Experimental Investigation of the Impact of Environmental Conditions on the Measurement of Building Infiltration, and its correlation with Airtightness

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ABSTRACT

The air infiltration of a building, which fundamentally depends on its airtightness, can be a significant contributor to its heat loss. It can also be affected by other factors such as external terrain, leakage distribution, sheltering factor and environmental conditions. The infiltration rate of a detached UK house was monitored for 2 months in early 2018 using constant concentration and decay tracer gas methods under various temperature and wind conditions. Different temperature differences across the building envelope were achieved by heating up the indoor air with the assistance of fan heaters. Various wind conditions were covered by carrying out tracer gas tests continuously over a few days during which different wind conditions were captured. The external pressure distribution on each side of the building envelope was also monitored using differential pressure transducers. The impact of the wind on the external pressure distribution was investigated in order to understand how the building pressures across the envelope of the test house is affected by different wind conditions. Hence, better understanding on how the wind physically affects the infiltration can be gained. Initial results agree with previous findings that both wind and stack effects are two dominant environmental factors that affect the infiltration rate. Differential pressure measurements confirmed the relevance of wind speed and direction.

KEYWORDS

Air infiltration, Airtightness, PULSE, Wind, Buoyancy

1 INTRODUCTION

Air infiltration in buildings is a significant contributor to ventilation heat losses (Etheridge , 2015; Sherman, 1983; Energy Saving Trust;, 2006); it accounts for up to one third of all the heat losses. It is fundamentally determined by building airtightness, which can be quantified in a variety of ways, but usually falls under the label of air leakage. Infiltration can also be affected by other factors such as external terrain, leakage distribution, sheltering factor (Walker & Wilson, 1990) and environmental conditions. Among the environmental conditions, wind and buoyancy effects are the most predominant ones (Kraniotis, et al., 2014; Kraniotis, 2014) that impact the building infiltration by changing the pressure profile in the proximity of building envelope.

While a number of studies (Walker & Wilson, 1990; Kraniotis, 2014; Kraniotis, et al., 2014; Sherman, 1983) have been undertaken to investigate the impact of terrain, shielding factor or environmental conditions on infiltration rate, few of them have experimentally investigated how environmental conditions affect the infiltration rate from the perspective of incurred pressure distribution. Hence, the monitoring of pressure difference across the building envelope on different sides could provide a different insight to how wind and buoyancy effects, the dominant environmental factors, impact the infiltration rate.

On the other hand, there are many studies and models correlating the airtightness level of a building with its air infiltration rate and the environmental conditions (Sherman, 1980; Walker & Wilson, 1990; Liddament & Allen, 1983; Orme & Leksmono, 2005; Jones, et al., 2013; Lowe, 2000), nevertheless, they follow similar assumptions and metrics, such as the usage of a power law (Walker, et al., 1997) and the steady pressurization method such as blower door (The Air Tightness Testing & Measurements Association;, 2016) to measure the airtightness level of a building to predict the infiltration rate. It provides a quicker and less disruptive method for estimating building infiltration rate so that the energy loss caused by building infiltration can be calculated. However, the blower door measures the building leakage in a range of pressures that are higher than the pressure level that buildings are subject to under natural conditions. Hence, errors, either caused by extrapolation or building valving effect could be translated into the infiltration rate.

In order to mitigate this issue, the pulse technique, a method for measuring building airtightness at low pressures, was developed (Cooper & Etheridge, 2007; Cooper, et al., 2014; Cooper, et al., 2015). It is implemented by rapidly releasing a known volume of air from a compressed air tank into the test building, thereby creating an instantaneous pressure rise that quickly reaches ‘quasi-steady’ conditions. The pressure variations in the building and tank are monitored and used for establishing a correlation between leakage and pressure. The building air leakage result is quoted at low pressure, i.e. 4 Pa which is regarded as a typical weather-induced pressure level (Sherman 2004, Cooper 2007). However, no correlation between the pulse test result and building infiltration rate has been established to allow a quick estimation of building infiltration when a pulse test is carried out to a building.

