings tested, however, in a graph presented the initial concentration of CO_2 was under 700 ppm, this only allowed a decay of less than 300 ppm, this small decay leads to high uncertainty in the predictions; perhaps such testing arrangement resulted in higher infiltration measurement even when the air permeability (q_{50}) was in all cases under 8.48 $m^3h^{-1}m^{-2}$.

Table 12 Values for N found in literature

Source	**Value of N**	**Sample location**
Meier, 1986 [41],Sherman, 1987 [30]	20	US, Sweden
Johnston and Stafford, 2016 [20]	20	UK
Keig et al. 2016 [19]	30	UK
This study	37	UK

The sample size reported in this study is larger than the ones presented by the previous studies, and whilst different results have been obtained concerns over the applicability of the divide-by-20 rule arise once more. These results suggest that the current divide-by-20 rule is not representative of the leakage-infiltration ratio identified in this study. The results show that the value of N spreads in a wide range that is highly dwelling and context dependent. If a leakage-infiltration ratio is to be used as a quick measure for predicting the infiltration rate from an airtightness measurement, 37 will offer a better representativeness for the UK dwellings than any ratio available according to this study. Nevertheless, the sample size of the tested dwellings in this study is not large enough for us to make any solid conclusion on which ratio should be used and further experimental investigations are required to fill the gap.

7. Conclusion

Airtightness is the most influencing factor to calculate the air infiltration in a house, namely air infiltration. Twenty one houses in the east midlands region of the UK were tested by means of blower door and tracer gas methods according to standards to provide an experimental insight into the leakage-infiltration ratio in the UK context.

The rule of thumb was evaluated and results suggest that, if a ratio is used, a number closer to reality is 37. This is true when using both, q_{50} and n_{50}, since most of the house had a volume to envelope area ratio close to 1. The error of using the rule of thumb ranged from 3% to 175%. After an error analysis it was seen that based on the dwellings from this sample there is a 41% probability that the value for N 37 ±20% represents the infiltration rate of a dwelling, which is twice as high as the current divide-by-20 rule suggesting the divide-by-20 rule is not representative of the leakage-infiltration ratio given by the dwelling sample reported in this study.

After adding the modifying factors for sheltering and local wind, SAP overestimated the air infiltration rate creating errors larger than 500% in airtight houses. As homes are built with ever lower air permeability values, the error in the air infiltration rate calculations will be larger. If the main UK Government policy instrument used for driving energy efficiency in buildings, SAP, doesn’t rectify this issue, there is a really risk of and ever growing mismatch in how fabric performance, air tightness and ventilation is presented and dealt with in the industry. The potential consequences of this are significant, with the infiltration rate contributing to the overall whole fabric heat loss rate for a dwelling whilst also serving to guide ventilation system strategies which in turn have bearing on indoor air quality, health and wellbeing.

A modification of the divide-by-20 rule of thumb in UK legislation is advised alongside revisions to the modification factors currently adopted. A more accurate approach in our view would be to predict infiltration rates through the use of infiltration models [17].

Acknowledgements

The experimental data used in this study was obtained in collaboration with Build Test Solutions Ltd in a project supported by Department for Business, Energy and Industrial Strategy Energy Entrepreneurs Fund Scheme, Phase 5 (EEF5029).Part of this work was funded by the Mexican Council of Science and Technology (CONACYT), and EPSRC Impact Acceleration Grant and their full support is acknowledged by the authors.

References

[1] B. Lapillonne, K. Pollier and N. Samci, “Energy efficiency trends for households in the EU.,” pp. 1-51, 2015.

[2] International Energy Agency;, “Tracking Buildings,” IEA, Paris, France, 2019.

[3] D. Etheridge , “A perspective of fifty years of natural ventilation research,” *Building and environment,* vol. 97, pp. 51-60, 2015.

[4] M. Santamouris and D. Asimakopoulos, Passive Cooling of Buildings, James & James (Science Publishers) Ltd., 1996.

[5] M. Ringger and P. Hartmann, “Evaluation of an Acoustical Method for Detecting Air Leaks,” *Air Infiltration Review,* vol. 11, no. 1, 1989.

