Comparison between infiltration rate predictions using the divide-by-20 rule of thumb and real measurements.

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ABSTRACT

Across different territories there are various normative models for assessing energy demand of domestic dwellings, which use simplified approaches to account for the heat loss due to the air infiltration of a building. For instance, the United Kingdom uses a dwelling energy model, known as the Standard Assessment Procedure (SAP), and this utilises a process where the measured air permeability value (q_{50}), is simply divided by 20 to provide an infiltration rate (subsequent modification factors are then used for factors such as sheltering etc.). This rule is commonly known as the divide-by-20 rule. As a starting point, building air leakage rate is measured through a steady pressurisation (blower door) test, and normalised by envelope area to provide a value of air permeability. In this study the air infiltration rate of five dwellings based in Nottingham, UK was investigated. Air infiltration was measured and calculated using the conventional approach with the divide-by-20 rule and also with tracer gas methods, which directly assessed air infiltration at ambient pressure levels. Results showed that for the test dwellings, a divide-by-39 (q_{50}/39) rule would predict air infiltration more accurately (than the divide-by-20). It was also seen that the air change rate is overestimated by SAP when modifying factors are added. The errors in more than half of the properties are higher than 225%. The most significant differences were seen in the dwellings with more airtight building envelopes.

KEYWORDS

Air infiltration, airtightness, blower door, pulse, permeability

1 INTRODUCTION

Energy efficiency of buildings plays a crucial role in the efforts to tackle climate change (Lapillonne, Pollier, & Samci, 2015). The energy used for heating and/ or cooling of the internal air represents the largest source of energy usage in a building in many territories, therefore, reducing the loss of conditioned air is key to achieving an energy efficient building. In the UK for instance, one third of a dwellings heat loss can come from air infiltration (Etheridge , 2015). Air infiltration (h^{-1}) is the unintended ventilation of a building, and is not only important for energy efficiency, but also for indoor air quality and thermal comfort.

Correspondingly, building airtightness is the property that impacts the most on the air infiltration rate. The first step to understand the infiltration properties of a building is to measure its airtightness. Airtightness can take units of: air change rate (h^{-1}), air permeability ($m^3h^{-1}m^{-2}$) when the flow (m^3/s) is normalised by volume and envelope area.

1.1 UK context

As mentioned, airtightness is measured prior to obtaining the heat losses attributed to air infiltration. Air permeability (q), or air change rate (n), are airtightness metrics and regularly are quoted at a certain pressure difference; for example, British legislation requires the measurement of air permeability to be quoted at 50 Pa, thus this metric is shortened as q_{50}, the subscript 50 references the 50 Pa of pressure difference obtained by the pressurisation method when measuring air permeability.

The steady pressurisation method, most commonly known as “blower door”, is an airtightness measuring technique which increases the pressure difference of a building by pressurising or depressurising the internal space with aid of a fan mounted in a doorway. Measurements are taken while the building covers a range of pressure differences, typically between (-)10 to (-)60 Pa (The British Standards Institution, 2015).

This pressure difference is correlated with the airflow through the fan, the technique quotes the results at 50 Pa. Flow and pressure difference are related by the power law in equation 1 (The British Standards Institution, 2015).

$$Q = C\Delta p^n \tag{1}$$

where:
Q= fan air flow rate (m^3h^{-1});
C = air flow coefficient ($m^3h^{-1}Pa^{-n}$);
Δp = Indoor-outdoor pressure difference (Pa);
n= flow exponent (dimensionless), in the range from 0.5 to 1 (turbulent to laminar flow).

Due to the nature of the method (pressurising), which increases the pressure difference experienced by the building; some authors have questioned that the pressurisation method results do not represent the air change rate occurring under natural conditions (Cooper & Etheridge, 2007), which usually lie between 1-4 Pa of pressure difference. To obtain a value in a lower pressure range, an extrapolation is needed.