To provide initial insight to the correlation between the airtightness the pulse technique and building infiltration, the pulse and tracer gas methods were used to measure the airtightness and infiltration rate of a detached UK home over a range of days where various environment conditions were obtained under natural conditions or with the assistance of fan heaters. Blower door method was also used alongside to measure the airtightness of the same building to provide an insight on how current standard test result stands in this correlation. The pressure differences across the building envelope on four different sides were also monitored to allow us to understand how the wind conditions fundamentally affects the building infiltration.

2 METHODOLOGY

2.1 Equipment

The measurement of air infiltration is made using tracer gas means (Sherman , 1998; British Standards Distribution;, 2017; American Society for Testing and Materials, 2011) in two different ways: constant concentration method and decay method. The constant concentration method is seen to be the most accurate one among three tracer gas methods for measuring air infiltration (Sherman, 1989)., however its operation requires high spec equipment and the test itself is time consuming to implement. In order to have a different and punctual air infiltration result, the tracer gas decay method, which cheaper and quicker to use, was also employed to compare with the constant concentration results in order to assess the feasibility of using this method in further field trials.

The equipment used is described in Table 1, an INNOVA 1412i gas analyser and a LumaSense 1303 multi point gas sampler and doser were employed in the house that was tested using both tracer gas methods. The selected gas to be traced was carbon dioxide (CO_2); six carbon dioxide sensors (TinyTag) were also allocated in the test house. The methods to calculate the infiltration rate were obtained from (British Standards Distribution;, 2017) and (American Society for Testing and Materials, 2011); the tracer decay test was analysed to give the infiltration rate using the average and the regression method.

Table 1. Equipment utilised in the experimental study

Equipment		
Airtightness	PULSE	
Tracer Gas	Gas	Carbon Dioxide
	Gas measuring	INNOVA 1412i gas analyser
		TinyTag CO_2 logger
	Gas sampling/dosing	LumaSense 1303 multipoint gas sampler and doser
Other	Fan heaters	
	Wind Speed low inertia cup and wind vane WSD1	
	+/-20 Pa Differential pressure transducers FCO-44	
	Temperature sensors PT100 RTD	

Four differential pressure transducers (FCO-44, ±20 Pa) were used to monitor the pressure difference across the building envelope, all of them were connected to the same pressure reference which was located on the ground floor, and the pressure points to measure were placed in every façade of the building. A fifth differential pressure transducer was used to monitor the internal pressure difference between approximate building height level and ground level.

2.2 Test house and setup

The building under test is three bed detached house built with innovative construction materials, which is part of the Creative Energy Homes in the University of Nottingham. The main façade is facing south to an open green space with a number of trees 30 meters away; the other three sides of the house have a regular suburban neighbouring area. This house might not represent a regular house in the building stock of the UK, however it provides a useful test dwelling for comparing airtightness and air infiltration. Figure 1 shows the test house and some measuring devices.

a) b) c)

Figure 1. a) Test house; b) pressure measuring devices, five differential pressure transducer; c) tracer gas measuring equipment

The location of the tracer gas equipment can be seen in Figure 2, the cylinder is secured in corner on the ground floor, next to the gas analyser and multiplexer. The house, as seen, was divided into 6 different thermal zones: the first three zones cover 3 bedrooms on the top floor; the fourth zone is the corridor and the bathroom on the top floor; zones five and six represent the living room and kitchen on the ground floor respectively. Zone three was noted to be leakier than the others due to a poor fit window rail. In every zone, a floor fan was installed to provide to mix the carbon dioxide supplied and achieve a uniform concentration; the fans were left on during the length of the tests.