[6] V. Iordache and T. Catalina, “Acoustic Approach for Building Air Permeability Estimation,” *Building and Environment,* vol. 57, pp. 18-27, 2012.

[7] O. Hassan, “An Alternative Method for Evaluating the Air Tightness of building Components,” *Building and Environment,* vol. 67, pp. 82-86, 2013.

[8] E. Cooper and D. Etheridge, “Determining the Adventitious Leakage of Buildings at Low Pressure, Part 2: Pulse Technique,” *Building Services Engineers Research Technology,* vol. 28, pp. 81-96, 2007.

[9] E. Cooper, Z. Xiaofeng, C. Wood, M. Gillott, D. Tetlow, S. Riffat and L. De Simon, “Field Trialling of a New Airtightness Tester in a Range of UK homes,” *International Journal of Ventilation,* vol. 18, no. 1, pp. 1 - 18 , 2016.

[10] W. H. Card, A. Sallman, R. A. Graham and E. Drucker, “Air Leakage Measurement of Buildings by an Infrasonic Method,” Syracuse University, Technical Report TR-78-1, 1978.

[11] S. Sharples and D. Thompson, “Experimental Study of Crack Flow with Varying Pressure Differentials,” in *Proceedings: Optimum Ventilation and Air Flow Control in Buildings, 17th Air Infiltration and Ventilation Centre Conference*, Gotenburg, Sweden, 1996.

[12] M. H. Sherman and M. P. Modera , “Low Frequency Measurement of the Leakage in Enclosures,” *Review of Scientific Instruments,* vol. 57, no. 7, pp. 557-561, 1986.

[13] X. Zheng, J. Mazzon, I. Wallis and C. J. Wood, “Airtightness measurement of an outdoor chamber using the Pulse and blower door methods under various wind and leakage scenarions,” *Building and Environment,* vol. 179, 2020.

[14] X. Zheng, E. W. Cooper, J. Mazzon, I. Wallis and C. J. Wood, “Experimental insights into the airtightness measurement of a house-sized chamber in a sheltered environment using blower door and pulse methods,” *Building and Environment,* vol. 162, 2019.

[15] X. Zheng, E. Cooper, Y. Zu, M. Gillott, D. Tetlow, S. Riffat and C. J. Wood, “Experimental studies of a Pulse pressurisation Technique for measurig building airtightness,” *Future cities and environment,* vol. 5, pp. 1 -17 , 2019.

[16] X. Zheng, E. Cooper, M. Gillott and C. Wood, “A practicar review of alternatives to the steady pressurisation method for determining building airtightness,” *Renewable Sustainable Energy Reviews,* vol. 132, 2020.

[17] M. Orme and N. Leksmono, AIVC guide 5: Ventilation modelling data guide, International Energy Agency, AIVC, 2005.

[18] M. W. Liddament, “Air Infiltration Calculation Techniques An Applications Guide,” The Air Infiltration and Ventilation Centre, Coventry, United Kingdom, 1986.

[19] P. Keig, T. Hyde and G. McGill, “A comparison of the estimated natural ventilation rates of four solid wall houses with the measured ventilation rates and the implications flor low-energy retrofits,” *Indoor and Built Environment,* vol. 25, no. 1, pp. 169-179, 2016.

[20] D. Johnston and A. Stafford, “Estimating the background ventilation rates in new-build UK dwellings - Is n50/20 appropriate?,” *Indoor and Built Environment,* vol. 26, no. 4, pp. 502-513, 2016.

[21] The Air Tightness Testing & Measurements Association;, “Technical Standar L1: Measuring Air Permeability of Buildings - Fan Pressurization Method,” BS EN ISO 9972:2015, United Kingdom, 2016.

[22] The Energy Conservatory;, “Minneapolis Blower Door Operation Manual for Model 3 and Model 4 Systems,” The Energy Conservatory, Minneapolis, U.S.A., 2012.

[23] D. Etheridge, “Crack flow equations and scale effect,” *Building and Environment,* vol. 12, pp. 181-189, 1977.

[24] D. Etheridge, “A note on crack flow equations for ventilation modelling,” *Building and Environment,* vol. 33, pp. 325-328, 1998.

