Experimental study on the measurement of Building Infiltration and Air Leakage rates (at 4 and 50 Pa) by means of Tracer Gas methods, Blower Door and the novel Pulse technique in a Detached UK Home

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ABSTRACT

Air infiltration contributes to a heat loss typically representing up to one third of the heating demand of a building. The building airtightness, also quantified as air leakage, is the fundamental building property that impacts infiltration. The steady (de)pressurization method (blower door) is the widely accepted standard process for measuring building air leakage. However, this method requires the enclosure to be pressurised to a typical range of 10-60 Pa, which is not physically representative of the pressures experienced by buildings under natural conditions. The Pulse technique is a novel alternative method, which measures air leakage at low pressures; quoting it at a reference pressure of 4 Pa. An experiment was designed to test the leakage characteristics of a detached house in the UK and compare them with the infiltration rate; which were measured by tracer gas techniques, utilising the decay method. The blower door and Pulse tests were both performed multiple times during a six week period to cover a range of different environmental conditions. Initial results have shown that there might be correlation between the infiltration rate and air leakage at 4 Pa and 50 Pa. It was concluded that Pulse technique's results induce less uncertainty when predicting air infiltration. Further experimental testing is required to be carried out in a range of properties to investigate how this conclusion stands and how the results given by existing infiltration models compare with the experimentally obtained infiltration rate.

KEYWORDS

Air Infiltration, Air leakage, Tracer gas, PULSE, Blower door

1 INTRODUCTION

Air infiltration rate is the most important parameter to determine the energy loss caused by non-intended ventilation. Air infiltration can represent up to one third of the heating demand of a house (Etheridge , 2015; Energy Saving Trust;, 2006). Infiltration is fundamentally dependent on the building airtightness (Sherman & Grimsrud, 1980), it is driven mainly by wind and stack effects through cracks and gaps.

Air infiltration is measured through tracer gas tests, several gases can be used among which carbon dioxide is probably the most used one (British Standards Distribution;, 2017; Liddament, 1996). The most accurate tracer gas method to measure air infiltration is the constant concentration method, however, the decay method is the easiest and less costly one (Sherman , 1998). Although the infiltration rate is the most important parameter to calculate heat losses, measuring it is expensive, disruptive and time taking; for this reason, the common practice is to measure the air leakage rate and predict a representative infiltration rate.

Fan pressurization method (commonly known as "blower door") is the most used method for measuring the air leakage rate. The blower door pressurizes or depressurizes the building typically from 10 to 60 Pa using a fan mounted on a doorway; the pressure difference in the building and the flow passing through the fan are measured; the air leakage rate is typically quoted at 50 Pa (The British Standards Institution, 2015), but also quoted at other reference pressures such as 4 Pa and 10 Pa.

On the other hand, the PULSE technique is a novel technique to measure air leakage rate at low pressures (Cooper, et al., 2014; Cooper & Etheridge, 2007; Cooper, et al., 2015). It is implemented by releasing compressed air into the test space in a short period of time (usually for 1.5 seconds) and measuring the pressure change in the building and in the compressed air vessel to calculate the amount of air leaking through building envelope; and the test result is quoted at weather induced pressure level, typically at 4 Pa.

Finally, via different infiltration models or empirical ratios, the air infiltration rate can be predicted using the measurements taken from the fan pressurisation test, however, it has been mentioned that this can lead to high uncertainty due to an extrapolation procedure (Cooper & Etheridge, 2004). Conversely, the Pulse method cannot predict infiltration rates, since there have not been studies used to correlate the results from the method with the infiltration rates.

The objective of this experimental study is to start understanding the correlation between air infiltration and the air leakage measurements taken at 4 Pa by the pulse technique and how it compares with the correlation obtained for air infiltration and air leakage measured at 50 Pa by the blower door.