Pressure tappings were placed on every side of the building, and connected to the same reference, represented in Figure 2 depending on the façade, the letter in the circle stands for the cardinal point where the device is placed. The indoor pressure reference for the differential pressure transducer was placed in the middle of zone 5. The weather station used to verify wind speed and direction was located few meters away from the house at the test house's roof ridge height. The internal temperature was measured using resistance temperature detectors (PT100 RTD) located in each thermal zone and outside the test house. The pulse unit was allocated between zones five and six, and was left in the same place for the whole duration of all experimentation. There were also several fan heaters located across the enclosure to achieve the desired temperature conditions.

Figure 2. Floor plans of the test house and location of testing devices, left: ground floor; right: first floor.

2.3 Testing arrangement

Fan heaters were used to provide various indoor temperatures to see how the infiltration is influenced by the stack effect. Table 2 shows the different heating scenarios which were obtained using automated fan heaters and temperature sensors. When heating was used, with no set point temperature i.e. not a constant temperature, a set heating power input was used. Therefore there was an increasing temperature difference between internal and external environments throughout the heating period. A number of tracer gas tests including constant concentration and decay were performed over a period of over two months' time, the details are listed in Table 2.

Table 2. Description of the tracer gas tests and the heating conditions of the test building.

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

During the tracer gas test, both pulse and blower door tests were also performed in order to provide a marking measurement of the building airtightness over the whole duration of tracer gas test. Both tests were carried out before and after each set of tracer gas test. Pressure difference across the building envelope was measured at a sampling rate of one second over the whole testing duration.

3 RESULTS AND DISCUSSION

3.1 Impact of wind and buoyancy on air infiltration

Figure 3 shows how the building infiltration rate varied with the wind in a day when strong wind (mostly above 6m/s) was present. It shows that the air infiltration rate variation follows the trend of average wind speed, suggesting the dominant impact of wind on the air infiltration rate.

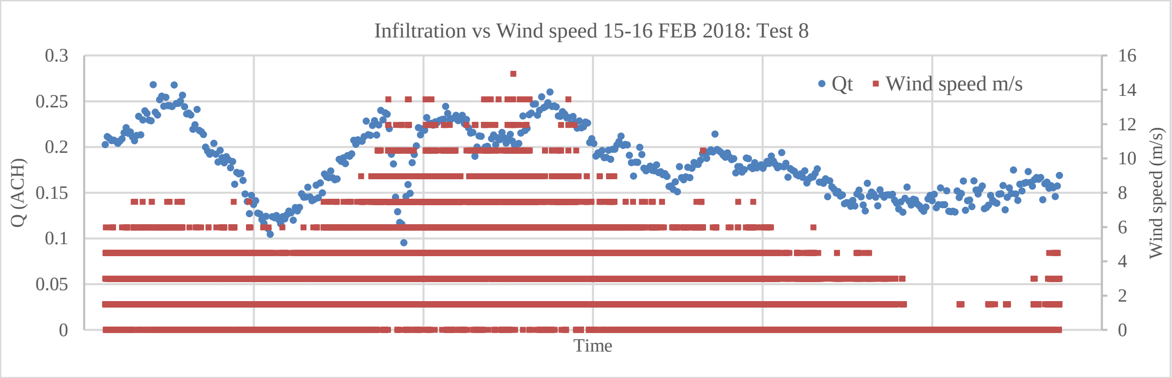

Figure 3. Infiltration rates (ACH) against Wind speed (m/s), example of a graph witch high wind speeds, taken from the results in test 8, from the 15th to the 16th of February 2018.

Figure 4 shows the variations of measured infiltration rate over a day when the wind speed was mostly below 2.5 m/s. The temperature difference started increasing at 15:00 (heating on) and started decaying at 00:00 (i.e. heating off), with the temperature difference reaching above 20 K. It shows that the infiltration rate followed the same trend with achieved temperature difference across the building envelope.