Air infiltration prediction models are the tool to estimate an infiltration rate (under natural conditions) from airtightness measurements (Orme & Leksmono, 2005). Models vary in complexity; the simplest way to predict an infiltration rate (n_1) is to use an airtightness – infiltration ratio (equation 2).

$$n_{50}/n_1 = N \tag{2}$$

where:
n_{50} = air change rate at 50 Pa (h^{-1});
n_1 = air infiltration rate (h^{-1});
N = ratio constant (dimensionless).

Research in the United States (Jones, Persily, & Sherman, 2016; Sherman, 1987; Persily, 1982) determined that the value of N in equation 2 can be taken as 20, and it should be modified by a number of environmental factors. In other words, if the air change rate obtained in a pressurisation test is divided by 20, the obtained result is the air infiltration rate under natural conditions; this was called the divide-by-20 rule of thumb (equation 3).

$$n_{50}/20 = n_1 \tag{3}$$

Even when this rule was created, tested and validated in the United States, the United Kingdom adopted it as the way to predict the infiltration rate (Building Research Establishment, 2013). The usage of this ratio in the UK has been questioned before due to its simplicity (Keig, Hyde, & McGill, 2016; Johnston & Stafford, 2016). Furthermore, UK legislation does not utilise an air change rate at 50 Pa (n_{50}) to predict the infiltration rate, air permeability (q_{50}) is the airtightness metric used. Then, for UK legislation, equation 3 turns into equation 4. This change assumes that a building has a volume – envelope to area ratio of 1.

$$q_{50}/20 = n_1 \qquad (4)$$

1.2 Measurement of air infiltration

Air infiltration rate is usually predicted from airtightness measurements, nevertheless the possibility of measuring it does exist. This is regularly carried out through tracer gas methods. Several tracer gas methods have been standardised (American Society for Testing and Materials, 2011; British Standards Distribution;, 2017), yet the tracer gas concentration decay method is the most popular one due to its simplicity, low cost, and relatively good accuracy (Sherman, 1989).

In a standard concentration decay test, the gas is released and mixed in the test space, and the concentration decay is monitored over time. Different gases can be used, however carbon dioxide is probably the most widely used. Normally, fans are employed to ensure a good mix of tracer gas and air. Time, and the natural logarithm of the concentration are placed on a linear regression. The infiltration rate is given by the slope in the linear best fit of the time-$\log_e$ relationship. Furthermore, to comply with the standards, a minimum time for testing is required, depending on the airtightness of the building. Table 1 lists the approximate testing time required for buildings with various levels of airtightness.

Table 1: Minimum durations of tracer gas decay method (American Society for Testing and Materials, 2011)

Air Change Rate (h^{-1})	Minimum duration (h)
0.25	4
0.5	2
1	1
2	0.5
4	0.25

Tracer gas methods have been proved accurate when measuring air infiltration rate, yet they are not commonly utilised because they are invasive, time taking, costly and the tested property has to be unoccupied during the test.

The objective of this paper is to assess the UK building regulation's method of predicting air infiltration heat losses, which utilises the divide-by-20 rule of thumb (equation 4). The study involves pressurisation and tracer gas concentration decay tests in five dwellings located in Nottingham, United Kingdom.

2 METHOD

This project is part of a large airtightness testing campaign using different technologies in dwellings in the United Kingdom. Five houses located near the University of Nottingham in Nottingham, United Kingdom were selected to be tested using the tracer gas concentration decay method; in addition, pressurisation tests and weather monitoring were carried out in the houses. The characteristics of each dwelling are described in Table 2.

Pressurisation (and depressurisation) tests were carried out according to the British Standard (The British Standards Institution, 2015). The tracer gas tests and the calculations were carried out according to the British and ASTM standards (British Standards Distribution;, 2017; American Society for Testing and Materials, 2011). The equipment utilised in the tests is listed in Table 3.

