Insights into the impact of wind on the Pulse airtightness test in a UK dwelling

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ABSTRACT

Requirements for measuring the building airtightness have been proposed and included by many countries for national regulations or energy-efficient programs to address the negative effect of poor airtightness on building energy performance, durability and indoor environment. The methods for measuring building airtightness have continuously improved and evolved over a number of years. At present, the well-established and widely accepted method for quantifying the building airtightness is the fan pressurisation method (blower door being the most well-known), which can be implemented by pressurising the test building to a range of high pressures (usually in steps across 10–60 Pa range) and measuring the corresponding fan flow rate. As an alternative method, the Pulse technique can be utilised to measure building airtightness at low pressures (typically at 4Pa) by rapidly releasing a 1.5-second pulse of air from a pressurised vessel. It is known that the outdoor weather condition and in particular wind velocity can significantly influence building airtightness measurement. For example, ISO 9972 suggests a meteorological wind speed limit of 6m/s and 3m/s at ground level for the fan pressurisation test. However, limited studies have been conducted to evaluate the performance of the Pulse technique under windy conditions. In this study, a series of tests were carried out to measure the building airtightness of a five-bedroom house located at the University of Nottingham, UK using the Pulse technique under various wind conditions. A Pulse unit with a 58.5-litre air tank was employed to measure the building airtightness while an ultrasonic anemometer, located 12 metres away from the building perimeter, was used to obtain the outdoor wind speed at the height of 2.2 metres above ground level. Tests were conducted in March 2019 in a range of wind speed up to 10m/s. Experimental results demonstrate the viability of the Pulse technique for delivering airtightness measurements under certain wind conditions, although analysis has also identified conditions where the test result becomes invalid. This study provides insight into those conditions, which adversely affect the result produced by the Pulse technique and discusses possible areas of improvement to the measurement and calculation process to mitigate such effects. Based on the 423 Pulse tests undertaken, it is recommended that the Pulse tests should be performed when the wind speed is lower than 5m/s (with relative percentage difference of ±10%) in calm conditions and 7.4m/s (with relative percentage difference of ±20%) in windy conditions at the height of 2.2 metres above ground level to minimise the wind impact. If tests are to be carried out when the wind speed is above this limit, multiple Pulse tests should be carried out in order to reduce the wind impact on building airtightness measurement.

KEYWORDS

Building airtightness, Pulse technique, Wind speed, Ultrasonic anemometer, Wind impact

1 INTRODUCTION

Building airtightness is defined as the resistance to inward or outward air leakage through unintentional leakage cracks or gaps in the building envelope, which indicates how well the building envelope is sealed (Guyot et al., 2010). Airtightness of the building envelope needs to be measured because visual observations are difficult to detect gaps and cracks that already exist in building envelope. In addition, leakage paths into the building envelope may be tortuous, and gaps are commonly obscured by internal architectural facings or external cladding (Vinha et al., 2015). Generally, the building airtightness is measured by a pressurization test using a large calibrated fan to create a pressure difference between the inside of the building and the outside; *alias* fan pressurisation test. The most common reference pressure used in this test is 50Pa, though other reference pressures such as 1Pa, 10Pa, 25Pa and 75Pa (Sherman and Chan, 2006), are also used in a number of territories. An alternative to the fan pressurisation test is the novel Pulse technique, which measures the airtightness of a building at a low pressure differential; typically 4Pa. The Pulse method measures the building air leakage by rapidly releasing a 1.5 second pulse of air from a pressurised vessel. This known volume of air release creates an instantaneous pressure rise in the building that quickly reaches a “quasi-steady” condition (Cooper et al., 2007); whereby, with the appropriate analysis the air leakage rate of the building can be deduced.

In recent years, the uncertainty of building airtightness measurement has become an important concern (Cooper and Etheridge, 2007). Based on the review of the literature (Sherman and Palmiter, 1995, Andrews, 1997, Geissler, 1999, Kraniotis et al., 2013, Kraniotis et al., 2014, Leprince et al., 2017, Leprince and Carrié, 2018, Zheng et al., 2019b, Zheng et al., 2019a), the main sources of uncertainty for the airtightness testing include: building preparation for testing, tester behaviour, uncertainties of repeatability and reproducibility, measurement error, uncertainties of measurement instrument, weather effect, thermal draft impact, seasonal variation of building airtightness, leaks with different flow exponents and linear regression. For example, the pressure difference between the building indoor and the outdoor environment could be influenced by the indefinite nature of the wind and buoyancy effect, which would lead to an imprecise measurement of the building airtightness. The impact of outdoor weather condition on building airtightness measurement has been noted from both numerical and experimental work. To address it, requirements on the testing weather condition have been set in the standards for the fan pressurisation method. Table 1 lists the meteorological requirements for performing the fan pressurisation test set out in for the standards of EN13829, ASTM 779-03 and ISO 9972 (EN, 2000, ASTM, 2004, ISO, 2015).