Hence, the findings suggested that both wind and temperature difference can define a trend of the infiltration. It agrees with previous studies (Lyberg, 1997; Sherman, 1980), which proved infiltration rate was mostly influenced by wind speed and temperature difference. However, most authors suggest that wind is the main driving force (Kraniotis, 2014). The results in this study showed that when temperature differences across the building envelope is high enough (achieved temperature difference was higher than 23K) when the wind is below 2.5 m/s, the infiltration rate is dominated by the temperature difference. These findings are consistent with Liddament (Liddament, 1986).

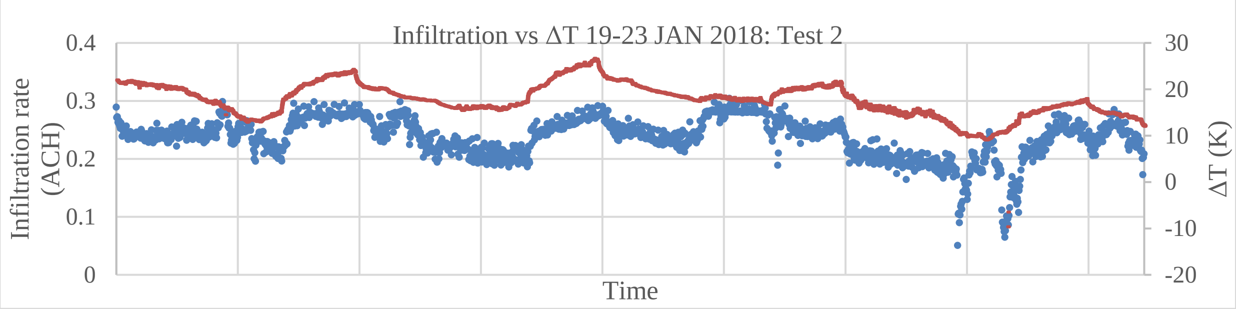

Figure 4. Infiltration rates (ACH) against temperature difference (K), example of a graph when wind speed is low, taken from the results in test 2, from the 19th to the 23rd of January 2018.

To better understand how the temperature difference affects the infiltration rates further studies should be carried out to measure the infiltration rate in a controlled environment when the wind speed is a controllable.

3.2 Impact of wind on the building pressure profile

The pressure distribution across the building envelope under various wind conditions is a key factor to understanding how the infiltration rate is affected by outdoor wind. During the tests two main wind directions were observed: northeast wind and east wind. Considering the pressure difference at every façade was recorded every second and the constant concentration test was reported every 3-4 minutes, an 11-minute time window was selected to gain some insight into the overall wind effect on the building pressure distribution and infiltration. During this time the wind was mainly varying from 3 to 10 m/s. The pressure difference across the east façade of the test house is illustrated in Figure 5 together with the wind speed. Noticeably, when the wind speed peaks, the pressure difference does so, but there is a few seconds delay between the two. It could have been caused by the fact that the weather station is located 10 meters away in the upstream from the east façade of the test house. Furthermore, the time delay observed in the east façade was also observed in the west façade, the main differences were that in the west façade the pressure difference peaks were negative and it occurred 2 seconds (approximately) after the east façade. The south and north facades also showed a similar behaviour regarding the effect of strong winds.

Several graphs similar to figure 5 were plotted and consistent results were obtained: wind gusts are captured as extreme pressure differences depending on the side of the building exposed to the direction of wind gusts. There is an immediate (in the range of 1 to 5 seconds) reaction from the pressure changes due to the impact of the wind. A wider data set was studied to relate that pressure change to the infiltration rate and the main finding was that the pressure change reflected in infiltration is not as immediate as expected: it might take minutes to see the change. This is only an empirical conclusion and has to be backed with more similar studies. A similar analysis as the previous one was carried out to analyse the buoyancy effect. The main conclusion is that there is no immediate effect in changes in pressure difference due to the buoyancy effect. A way of investigating the effect of buoyancy in pressure is to control the wind variable, because it proves an immediate change in the pressure and a change which evolves over a longer time duration is difficult to analyse.