[25] X. Zheng and C. J. Wood, “On the power law and quadratic forms for representing the leakage-pressure relationship - Case studies of sheltered chambers,” *Energy and Buildings,* vol. 226, 2020.

[26] The British Standards Institution, “Thermal Performance of Buildings - Determination of Air Permeability of Buildings - Fan Pressurization Method,” BS EN ISO 9972:2015, United Kingdom, 2015.

[27] E. Cooper and D. Etheridge, “Determining the Adventitious Leakage of Buildings at Low Pressure, Part 1: Uncertainties,” *Building Services Engineers Research Technology* , vol. 28, pp. 71-80, 2007.

[28] M. H. Sherman and L. Palmiter, “Uncertainties in Fan Pressurization Measurements,” *Airflow Performance of Building Envelopes, Components and Systems,* vol. ASTM STP 1255, pp. 266-283, 1995.

[29] B. Jones, A. Persily and M. H. Sherman, “The Origin and Application of Leakage-Infiltration Ratios,” in *ASHRAE AIVC IAQ 2016, Defining Indoor Air Quality: Policy, standards and Best Practices,* Alexandria, Virginia, U.S.A., 2016.

[30] M. H. Sherman, “Estimation of Infiltration from Leakage and Climate Indicators,” *Energy and Buildings,* vol. 10, pp. 81-86, 1987.

[31] Building Research Establishment, “The Government's Standard Assessment Procedure for Energy Rating of Dwellings,” Building Research Establishment on behalf of the Deparment of Energy and Climate Change, Watford, United Kingdom., 2013.

[32] M. H. Sherman, “Uncertainty in air Flow Calculations Using Tracer Gas Measurements,” *Building and Environment,* vol. 24, no. 4, pp. 347-354, 1989.

[33] American Society for Testing and Materials, “Standard Test Method for Determining Air change in a Single Zone by Means of Tracer Gas Dilution,” ASTM designation E741-11, 2011.

[34] International Organization for Standardization;, “BS EN ISO 12569:2017 Thermal Performance of Buildings ans Materials - Determination of Specific Aiflow Rate in Buildings - Tracer Gas Dilution Method,” BSI Standards limited, United Kingdom, 2017.

[35] P. L. Cheng and X. Li, “Air infiltration rates in the bedrooms of 202 residences and estimated parametric infiltration rate distribution in Guangzhou, China,” *Energy & Buildings,* vol. 164, pp. 219-225, 2018.

[36] S. Cui, M. Cohen, P. Stabat and D. Marchi, “CO2 tracer gas concentration decay method for measuring air change rate,” *Building and Environment,* vol. 84, pp. 162-169, 2015.

[37] M. H. Sherman and B. Dickinson , “The Prediction of Air Infiltration,” in *Proceedings of the CLIMA 2000 Conference,* Copenhagen, Denmark, 1985.

[38] International Organization for Standardization, “BS EN ISO 9972:2015 Thermal Performance of Buildings - Determination of Air Permeability of Buildings- Fan Pressurization Method,” BSI Standards, United Kingdom, 2015.

[39] ASHRAE;, “Standard 62.1-2016 - Ventilation for Acceptable Indoor Air Quaility,” ASHRAE, U.S.A., 2016.

[40] A. Vega Pasos, X. Zheng, V. Sougkakis, M. Gillott, J. Meulemans, O. Samin, F. Alzetto, L. Smith, S. Jackson and C. J. Wood, “Experimental investigation of the impact of environmental conditions on the measurement of building infiltration, and its correlation with airtightness,” in *39th AIVC Conference Proceedings,* Juan-les-Pins/antibes, France, 2018.

[41] A. Meier, “Infiltration: Just ACH50 divided by 20?,” *Energy auditor and retrofitter,* Jul/Aug 1986.

[42] A. Vega Pasos, X. Zheng, V. Sougkakis, M. Gillott, J. Meulemans, O. Samin, F. Alzetto, L. Smith, S. Jackson and C. J. Wood, “Experimental study on the measurement of building infiltration and air leakage rates (at 4 and 50 Pa) by means of tracer gas, blower door and the novel Pulse technique in a detached UK home,” in *39th AIVC Conference*, Antibes, Juan-les-Pins, France, 2018.