2 METHODOLOGY

Tracer gas methods have regularly been used to measure the air infiltration in buildings; several studies have used the techniques to measure infiltration rates and compared them to physical phenomena, prediction models, to define the infiltration rates of certain buildings or only to test the methods. (Cui, et al., 2015; Guyot, et al., 2016; Hayati, et al., 2014; Hong & Sean Kim, 2016; Laussmann & Helm, 2011; Sherman , 1998; Turner , et al., 2012). This study focuses on how the measured infiltration rates are related to the air leakage characteristics of the house measured at 4 Pa and 50 Pa by pulse and blower door methods respectively.

Using an INNOVA 1412i gas analyser and a LumaSense 1303 multi point gas sampler and doser, a detached UK house was tested using tracer gas methods. The selected gas to be traced was carbon dioxide (CO_2) because of its physical properties, low price and being easy-to-obtain**Error! Reference source not found.**.

During the months of January and February in 2018, several tracer gas constant concentration and decay tests were carried out during different climate conditions. The internal temperature of the house was controlled by the research team. Indoor temperature was varied to provide various temperature scenarios. The two tracer gas methods were exchanged according to the conditions selected. The duration of the constant concentration test varied from 2 to 6 days depending on the nature of the test. Table 2 shows how the heating conditions were changed, the objective was to create different temperature differences during different periods of the day and to do a side-by-side studies with QUBe and Co-Heating tests, however, those tests are not part of the scope of this paper.

Table 1. List of equipment and materials for testing

Airtightness	Infiltration	Others
PULSE-60, BD-4	**Gas**: Carbon dioxide **Measuring**: INNOVA 1412I gas analyser **Dosing/sampling**: TinyTag CO2 logger, LumaSense 1303 multipoint gas sampler and doser	Fan heaters, Weather station, Differential pressure transducers and Temperature sensors

Note: PULSE-60 stands for a pulse unit with a 60 litre air receiver; BD-4 stands for Minneapolis blower door model 4.

To calculate the infiltration rate equation 1 is used for the constant concentration method; where *Q* is the infiltration rate (h^{-1}) *m* is the tracer gas dose (m^3/h), *n* is the number of zones in the building, *Ct* is the concentration target (m^3). For the decay method, the infiltration rate is represented by the slope *a* in the equation of the line (*y=ax+b*), to develop this equation a regression of elapsed time against the natural log of the average concentration is done.

$$Q=\sum^{n}_{1} m/Ct \qquad (1)$$

Correspondingly, several repeated (three as a minimum) Pulse tests were performed every day with the objectives to first, assess the repeatability of the method under various weather conditions. Pulse test doesn't affect the integrity of the building's envelope (Cooper, et al., 2014), that is why the technique was employed while the tracer gas tests were running. The operational disturbance (opening of door and presence of a person) in the test was considered during the air infiltration's calculation. Both Pulse and blower door tests were carried out before and after each constant concentration test with extra pulse tests done in week days during the test. The blower door requires to open a door, therefore it could only be done before and after the tracer gas tests which require to maintain the building's envelope constant.

A bias noticed worth mentioning is that during the blower door tests, the fan heaters were turned off, whereas the Pulse tests were done with fan heaters on. Different weather conditions were captured in the form of wind and temperature conditions in the constant concentration tracer gas test. It provides insight to the impact of weather condition on the measurement of air infiltration rates, which were then compared to air leakage rates measured by PULSE-60 and BD-4.

2.1 Description of the case study

The house used for the experiment is a two-storey detached house located on the University Park campus of the University of Nottingham. The house is located with 6 other houses on top of a hill, it is blocked by a barrier of trees 30 meters away on the south, 5 meters from the house on the east and west there are two other detached houses with a road on the North. **Error! Reference source not found.** shows the location of the house and its neighbouring environment and a view of east façade and north façade (with glazing).