Table 1: EN13829, ASTM 779-03 and ISO 9972 requirements regarding the testing weather condition

	Wind speed	**Temperature**	**Zero-flow pressure**
ISO 9972	Wind speed near the ground ≤ 3m/s; meteorological wind speed ≤ 6m/s or ≤ 3 on the Beaufort scale	Large indoor-outdoor temperature difference shall be avoided. The product of the indoor/outdoor air temperature difference by the height of the building ≤ 250m.K	30-second averages, before and after a test. The test is not valid if one zero low-pressure average (in absolute) ≥ 5Pa

EN13829	The wind speed must be Beaufort scale 3 or less. If measured, should be 6m/s or less	The product of the absolute value of the indoor/outdoor air temperature difference (ΔT) multiplied by the building height must be lower than 500m.K (226.85m°C)	30-second averages, before and after a test must be less than 5Pa
ASTM E779-03	Wind speed of 0 to 2 m/s (0 to 4 mph)	Outside temperature: 5-35°C or 41-95°F. The product of the absolute value of the indoor/outdoor air temperature difference (ΔT) by the height of the building shall be ≤ 200m°C	10-second averages, before and after flow measurements to within ±10% of the measured inside/outside pressure difference

The wind pressures are dependent on the wind characteristics, such as the velocity and direction, the shape of the building envelope and the topography of building location and surrounding environment (Kraniotis, 2014). Consequently, measurements are commonly recommended to be performed in low and steady wind speed. Based on ISO 9972 standard, the overall uncertainty of a blower door test can be estimated using error propagation calculation, which is lower than 10% in calm conditions and ±20% in windy conditions (ISO, 2015). The influence of the weather condition leads to specific recommendations for the wind velocity. For instance, Nevander (1978) established static wind loads and simplified load distribution models and suggested a lower outdoor wind speed limit of 5m/s for building airtightness measurement. It has also been noted that a proper definition of wind speed is hard to find in the existing literature. Typically, there are two different definitions of wind speed, namely the meteorological wind speed, which represents wind speed at 10m above the ground and the local wind speed representing the wind speed at the height of the building. Besides, ISO 9972 provides another wind speed reference, which is the wind speed near the ground. Owing to the different wind speed references, confusion may occur, and significant differences can be noticed for measuring or calculating wind speed as researchers employed different definitions of wind speed for investigating the wind effects on building airtightness measurement. For instance, in the numerical study conducted by Bailly et al. (2012), the wind speed at the height of the wall was defined depending on the wind speed at 10m. Based on their simulation results, they claimed that the measurement of building airtightness could be valid when wind speed is lower than 8m/s, which has not been well stated in ISO 9972 standard. On the other hand, Walker et al. (2013) directly adopted wind speed and direction taken from meteorological towers at the test site. Another concern is that the wind speed is usually measured only when the testing starts and after completion, while the variation in wind speed during testing is ignored. Due to the dynamic characteristics of wind, wind condition may vary during the testing period, which could affect the measurement of building airtightness.

Most of the investigations addressing wind impact on building airtightness measurement have been conducted for fan pressurisation testing, while limited studies related to the test performance of the Pulse technique under different wind conditions have been found in the literature. It was reported by Cooper et al. (2016) that seasonal changes in the environmental conditions produced testing repeatability of ±8% in repeated tests to a detached house over a year time. On the other hand, Zheng et al. (2018) conducted a repeatability assessment to the Pulse testing by using a multi-gear portable trailer fan to provide various artificially imposed steady wind conditions. They found that a small uncertainty (within ±3%) was obtained when the wind speed was below 3.5m/s. However, the uncertainty increased up to ±25.6% as the wind speed was in the range of 4.5-9m/s. Furthermore, currently, no relevant standards or regulations concerning wind condition for the Pulse test are in place. In this study, a large number of the Pulse tests were implemented for measuring building airtightness of a five-bedroom detached house located at the University of Nottingham, UK under wind speeds up to 8.5m/s. Experimental work was conducted in 7 days for 423 Pulse tests in March 2019. Tests were accomplished in a short period in order to minimise the impact of variable ambient conditions. The viability of the Pulse technique for delivering airtightness measurements under different wind conditions was evaluated.