Table 2: Description of dwellings

Dwelling	Date of test	Form	Main construction type	Volume (m^3)	Envelope area (m^2)
1	25/04/2018	Detached	Cavity	278	269
2	03/08/2018	Detached	Timber frame	188	227
3	16/08/2018	Detached	Solid	478	435
4	07/06/2018	Semi-detached	Solid	264	252
5	18/01/2018	Detached	Cavity	285	290

Table 3: Testing equipment

Airtightness		Minneapolis blower door model 4. (BD-4)
Tracer gas	Gas:	Carbon dioxide
	Sensor:	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

The selected tracer gas was carbon dioxide; each dwelling was divided into six different "zones". A set of CO_2 and temperature sensors were placed in each dwelling, one sensor for each zone. The sensors were connected to a data logger which recorded the temperature and gas concentration at a sampling rate of 1 *Hz*. The gas was released into each zone until the concentration was close to 5000 *ppm* and to ensure adequate mixing of the CO_2 with the bulk air volume, a floor fan located in each zone was used to achieve homogeneity. The CO_2 was left to decay for as long as possible, considering the minimum times stated in Table 1. Figure 1 shows part of the equipment utilised for the tracer gas tests. In addition, an ultrasonic anemometer connected to the same data logger recorded every second the wind speed and direction during the tracer gas decay period.

a) *b)* *c)*

Figure 1. Equipment utilised for tracer gas decay method tests. a) Data logger with sensors connections, b) carbon dioxide canisters, c) example of a building zone, with a temperature sensor, a carbon dioxide sensor and a fan.

3 RESULTS AND DISCUSSION

In the following analysis two aspects will be investigated to test the appropriateness of the so-called 'divide by 20 rule' in relation to the test dwellings. The ratio of air permeability (at 50 *Pa*) to infiltration rate (as per the UK's requirement under the Standard Assessment Procedure, SAP) and also in the original form of air changes rate per hour (at 50 *Pa*) to infiltration rate. Pressurisation tests, results were obtained in the form of air permeability at 50 *Pa* (q_{50}, $m^3h^{-1}m^{-2}$) and also the air change rate at 50 *Pa* (n_{50}, h^{-1}). The air infiltration rates, determined by the concentration decay tests and by calculation from pressurisation tests (via the 'divide-by-20 rule) are given in air changes per hour (n_1, h^{-1}).

3.1 Pressurisation tests results

Table 4 includes the mean value of pressurisation and depressurisation tests for each dwelling tested, in air change rate (n_{50}) and air permeability units (q_{50}). It is believed that in the UK, dwellings have a volume – envelope area ratio close to one (as per its application in SAP). It can be seen that this is true for most of the test properties, as relatively similar values of air change rate and air permeability confirm this.

Table 4. Blower door tests results

Dwelling	ACH @50 Pa (n_{50}) h^{-1}	Air Permeability @50 Pa (q_{50}) $m^3h^{-1}m^{-2}$	Volume (m^3)	Envelope area (m^2)
1	7.62	7.88	278	269
2	5.31	4.40	188	227
3	3.51	3.86	478	435
4	5.77	6.04	264	252
5	7.73	7.60	285	290

The data set showed that property number 3 is the most airtight; furthermore, all the properties comply with the UK standard that requires a minimum air permeability of 10 $m^3h^{-1}m^{-2}$. The average air permeability of all five dwellings is 5.96 $m^3h^{-1}m^{-2}$.

3.2 Tracer gas results

Each CO_2 sensor measured the concentration decay in each zone. Figure 2 shows an example of the concentration decay of the average of the concentration from all the zones; this example shows a decay from (circa) 4200 *ppm* to 2000 *ppm*.

ASTM E741-11 (American Society for Testing and Materials, 2011) requires a least square regression performed between the elapsed time and the natural logarithm of the concentration. The best linear fit is produced, and, the slope of the equation represents the air infiltration rate of the building. Figure 3 shows the time against natural logarithm of the concentration regression in dwelling 4; it also shows the equation of the best fit and the r^2 value. The infiltration rate was $0.1645\ h^{-1}$. Both Figure 2 and Figure 3 are examples of how the air infiltration rate is obtained from a tracer gas decay test.