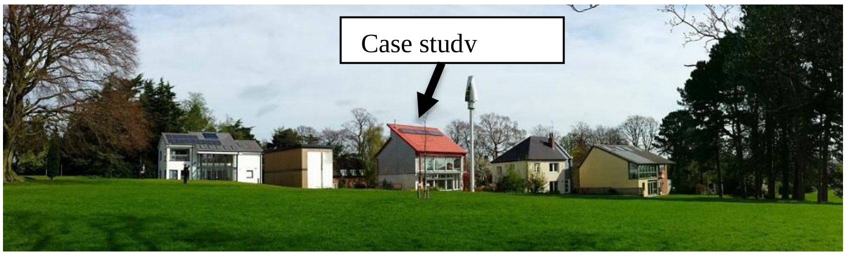

Figure 1: Location of the case study house and perspective view of its South and East facades

The thermal envelope of the house has an approximate area of 290m^2 and approximate 285 m^3 of conditioned space. For the tracer gas tests, 6 zones were defined within the house, each one had a tracer gas dosing tube, a CO_2 measuring tube and a CO_2 sensor, a fan, and heaters to vary the internal temperature of the house. Zones 1, 2, 3 and 4 were on the first floor while zones 5 and 6 were on the ground floor. Figure 2 shows the floorplans of the house and the location of dosers and samplers for the tracer gas analysis.

Figure 2. Floor plans of the case study house and location of equipment setup

Table 2: Description of the tracer gas tests and the heating schedules in the test house

Test	Date	Tracer gas test	Heating conditions	Duration
1	18–23 Jan	Constant Concentration for 110 hours + decay method for 8 hours	Heating from 5 pm to 12 am	5 days
2	23-26 Jan	Constant concentration for 61 hours + decay method 5 hours (7am to 12 pm)	Heating from 5 pm to 12 am	3 days
3	26-29 Jan	Constant concentration from 3 pm to 7 am and decay method from 7 am to 3 pm.	Heating from 5 pm to 12 am	3.5 days
4	29 Jan – 02 Feb	Constant concentration for 80 hours + decay method for 8 hours	Heating from 5 pm to 12 am	4 days
5	02-05 Feb	Constant concentration from 2 am to 6 pm and decay method from 6 pm to 2 am.	Heating from 6 pm to 12.00 am	3 days
6	05-09 Feb	Constant concentration for 86 hours + decay method 7 hours	Constant temperature 23°C	4 days
7	09-12 Feb	Constant concentration from 4 pm to 6 am + decay method from 6 am to 4 pm.	Constant temperature 23°C	3 days
8	12-16 Feb	Constant concentration for 85 hours + decay method 5 hours (7am to 12 pm)	No heating, allowing heat losses	4 days
9	16-19 Feb	Constant concentration from 3 pm to 7 am and decay method from 7 am to 3 pm.	No heating, allowing heat losses	3 days
10	19-22 Feb	Constant concentration from 8 am to 12 am and decay method from 12 am to 8 am.	Heating from 5 pm to 12 am	3 days
11	23-28 Feb	Constant concentration for 131 hours + decay method for 9 hour	Heating from 5 pm to 12 am	6 days
12	28 Feb – 01 Mar	Decay method for 24 hours	Heating from 5 pm to 12 am	1 day

3 RESULTS AND DISCUSSIONS

Permeability given by BD-4 and PULSE-60 under various weather conditions are listed in **Error! Reference source not found.**, in the blower door case, both pressurisation and depressurisation tests were carried out with the result of each and an average of both represented. All tests were carried out according to standard (The British Standards Institution, 2015).