2 EQUIPMENT

In order to conduct experimental work in this study, several devices were used. The main device for building airtightness measurement is a PULSE-60 unit, which includes a 58.5-litre lightweight aluminium tank and oil-free compact air compressor. A ¾ inch (BSP) solenoid valve is installed at the outlet for releasing the compressed air from the air tank into the test building, which is capable of delivering a 1.5-second pressure rise. A photo of the Pulse unit is shown in Figure 1. The Pulse test data are recorded and analysed by the control box, including test room temperature, chamber and tank pressures, with the results displayed on a LCD screen. An ultrasonic anemometer was used to measure the outdoor wind speed (Figure 2), which adopts the time of flight method of air velocity measurement. The anemomter includes four ultrasonic transducers that are arranged as two pairs at right angles to each other, and each pair measures the component of the wind in the direction between the transducers. The accuracy of the anemometer is ±2% at 12m/s for speed and ±3° at 12m/s for direction. Besides, Datataker DT85 was employed for data acquisition.

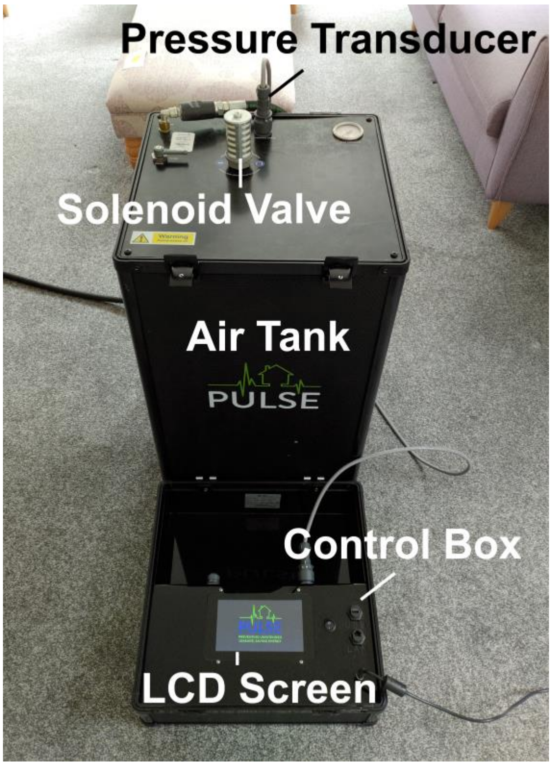

Figure 1: PULSE-60 unit

Figure 2: Ultrasonic anemometer

3 DWELLING AND SETUP

The test building is a five-bedroom detached house located in the Department of Architecture and Built Environment, University Park, Nottingham, UK. The front and back views of the dwelling are presented in Figure 3 and Figure 4. As seen from the floor plans in Figure 5 and Figure 6, the house has one bedroom, one living room, one kitchen on the ground floor and four bedrooms on the first floor. The building parameters are listed in Table 2 and the measurement and calculation of envelope area and volume of the test dwelling complied with ISO 9972.

Figure 3: Front view of test building

Figure 4: Back view of test building

Figure 5: Ground floor plan of test building

Figure 6: First floor plan of test building

Table 2: Envelope area and volume of the test dwelling

Dwelling	Wortley 5 - University of Nottingham, University Park, Nottingham
Volume (m^3)	447
Envelope area (m^2)	416
Approximate ACH @50Pa	3.71 (Blower door tested on December 2018)
Approximate ACH @4Pa	0.73 (PULSE-60 tested on December 2018)