Another finding of this study is that the pressure distribution across every façade over the same period of time as figure 5. Two conclusions can easily be drawn (Figure 6): the pressure distributions seem to follow a normal distribution and; the majority of the pressure difference occurs in the range of 0 to 5 Pa. Figure 6 shows the results only for a short period of time (eleven minutes), when gusty wind was present.

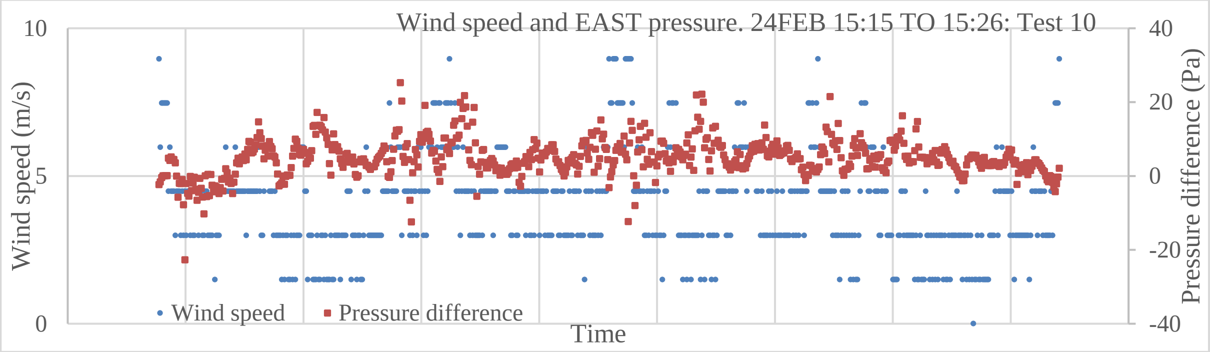

Figure 5. Pressure difference again wind speed from the EAST façade of the test house during 11 minutes when high wind gusts were occurring, on the 24th of February.