Table 3. Permeability measured by both and relative percentage difference (RPD) against the average

		18-Jan	19-Jan	22-Jan	23-Jan	25-Jan	26-Jan	29-Jan	30-Jan	31-Jan	01-Feb
BD-4 @50 Pa	**Pressurisation**	7.48	N/A	N/A	7.21	N/A	7.45	7.35	N/A	N/A	N/A
	RPD	-2%	N/A	N/A	2%	N/A	-1%	0%	N/A	N/A	N/A
	Depressurisation	7.70	N/A	N/A	7.73	N/A	7.84	7.43	N/A	N/A	N/A
	RPD	-1%	N/A	N/A	-1%	N/A	-3%	3%	N/A	N/A	N/A
	Average	7.59	N/A	N/A	7.47	N/A	7.65	7.39	N/A	N/A	N/A
	RPD	0%	N/A	N/A	0%	N/A	-1%	1%	N/A	N/A	N/A
PULSE-60 @4 Pa		1.54	1.45	1.59	1.56	1.49	1.58	1.58	1.60	1.43	1.53
RPD		5%	-1%	8%	6%	1%	7%	8%	9%	-3%	4%
Maximum wind speed (m/s)		7.50	11.90	7.50	7.50	7.50	4.50	10.45	5.97	7.50	11.9
Average wind speed (m/s)		2.72	3.32	2.32	2.71	2.86	1.00	3.33	2.31	2.84	4.17
Average outdoor temperature (°C)		6.44	4.29	8.27	11.92	8.05	7.59	8.34	7.22	5.25	6.63

		02-Feb	05-Feb	06-Feb	08-Feb	09-Feb	12-Feb	13-Feb	14-Feb	15-Feb	16-Feb
BD-4 @50 Pa	**Pressurisation**	7.30	7.60	N/A	N/A	N/A	N/A	N/A	N/A	N/A	7.04
	RPD	1%	-4%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-2%
	Depressurisation	7.64	7.95	N/A	N/A	N/A	N/A	N/A	N/A	N/A	7.78
	RPD	0%	-4%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-2%
	Average	7.47	7.78	N/A	N/A	N/A	N/A	N/A	N/A	N/A	7.41
	RPD	0%	-2%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0%
PULSE-60 @4 Pa		1.54	1.49	1.38	1.41	1.40	1.43	1.19	1.37	1.42	1.49
RPD		5%	1%	-6%	-4%	-4%	-3%	-19%	-7%	-3%	2%
Maximum wind speed (m/s)		7.50	7.50	2.99	10.45	11.9	10.45	8.95	8.95	13.4	7.50
Average wind speed (m/s)		1.83	2.40	0.45	2.92	4.48	4.48	3.38	3.38	4.49	2.14
Average outdoor temperature (°C)		6.92	3.96	1.63	7.18	6.13	3.84	4.71	4.22	7.46	8.63

		19-Feb	20-Feb	21-Feb	22-Feb	23-Feb	26-Feb	27-Feb	28-Feb	01-Mar
BD-4 @50 Pa	**Pressurisation**	7.60	N/A	N/A	6.91	N/A	N/A	N/A	N/A	7.60
	RPD	-3%	N/A	N/A	4%	N/A	N/A	N/A	N/A	-3%
	Depressurisation	7.72	N/A	N/A	7.32	N/A	N/A	N/A	N/A	7.24
	RPD	-1%	N/A	N/A	4%	N/A	N/A	N/A	N/A	5%
	Average	7.66	N/A	N/A	7.12	N/A	N/A	N/A	N/A	7.42
	RPD	-3%	N/A	N/A	3%	N/A	N/A	N/A	N/A	1%
PULSE-60 @4 Pa		1.51	1.54	1.45	1.33	1.49	1.53	1.42	1.53	1.38
RPD		3%	5%	-1%	-9%	1%	4%	-4%	4%	-6%
Maximum wind speed (m/s)		5.97	11.90	5.97	7.47	8.96	8.96	8.96	7.50	11.9
Average wind speed (m/s)		1.69	3.23	1.52	2.68	2.32	2.78	2.37	2.92	3.83
Average outdoor temperature (°C)		10.38	8.49	7.46	2.83	2.55	0.62	-0.31	-2.86	-3.27

		MEAN	MIN	MAX
BD-4 @50 Pa	**Pressurisation**	7.35	6.91	7.60
	Depressurisation	7.64	7.24	7.95
	Average	7.49	7.12	7.78
PULSE-60 @4 Pa		1.47	1.19	1.60

As shown in Table 3 and Figure 3, the results of blower door tests carried out on different days do not differ from each other significantly. There are a few variations, but they represent a slight change in the weather conditions. Hence, a good repeatability has been demonstrated.