4 RESULTS AND ANALYSIS

The evaluation was conducted based on 423 Pulse tests under different wind conditions; simultaneously, the outdoor wind condition was measured by an anemometer. The anemometer was installed at the height of 2.2m above the ground in the backyard and a distance of 12m away from the perimeter of the test building, without any obstructions within a radius of 12m. In total, 423 Pulse tests were implemented under a variety of wind speed. Figure 7 shows the test results of building air leakage rate (ALR) in the wind speed range of 0-3.5m/s, which includes a total of 133 Pulse tests. Based on the three Pulse tests at low wind speed condition which within 0.5m/s, the average ALR is 288.02m³/h. Therefore, the relative percentage difference is used to indicate the wind impact on building airtightness measurement, which is calculated by comparing the ALR of each single test with the average ALR of 3 Pulse tests at low wind speed condition. Also, Figure 7 presents the relative percentage difference of the 133 tests under the wind speed ranging from 0 to 3.5m/s. Compared to the average of low wind speed ALR, similar results of ALR were obtained when wind speeds were below 2.08m/s, with the highest relative percentage difference within ±3%. Also, it can be noted the relative percentage difference rises above ±5% when the outdoor wind speed higher than 3.14m/s, which indicate that more accurate building airtightness measurement could be achieved for the Pulse test under wind speed around 3m/s with less significant wind impact. Comparatively, a higher relative percentage difference was observed for tests under 3.5 m/s, which is 7.7%.

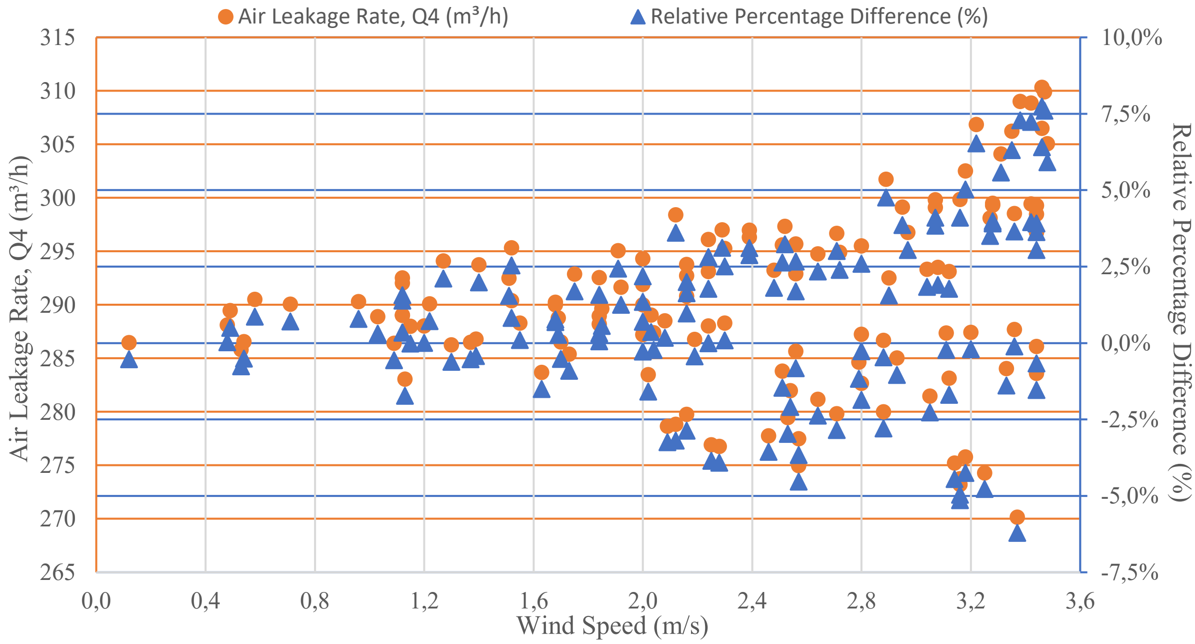

Figure 7: Tests results in the wind speed range of 0- 3.5m/s

The measurement results of ALR for the Pulse tests in the wind speed range of 3.5- 6m/s and the relative percentage difference of each test are presented in Figure 8. As shown in the figure, when wind speed exceeds 5.03m/s, the relative percentage difference is higher than ±10%. Based on the results for wind speed in the range of 3.5- 6m/s, the highest relative percentage difference of -12.19% at wind speeds 5.82m/s is noticed. Compared to the wind speed limit stated in the available standards for blower door testing, for example, ASTM E779-03, the suggested ground wind speed limit is 2m/s and in the ISO 9972, a wind speed limit of 3m/s at ground level is also regulated. Based on the obtained results in this study, building airtightness measurement using Pulse technique is not suggested at wind speed higher than around 5m/s (i.e. at the ground level of 2.2m) as more significant deviation (i.e. >±10%) could be associated.