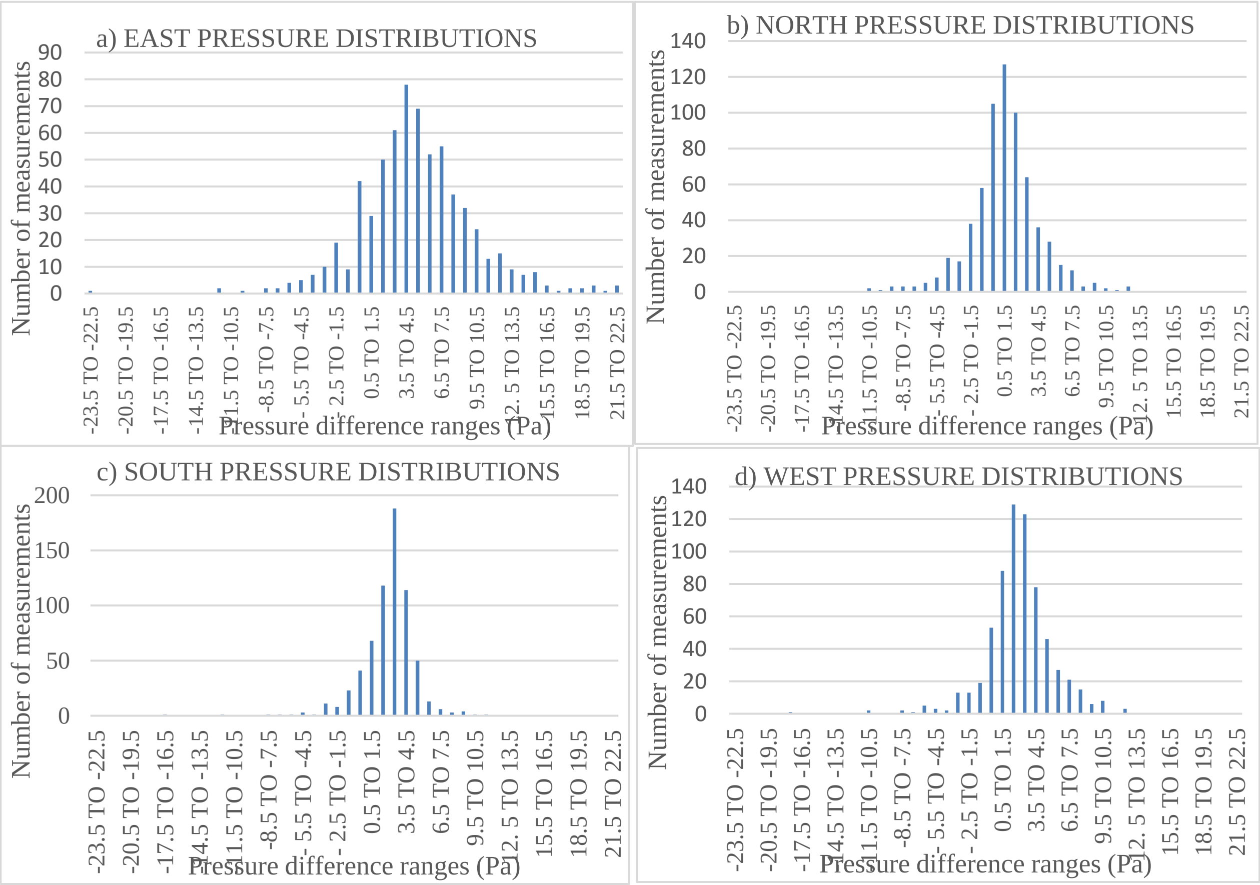

Figure 6. Pressure distributions in the windward facades a) and b), and the leeward facades c) and d), of the test building for eleven minutes on the 24th of February

A similar study was carried out for a data set of pressure differences taken every second over five days (23rd to 28th of February). During this period different wind and temperature conditions were measured. From this period of time, in two of the facades (East and South) the dominating pressure difference was between 3.5 to 4.5 Pa, the North and West facades have dominating pressures from 1.5 to 2.5 Pa and 2.5 to 3.5 Pa respectively. An example of one of the results for one of the facades studied is observed in Figure 7.

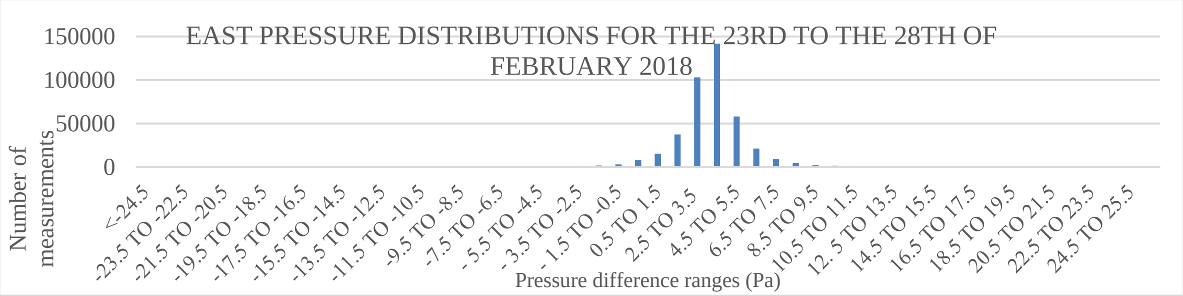

Figure 7. Pressure difference repetitions for the 23rd to the 28th of February 2018 in the test house.

The results in this case study showed the building pressure difference incurred under natural conditions mostly lied in a range from 1.5 to 4.5 Pa. This agrees with what Cooper (Cooper & Etheridge, 2007) found, and hence measuring air leakage at lower pressures should be more representative and infiltration rates obtained from airtightness measured directly at low pressures should be more reliable.