A similar analysis was made to the Pulse tests, the results, as shown in Figure 4 and Table 3, differ more from the average than blower door. However, the pulse results are based on tests that were carried out on more days where the tests were subjected to wider range of weather conditions. Nevertheless, the uncertainty of the pulse tests mostly lies within ±10% which agrees with previous finding (Cooper and Zheng 2016).

To illustrate the environment conditions, Table 3 shows the average wind and outdoor temperature during the Pulse tests. Different conditions were captured and it was seen that high wind speed has relatively bigger impact on the Pulse test at lower pressures. The test results presented in this paper didn't exclude the lower range test. When the lower range measurements were taken out from the analysis, the agreement with the average value improved significantly, which agrees with recent finding (Zheng and Mazzon 2018) and suggests that when high wind condition is present, the lower range measurements should be discarded in pulse test data analysis in order to reduce the wind impact on the pulse test.

The infiltration rates were measured using the tracer gas constant concentration and decay methods. The results from both methods are listed in Table 4.

Table 4. Air infiltration rate of the constant concentration and decay tracer gas tests

		Test	1	2	3		4		5			6	7
		Sub test			3.1	3.2	4.1	4.2	5.1	5.2	5.3		
Infiltration rate (h^{-1})	**Constant Concentration**	**Range**	0.05-0.30	0.19-0.27	0.12-0.26		0.13-0.32		NOT VALID			0.18-0.30	0.19-0.26
		Average	0.24	0.23	0.21		0.25					0.26	0.25
	Decay		N/A	0.18	0.15	0.15	0.18	0.13	0.18	0.18	0.19	0.15	0.15

		Test	8		9			10			11	12
		Sub test	8.1	8.2	9.1	9.2	9.3	10.1	10.2	10.3		
Infiltration rate (h^{-1})	**Constant Concentration**	**Range**	0.14-0.20	0.10-0.27	0.11-0.17	0.09-0.20	0.07-0.25	0.17-0.23	0.21-0.25	022-0.24	0.19-0.29	N/A
		Average	0.17	0.18	0.15	0.14	0.14	0.20	0.22	0.22	0.24	
	Decay		0.16		0.17	0.13	0.10	0.19	0.19	0.20	0.17	0.24

		MEAN	MIN	MAX
Infiltration rate (h^{-1})	**Constant Concentration**	0.21	0.14	0.26
	Decay	0.17	0.10	0.24

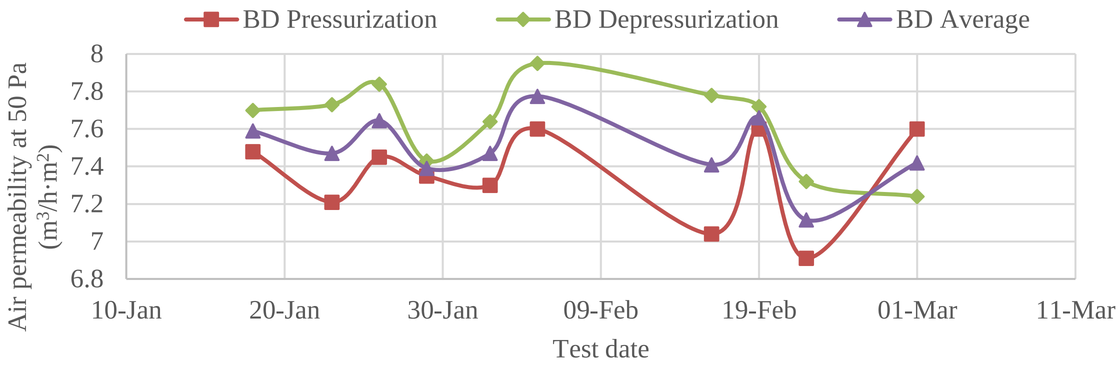

Figure 3. Blower door tests results.