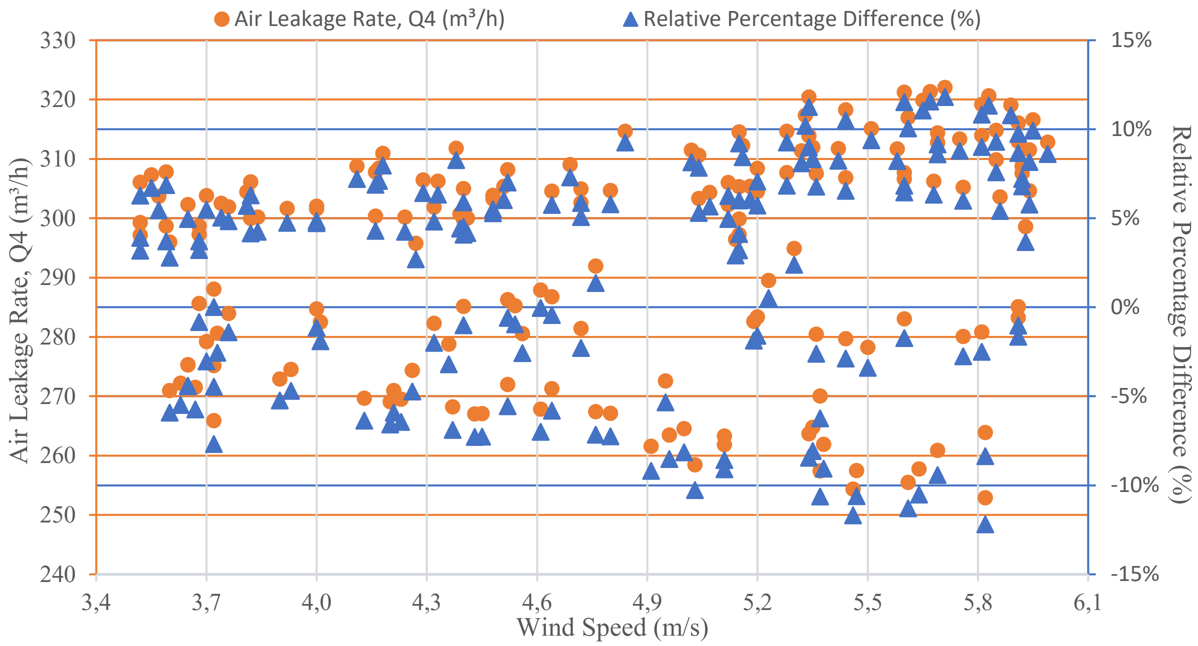

Figure 8: Tests results in the wind speed range of 3.5- 6m/s

Figure 9 shows the ALR and the relative percentage difference results of tests when the wind speed ranged from 6 to 10m/s. A larger difference against the average of low wind speed ALR (288.02m³/h) was observed under the wind condition of 6 to 10m/s. At a wind speed of 9.35m/s, the ALR was reached 348.95m³/h, while 183.67m³/h was obtained at a wind speed of 9.66m/s, with a great relative percentage difference of -36.23%. Even the lowest wind speed in this wind condition (i.e. 6.03m/s) has a relative percentage difference of 13.30%. It can be noted that the relative percentage difference rises above ±20% when the outdoor wind speed higher than 7.37m/s. Therefore, the results imply that for the Pulse test, wind impact should be taken into account under high wind speed condition as the measured building airtightness could vary significantly with the testing wind condition.