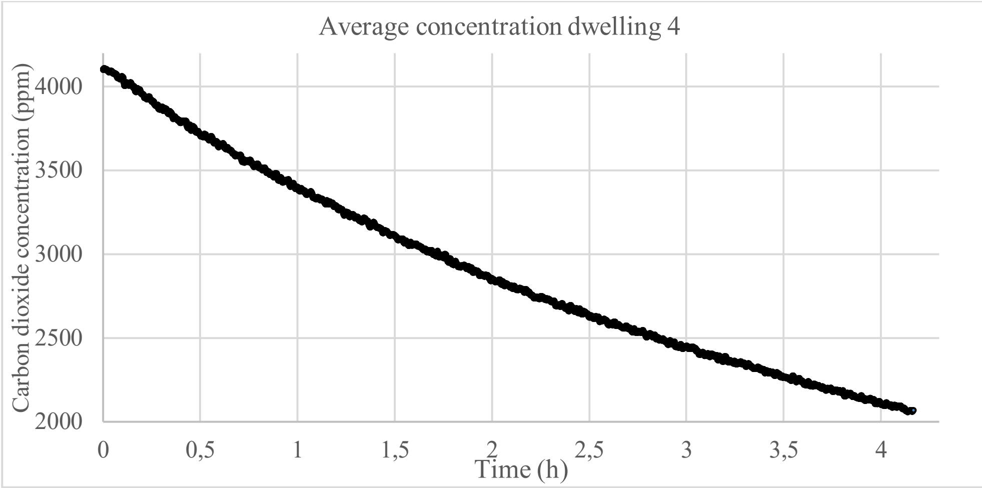

Figure 2. Concentration decay of dwelling 4.

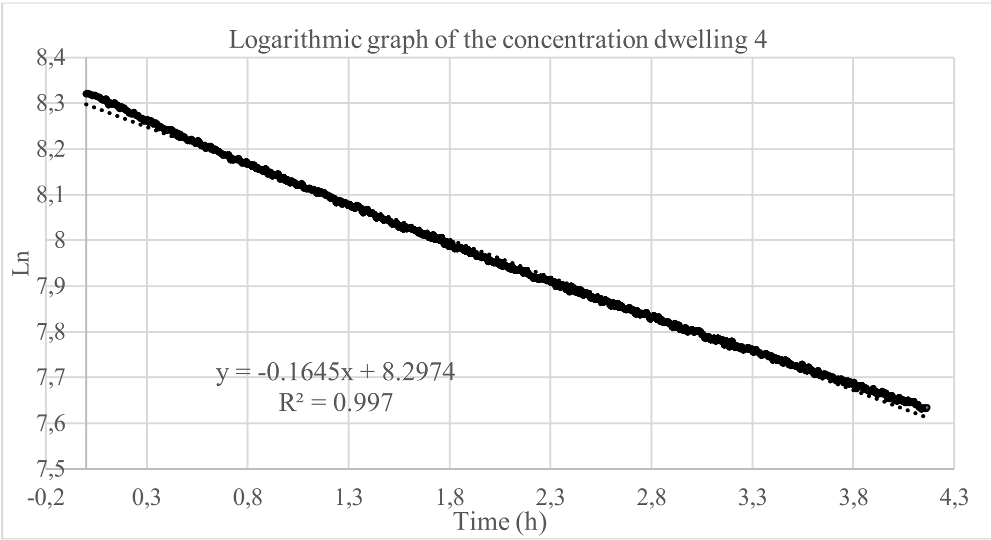

Figure 3. Natural log of the concentration decay for dwelling 4 and the best fit linear regression, and equation where the slope represent the air infiltration rate in h^{-1}.