3.3 Airtightness measurements against air infiltration rates

Table 3 below shows a summary of the results of the infiltration rates measured with two different tracer gas methods: the constant concentration method and the decay method. For the constant concentration method table 3 describes the minimum, maximum and average value of infiltration rate obtained from each test. The equipment took 3 minutes 32 seconds to sample and dose in every zone of the building, which means that one whole building infiltration rate was calculated for this period of time, i.e. in 10minutes 36 seconds, three different infiltration rates were calculated . This method was used to provide the building infiltration rate under various environmental conditions.

The results from the decay method (h^{-1}) were obtained from two different pieces of equipment; the innova gas analyser and separately “tinytag” CO_2 sensors. The infiltration rates were calculated using the average and regression methods from the standard (American Society for Testing and Materials, 2011). The airtightness of the building was measured using the PULSE technique. The last column of Table 3 lists the average airtightness result in air changes per hour (h^{-1}), for every test, quoted at 4 Pa.

If the results from tracer gas decay tests are averaged, a result that can be directly compared with the airtightness results quoted at 4 Pa is obtained. It is important to mention before making any comparison that the decay method delivers an average value of infiltration rate during certain period of time, however, its accuracy has been proven.

The method for obtaining an airtightness result was to perform several different PULSE tests every day. The value quoted in table 3 is the average of three valid tests in the case study building. The main problem found with the method was that some of the tests were invalid, therefore those test had to be discarded. The validity of the result is confirmed by a number of factors including the pulse pressure shape obtained and pressure range covered. The testing has shown that good daily repeatability has been achieved with the pulse results (±10%) providing confidence in the validity of those tests performed.

If one compares the infiltration rate values and the airtightness results within table 3 a certain proportional ratio within a small range becomes apparent. It is not ordinarily recommended to use leakage-infiltration ratios, however in this study a simple correlation can be seen, which is valid for this house only. The box and whisker plots from figure 8 show; a) that 75% of the results of the PULSE range between 1.45 and 1.568 ACH at 4Pa; and b) the infiltration rates are between 0.151 and 0.181, which corresponds to roughly one tenth of the airtightness. It is too soon to conclude that a correlation exists, however it is important to continue this type of tests for different buildings to test that hypothesis.

Table 3. Infiltration Rates obtained with two tracer gas methods in ACH, and airtightness level in ACH using the PULSE technique quoted at 4 Pa.

		Infiltration Rate (h^{-1})						
		Constant Concentration		**Decay method**				
				Analyser		**CO2 Sensors**		**PULSE (h^{-1})**
Test	Sub test	Range	Average	Average	Regression	Average	Regression	
1		0.05-0.304	0.236788					1.563012
2		0.186-0.274	0.225715	0.1794	0.178	0.1702	0.1583	1.581951
3	3.1			0.1527	0.1455	0.142	0.1439	
	3.2	0.122-0.26	0.213518	0.1506	0.1478	0.1562	0.1491	1.604865
4	4.1			0.1642	0.1775	0.1803	0.2	
	4.2	0.126-0.321	0.250261	0.1367	0.1322	0.1687	0.1665	1.564172
5	5.1	NOT VALID		0.1819	0.1835	0.1735	0.1764	
	5.2			0.1815	0.1829	0.1714	0.1751	
	5.3			0.1844	0.185	0.1768	0.1785	1.545928
6		0.18-0.298	0.256791	0.1504	0.1499	0.1562	0.1545	1.442151
7		0.188-0.262	0.246959	0.1548	0.1492	0.1503	0.1424	1.448636
8	8.1	0.136-0.204	0.17229					
	8.2	0.095-0.268	0.182168	0.1616	0.1551	0.1525	0.1521	1.415609
9	9.1	0.112-0.171	0.146068	0.1619	0.1653	0.1535	0.156	
	9.2	0.089-0.195	0.138139	0.1311	0.1269	0.1221	0.1176	
	9.3	0.073-0.249	0.143226	0.0978	0.099	0.0935	0.0946	1.529767
10	10.1	0.173-0.226	0.19947	0.189	0.1935	0.1819	0.1877	
	10.2	0.21-0.245	0.223794	0.1847	0.1913	0.1833	0.1873	
	10.3	0.215-0.24	0.224196	0.1985	0.2042	0.1959	0.2012	1.488186
11		0.194-0.288	0.239945	0.1745	0.1737	0.1642	0.1597	1.468089
12		N/A		0.244	0.2426	0.2348	0.2343	N/A