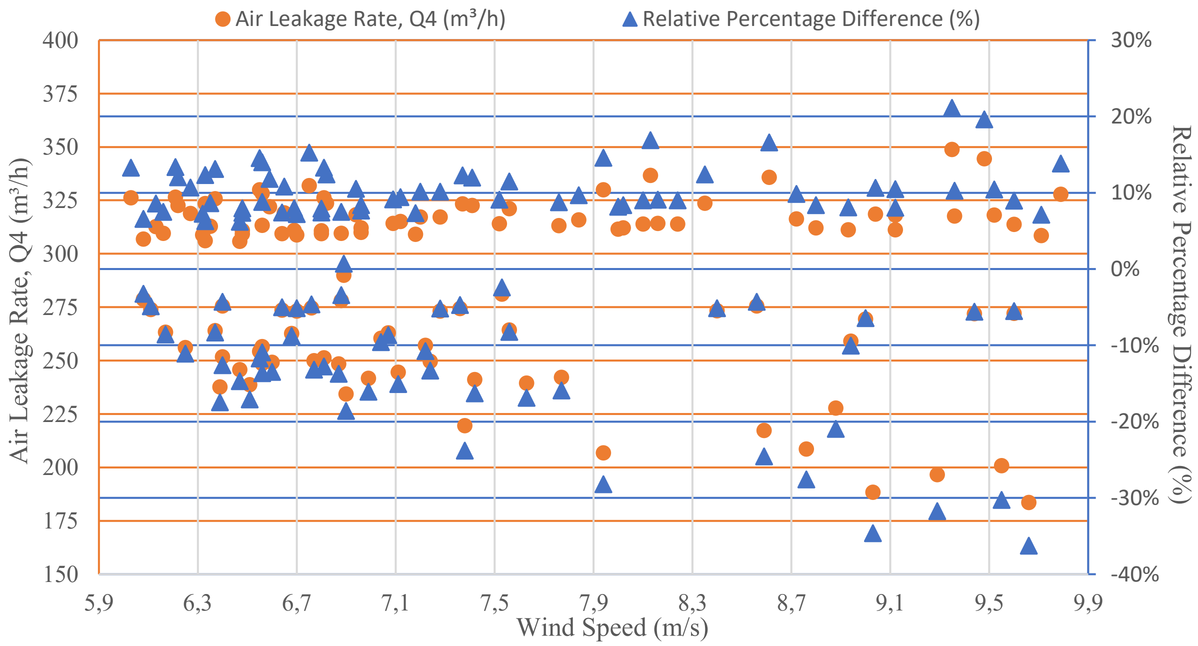

Figure 9: Tests results in the wind speed range of 6- 10m/s

Table 3 lists the measured building ALR of all 423 tests. With a wind speed interval of 0.5m/s, the total 423 tests can be divided into 20 groups for more detailed discussions. The relative percentage difference of each single test and each group are calculated by comparing with the average of low wind speed ALR. As seen in the table, an increased number of the Pulse tests could contribute to a more accurate building airtightness measurement. For instance, the relative percentage difference of each test in Group K (i.e. wind speed 5.0-5.5m/s) is around -11.69%. By considering all 43 Pulse tests in Group K, the overall relative percentage difference is only around 1.84%. As shown in the table, the measurement relative percentage difference of each group fell within ±5% when the wind speed was below 8m/s. That suggests the wind impact reduced significantly when multiple Pulse tests were carried out. However, in order to achieve accurate and rapid testing for multiple Pulse tests, the research also included group average ALR for the first three tests. As shown in the table, the measurement relative percentage difference of the first three tests fell within ±5% when the wind speed was less than 6m/s.

Table 3: Analysis of test ALR, Q4 (m^3/h) results for 423 Pulse tests

Test Group	**Wind Speed (Ground level)**[1]	**Number of Tests**	**Group Average ALR**	**Group Average ALR (First three tests)**	**Relative percentage difference**		
					Each Test[2]	**Each Group**[3]	**First Three Tests**[4]
A	**0 – 0.5 m/s**	3	288.02	288.02	-0.53%	0.00%	0.00%
B	**0.5 – 1.0 m/s**	5	288.66	287.64	-0.76%	0.22%	-0.13%
C	**1.0 – 1.5 m/s**	15	288.97	288.12	-1.72%	0.33%	0.03%
D	**1.5 – 2.0 m/s**	17	290.01	292.74	2.54%	0.69%	1.64%
E	**2.0 – 2.5 m/s**	28	288.84	289.72	-3.91%	0.28%	0.59%
F	**2.5 – 3.0 m/s**	26	288.63	292.25	-4.53%	0.21%	1.47%
G	**3.0 – 3.5 m/s**	39	293.85	291.30	7.74%	2.02%	1.14%
H	**3.5 – 4.0 m/s**	33	291.13	300.87	-7.68%	1.08%	4.46%
I	**4.0 – 4.5 m/s**	33	292.31	296.14	-7.28%	1.49%	2.82%
J	**4.5 – 5.0 m/s**	23	286.88	287.92	-9.18%	-0.40%	-0.03%
K	**5.0 – 5.5 m/s**	43	293.33	278.19	-11.69%	1.84%	-3.42%
L	**5.5 – 6.0 m/s**	41	301.65	301.69	-12.19%	4.73%	4.74%
M	**6.0 – 6.5 m/s**	24	294.78	304.01	-17.47%	2.35%	5.55%
N	**6.5 – 7.0 m/s**	33	288.54	274.40	-18.60%	0.18%	-4.73%
O	**7.0 – 7.5 m/s**	16	281.42	279.31	-23.77%	-2.29%	-3.03%
P	**7.5 – 8.0 m/s**	10	282.87	286.57	-28.18%	-1.79%	-0.50%
Q	**8.0 – 8.5 m/s**	8	312.50	312.63	16.93%	8.50%	8.54%
R	**8.5 – 9.0 m/s**	9	273.82	276.31	-27.56%	-4.93%	-4.07%
S	**9.0 – 9.5 m/s**	10	288.59	258.85	-34.59%	0.20%	-10.13%
T	**9.5 – 10 m/s**	7	275.05	263.75	-36.23%	-4.50%	-8.43%