Pressurisation tests were carried out prior to the tracer gas tests, and all building conditions were kept as per the pressurisation test standard for both tests: all windows and external doors were closed, internal doors were opened, vents, flues and trickle vents were closed and sealed. Therefore, the obtained infiltration rate was only due to adventitious openings and represents a direct comparison with the airtightness tests. All the results and characteristics of the concentration decay tests are presented in Table 5. The valid duration of test is shown, the uncertainty of the regression is given, and finally, the average weather conditions during the tests are presented.

Table 5. Tracer gas decay method results

Dwelling	**Date of test**	**infiltration rate (n_1, h^{-1})**	**r2**	**Test duration h**	**Uncertainty $\pm h^{-1}$**	**Wind m/s**	**Δt K**
1	25/04/2018	0.1484	0.99	7.32	0.0009	2.736	4.73
2	03/08/2018	0.1241	0.999	8.5	0.0019	1.08	3.69
3	16/08/2018	0.0787	1	8.00	0.0036	0.710	3.39

4	07/06/2018	0.1645	1	4.17	0.0020	1.700	0.94
5	28/02/2018	0.3618	0.99	7.64	0.0007	0.350	11.00

As per the duration, all tests fulfilled the standard ASTM E741-11 (American Society for Testing and Materials, 2011), the regressions had high correlation values of both variables, and the uncertainty created was low (less than 5% in all cases), within the limits given by other authors (Sherman, 1989); proving the validity of the tests. The average infiltration rate of all five dwellings was $0.1755\ h^{-1}$. Regarding the measurement of the on-site wind, the anemometer was positioned near the houses in spaces, as open as possible, however, this was not always achieved due to various site conditions, the anemometer's height varied from 1.8 to 2.5 metres. Finally, the indoor-outdoor temperature difference was calculated by averaging all the measured internal temperatures (one sensor was placed next to each CO_2 sensor) and, subtracting the measured outdoor temperature, which was placed next to the anemometer.

3.3 Air Infiltration ratios

To obtain the air infiltration rate from airtightness measurements, the British Standard Assessment Procedure (SAP) requires to use the divide-by-20-rule. The new calculated value is then modified by certain factors. Table 6 presents the calculated infiltration rates using equation 4 and how it compares with the real measurements, finally, the last column gives the real value of *N* if a divide-by-N rule is to be utilised.

Table 6. Air permeability – air infiltration

Dwelling	**Air Permeability @50 Pa $m^3h^{-1}m^2$ q_{50}**	**$q_{50}/20$**	**ACH h^{-1} n_1**	**Error**	**q_{50}/n_1**
1	7.88	0.3938	0.1484	165%	53.07
2	4.40	0.2200	0.1241	77%	35.46
3	3.86	0.1930	0.0787	145%	49.05
4	6.04	0.3020	0.1645	84%	36.72
5	7.60	0.3798	0.3618	5%	21.00
				Average	39.06
				Min	21.00
				Max	53.07
				Std dev	11.32
				Std error	5.06

Dividing the air permeability by 20 creates a large error compared to the measured infiltration rate. There is an overestimation of air infiltration, therefore if heat losses are calculated using the divide-by-20 rule this will result in a larger prediction of heat loss than that experienced by the dwelling in reality. The last column suggests that a much larger value is required; for these five properties a divide-by-39 value would be more accurate, which agrees with Vega Pasos (Vega Pasos, et al., 2018). The estimated average value of *N* is almost twice the figure used in SAP. For dwelling five, it can be seen that the figure for N is close to 20, this is the only property where this happens.

Table 7. Air change rate – air infiltration

Dwelling	ACH @50 Pa $m^3h^{-1}m^2$ q_{50}	$n_{50}/20$	ACH h^{-1} n_1	Error	n_{50}/n_1
1	7.62	0.3810	0.1284	157%	51.35
2	5.31	0.2656	0.1076	114%	42.81
3	3.51	0.1756	0.0700	123%	44.63
4	5.77	0.2883	0.1442	75%	35.05
5	7.73	0.3865	0.2426	7%	21.37
				Average	39.04
				Min	21.37
				Max	51.35
				Std dev	10.25
				Std error	4.58

Table 7 shows results when the divide-by-20 rule is used in its original form, (using n_{50} instead of q_{50}, or equation 3). Results do not differ much from those given in Table 6, because the volume-envelope area ratio is close to 1, it can be seen that the figure of N is still 39, and the minimum error created by using the divide-by-20 ratio is 7%.