For the tracer gas tests, the main difference from both methods is that the constant concentration gives real time infiltration rate measurements: therefore, during the length of the test i.e. more than one day, an analysis of the infiltration rates variation during time can be made. Alternatively, the decay method declares one value for infiltration rate that is obtained by observing the decay in concentration during a few hours.

Different from the previous techniques the air infiltration rates showed in Table 4 and Table 5 are in ACH (h^{-1}) that is a unit of ventilation, in this case used to identify the non-intended ventilation standardized by building's volume.

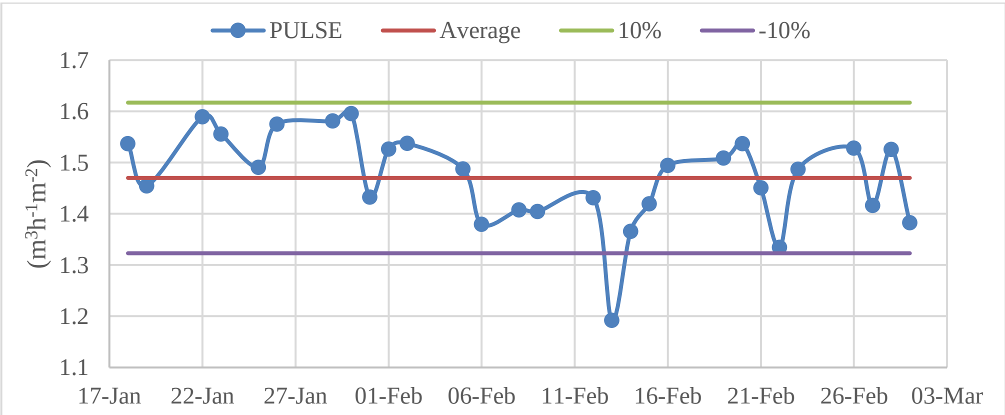

Figure 4. Air permeability at 4 Pa given by PULSE-60

It wasn't expected to obtain similar results for each test, because air infiltration is driven by the changes in pressure difference caused by the environmental conditions. While the tests were performed, outdoor temperatures above 10° and below -5° were captured, likewise, the wind speed captured ranged from 0 to 20 m/s, this means that different results of infiltration rates were expected, i.e. during test 12 cold winds from Siberia were hitting the United Kingdom, and there is when the most extreme results were obtained. From both a) and b) in table 5 it can be seen that the results differ quite a lot from one day to other in both techniques. Nevertheless, **Error! Reference source not found.** depicts a trend: the infiltration rates increased at the end of the testing period, these tests were the ones performed during the most extreme weather conditions.

Table 5. Deviation from average of tracer gas methods: a) Constant concentration average and b) Decay method

a)Infiltration Rate (ACH) Constant Conc.

Test	Sub test	CC Average	Dev from Av.
1		0.24	15%
2		0.23	9%
3	3.1		
	3.2	0.21	3%
4	4.1		
	4.2	0.25	21%
6		0.26	24%
7		0.25	20%
8	8.1	0.17	-17%
	8.2	0.18	-12%
9	9.1	0.15	-29%
	9.2	0.14	-33%
	9.3	0.14	-31%
10	10.1	0.20	-3%
	10.2	0.22	8%
	10.3	0.22	9%
11		0.24	16%

b)Infiltration Rate (ACH) decay method

Test	Sub test	Decay	Dev. From Av.
1		N/A	
2		0.18	6%
3	3.1	0.15	-13%
	3.2	0.15	-12%
4	4.1	0.18	6%
	4.2	0.13	-21%
5	5.1	0.18	10%
	5.2	0.18	9%
	5.3	0.19	10%
6		0.15	-11%
7		0.15	-11%
8	8.1	0.16	-7%
	8.2		
9	9.1	0.17	-1%
	9.2	0.13	-24%
	9.3	0.10	-41%
10	10.1	0.19	16%
	10.2	0.19	14%
	10.3	0.20	22%
11		0.17	4%
12		0.24	45%