Based on low wind speed condition 0 – 0.5 m/s (3 Tests)	**Average ALR, Q4 (m^3/h)**
	288.02

1. Wind Speed measured at the height of the 2.2m above ground
2. The maximum relative percentage difference of ALR of each single test to the average of low wind speed ALR
3. The relative percentage difference of average ALR of each group to the average of low wind speed ALR
4. The relative percentage difference of average ALR of first three tests to the average of low wind speed ALR

5 CONCLUSIONS

In this study, 423 Pulse tests were carried out to measure the building airtightness of a five-bedroom house under various wind conditions with wind speed up to 10m/s. A Pulse unit with a 58.5-litre air tank was employed to measure the building airtightness whilst an ultrasonic anemometer located 12 metres away from the building perimeter was used to obtain the outdoor wind speed at the height of 2.2 metres above ground level. A relative percentage difference of each test was defined by comparing with the average building air leakage rate at low wind speed condition within 0.5m/s and used to evaluate the wind impact on the measurement of building airtightness. Based on the experimental data, a more precise building measurement can be achieved for testing under wind speed lower than 5m/s as a relative percentage difference less than ±10% was obtained. When wind speed above 7.3m/s, the relative percentage difference of a single Pulse test can exceed ±20%, which indicates that the measurement may be imprecise owing to the wind impact. Therefore, the Pulse test is suggested to be implemented under wind speed lower than 5m/s at 2.2m above ground level (with relative percentage difference ±10%) in calm conditions and 7.4m/s (with relative percentage difference ±20%) in windy conditions for less wind impact on building airtightness measurement. On the other hand, the results also imply that multiple Pulse tests under a similar wind condition could greatly minimise the wind impact. For instance, the relative percentage difference of a single Pulse test under wind speed of 5.0-5.5m/s is approximate -11.69%, while by implementing 43 repeated Pulse tests, the relative percentage difference decreases to 1.84%. However, in order to achieve accurate and rapid testing for multiple Pulse tests, the measurement relative percentage difference of the first three tests in each group fell within ±5% when the wind speed was less than 6m/s. In addition, future work is recommended for the investigation of quicker air tank charging methods to allow more tests within a short period under similar wind conditions. Furthermore, improving the algorithm of the Pulse technique is also necessary in order to address the wind impact on measurement for wide applicability, especially under high wind speed conditions.

Different from Zheng et al. (2018) using a multi-gear portable trailer fan to provide various artificially imposed steady wind conditions, this study was conducted under natural wind conditions with unpredictable wind characteristics. Both studies investigated the wind speed limit that allowed the Pulse technique to give repeatable and accurate measurements. For the relative percentage difference within ±3%, Zheng et al. (2018) found the test conditions are under steady wind speed below 3.5m/s with fixed wind direction, while wind speed below 2.08m/s under natural wind condition (i.e. ±3%) is noted in this study. A different pattern in airtightness variation was shown between the two studies when the wind level was beyond the limit. This might be attributed to the different wind conditions experienced in the studies, i.e. artificially imposed steady wind in a fixed direction vs. random wind direction under natural conditions. This suggests the wind direction affects the measured airtightness when it is above a certain level. Future studies of the impact of wind direction and leakage distribution on the measurement of airtightness are recommended to obtain further insights into those factors.

6 REFERENCES

ANDREWS, J. 1997. Error analysis for duct leakage tests in ASHRAE Standard 152P. Brookhaven National Lab., Upton, NY (United States).