Using the divide-by-20 rule in the United Kingdom does not deliver accurate results for most of the properties, this is because the rule is rather crude and, the housing stock is different than the United States one where it was originally created. The authors recommend using different ways to predict infiltration rates. Continuing the testing campaign with more dwellings will give a more accurate vision of the usage of leakage-infiltration ratios.

3.4 Calculations using SAP

The SAP uses the divide-by-20 rule with the objective of estimating the infiltration heat losses in a building, after using it, the resulting value is modified by shelter, wind and ventilation factors. The wind factors depend on the location of the dwelling, for this study, all dwellings were in the East Pennines area of the United Kingdom.

Table 8 includes the -calculated by SAP- air infiltration rates (air change rates) after the modifying factors; two cases are considered: first, during the month when the tracer gas test was carried out and, second, an annual average of the air change rate. Errors calculated when comparing measured and predicted values are listed in the last two columns.

Table 8. Air change rates (h^{-1}) calculated using SAP, values of N from values calculated, and their error compared to measured values

Dwelling	SAP n_1 during test month	SAP n_1 annual average	N SAP during test month	N SAP annual average	ACH, tracer gas	Error SAP during test month	Error SAP annual average
1	0.6000	0.6000	13.1256	13.1261	0.1484	304%	304%
2	0.5150	0.5212	0.5444	8.4428	0.1241	315%	320%
3	0.5161	0.5228	7.4792	7.3838	0.0787	556%	564%
4	0.5352	0.5472	11.2852	11.0380	0.1645	225%	233%
5	0.6174	0.5873	12.3050	12.9340	0.3618	71%	62%

The values calculated by SAP overestimate the air change rate, thus the infiltration heat losses; the error is larger than 300% in some cases. First, the divide-by-20 rule makes an over-prediction, and second, the correction factors make this over-prediction even larger, this is because when a house is tight, the correction gives a minimum infiltration of $0.5h^{-1}$ (hence why all values are higher than 0.5). It is recommended to revise these correction factors, to avoid the large error and to design with ventilation rates closer to reality.

4 CONCLUSION

Five houses in the East Pennines region of the UK were tested by means of pressurisation. Air permeability ($m^3h^{-1}m^{-2}$) and air change rate (h^{-1}) quoted at 50 Pascals were presented. Tracer gas concentration decay tests were carried out, following the pressurisation tests in the same dwellings to directly determine the air infiltration rate.

Pressurisation tests showed that all the houses comply with the British building standard requirement with air permeability rates lower than 10 $m^3h^{-1}m^{-2}$. Tracer gas tests showed an average infiltration value of 0.1755 h^{-1}.

Standard Assessment Procedure (SAP) evaluates the energy efficiency of dwellings in the UK. An important factor in SAP is the air change rate and it is obtained through dividing the air permeability (q_{50}) value of the house (obtained by a pressurisation test) by 20. This rule is known as the divide-by-20 rule of thumb. The rule of thumb was evaluated and results suggest that, if a ratio is used, a number closer to reality is 39 for the test dwellings in this study. This was true for both, q_{50} and n_{50}. Errors between 5% and 165% were found; the rule overestimated the infiltration rate for all tested dwellings. After adding the modifying factors, SAP overestimated the air infiltration rate creating errors larger than 500%. The fact that dwellings are getting tighter might not be reflected by SAP.

Suggestion of the revision of the modifying factors and the utilisation of the rule of thumb were given. A larger testing campaign in different areas of the country would deliver a better vision on whether the rule should still be used, or a more accurate model must be included in the regulation.

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