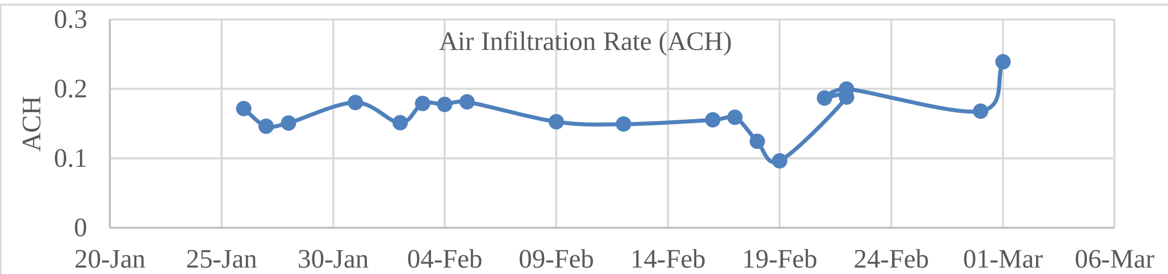

Figure 5. Air infiltration rates from tracer gas decay method.

From these results one might think that even when airtightness is the most important parameter affecting air infiltration, the variation in infiltration rate is high and therefore, one must consider all the weather conditions when trying to predict the infiltration rates.

The parameter needed to calculate the heat losses due to ventilation is the infiltration rate, in the UK, the standard assessment procedure (SAP) uses a leakage-infiltration ratio (Jones, et al., 2016), equation 2, where normally N takes the value of 20. Q_{50} represents the air permeability at 50 Pa given by a blower door test and Q_1 is the infiltration rate in h^{-1}.

$$Q_{50} / Q_1 = N \tag{2}$$

If the results obtained from this study are considered to test the ratio, it is observed that when the blower door average results are used, *N* would take a value between 31 and 50 (excluding extreme results) depending which value is used; if Q_4 average is used instead, *N* would take the values between 8 and 10. Using these ratios is not recommended, however using the blower door results, might lead to a creation of a high level of uncertainty.

If the environmental conditions are not considered, and the analysis is based only in the infiltration results, it can be said by observation that, the results from the PULSE technique hold a closer relationship with the infiltration rates, nevertheless, a statistical study needs to be carried out to support these statements.

4 CONCLUSION

Experimentation during the winter of 2018 was carried out in a house in the UK's East Midlands, to measure the airtightness properties and the air infiltration rates. Two techniques were employed to measure airtightness: the fan pressurisation method and the Pulse technique; likewise, two tracer gas methods including the constant concentration and decay method were used to measure infiltration rates.

Results showed that over the testing period both methods gave a measurement uncertainty within ±10% with the blower door demonstrating a smaller uncertainty (in the range of ±6% from the average) than the pulse. However, it needs to be noted that the pulse tests were undertaken in a bigger number of days where wider range of weather conditions were present. That could contribute to the difference. It was also noticed that the pulse test in lower pressure was more affected by high wind condition. When the lower range measurement was taken out from the pulse test analysis, a better agreement with the average value was observed. That finding provides some guideline on data analysis when a pulse test has to be carried out under high wind conditions.

Using the infiltration results, both tracer gas test showed the variability of the infiltration rate and its dependence to the environmental conditions. The Pulse technique showed higher potential (than the blower door) to predict infiltration rate, however, further statistical analysis is needed to support this statement, and to develop a correlation. Finally, development of studies including the environmental and shielding conditions must be made to compare the accuracy of both techniques when predicting air infiltration and therefore heat losses. The existence of a correlation needs to be investigated in a range of properties.

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