4 CONCLUSION

Several studies were carried out during the months of January and February 2018 in a detached house in Nottingham, United Kingdom. The experiments included measurements of air infiltration rates using tracer gas means; airtightness measurements using the PULSE technique; pressure difference measurements every second in every façade of the building and; constant monitoring of environmental conditions.

The investigation has shown that that there seems to be a close relationship between the changing infiltration rates and the airtightness level (@4Pa) of the house, (typically infiltration at around 1/10th of measured air leakage). It was also observed that a relative repeatability was achieved for both parameters even when different weather conditions were captured during the experimentation period. Further studies on this regard have to be carried out in order to find a potential correlation between those parameters.

Air infiltration is seen to be dependent upon both, wind and temperature difference; however, temperature difference can define, at least, a base level of infiltration rate and it can be the most important parameter when the wind velocities are low, consistent with previous studies.

The infiltration rate follows a similar trend to the one given by the temperature differences reflected in the infiltration results around thirty minutes later.

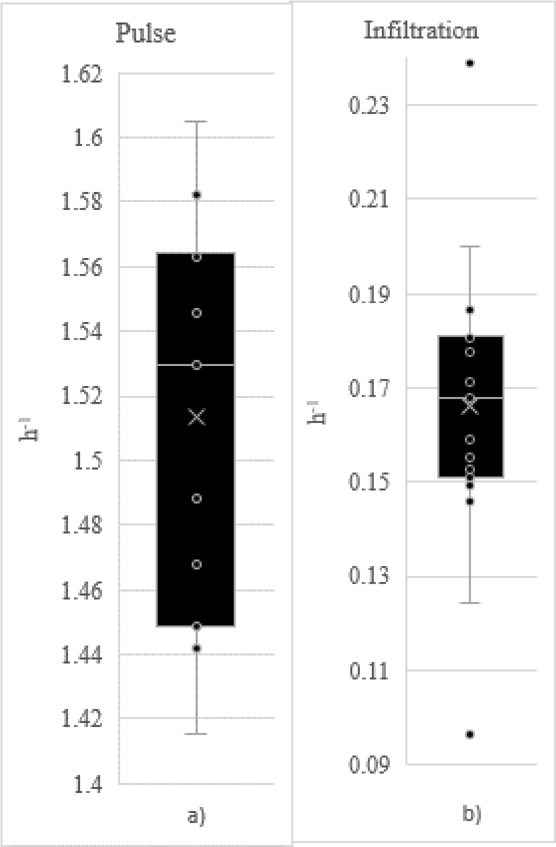

Figure 8. Box and whisker plot from a) PULSE technique results and b) Infiltration rates obtained using the tracer gas decay method

Results from pressure tappings sat around the facades of the dwelling were shown to record an immediate change when high wind gusts were imposed upon the envelope of the building. In the short term this change was only observable for wind but not for temperature difference, however it is difficult to analyse the impact of these on infiltration, in short time frames. Nonetheless, the study suggest that the use of pressure tappings is a useful method of observing the infiltration phenomena when the external parameters are controlled.

Finally, it could be seen that air movement through the fabric due to infiltration tends to exist when the pressure differential across the building envelope is in the range of 1.5 to 4.5 Pa. This may suggest the appropriateness of testing building air tightness at low pressures, such as with the pulse technique.

5 ACKNOWLEDGEMENTS

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