ASTM, A. 2004. E779-03" Standard Test Method for Determining Air Leakage Rate by Fan Pressurization. *American Society for Testing and Materials, USA.*

BAILLY, A., LEPRINCE, V., GUYOT, G., CARRIÉ, F. & EL MANKIBI, M. Numerical evaluation of airtightness measurement protocols. 33rd AIVC Conference" Optimising Ventilative Cooling and Airtightness for [Nearly] Zero-Energy Buildings, IAQ and Comfort", Copenhagen, Denmark, 2012. 252-255.

COOPER, E. & ETHERIDGE, D. 2007. Determining the adventitious leakage of buildings at low pressure. Part 1: uncertainties. *Building Services Engineering Research and Technology,* 28**,** 71-80.

COOPER, E., ETHERIDGE, D. & SMITH, S. 2007. Determining the adventitious leakage of buildings at low pressure. Part 2: pulse technique. *Building Services Engineering Research and Technology,* 28**,** 81-96.

COOPER, E., ZHENG, X., WOOD, C., GILLOT, M., TETLOW, D., RIFFAT, S. & DE SIMON, L. 2016. Field trialling of a pulse airtightness tester in a range of UK homes. *International Journal of Ventilation***,** 1-18.

EN, B. 2000. 13829 Thermal performance of buildings–Determination of air permeability of buildings–Fan pressurization method. *BSI, UK*.

GEISSLER, A. Error Estimation of blower door measurements by computer simulation. The 8th International Conference on Indoor Air Quality and Climate, 1999.

GUYOT, G., CARRIÉ, R., SCHILD, P., THOMSEN, K. E., ROSE, J. & AGGERHOLM, S. 2010. Stimulation of good building and ductwork airtightness through EPBD.

ISO 2015. Thermal performance of buildings–determination of air permeability of buildings–fan pressurization method. International Organization for Standardization (ISO) Geneva.

KRANIOTIS, D. 2014. *Dynamic characteristics of wind-driven air infiltration in buildings The impact of wind gusts under unsteady wind conditions.* Norwegian University of Life Sciences.

KRANIOTIS, D., THIIS, T. K. & AURLIEN, T. Wind direction and leakage distribution in buildings. A CFD transient analysis of their impact on air exchange rates under unsteady wind conditions. 6th European-African conference on wind engineering(EACWE 2013), 2013.

KRANIOTIS, D., THIIS, T. K. & AURLIEN, T. 2014. A numerical study on the impact of wind gust frequency on air exchanges in buildings with variable external and internal leakages. *Buildings,* 4**,** 27-42.

LEPRINCE, V. & CARRIÉ, F. R. 2018. Uncertainties due to steady wind in building pressurisation tests. *REHVA Journal,* 03**,** 53-57.

LEPRINCE, V., MOUJALLED, B. & LITVAK, A. 2017. *Durability of building airtightness, review and analysis of existing studies*.

NEVANDER, L. E. K., J. 1978. Airtightness of buildings - Research in Sweden. *IEA Seminar on R&D projects in the area of infiltration in buildings.* Paris, France.

SHERMAN, M. & PALMITER, L. 1995. Uncertainties in fan pressurization measurements. *Airflow performance of building envelopes, components, and systems.* ASTM International.

SHERMAN, M. H. & CHAN, W. R. 2006. Building air tightness: research and practice. *Building Ventilation.* Routledge.

VINHA, J., MANELIUS, E., KORPI, M., SALMINEN, K., KURNITSKI, J., KIVISTE, M. & LAUKKARINEN, A. 2015. Airtightness of residential buildings in Finland. *Building and Environment,* 93**,** 128-140.

WALKER, I., SHERMAN, M. H., JOH, J. & CHAN, W. 2013. Applying Large Datasets to Developing a Better Understanding of Air Leakage Measurement in Homes. *International Journal of Ventilation,* 11**,** 323-338.

ZHENG, X., COOPER, E., MAZZON, J., WALLIS, I. & WOOD, C. J. 2019a. Experimental insights into the airtightness measurement of a house-sized chamber in a sheltered environment using blower door and pulse methods. *Building and Environment*.

ZHENG, X., MAZZON, J., WALLIS, I. & WOOD, C. J. Experimental study of enclosure airtightness of an outdoor chamber using the pulse technique and blower door method under various leakage and wind conditions. 39th AIVC - 7th TightVent & 5th venticool Conference, 18-19 September 2018 2018 Antibes Juan-Les-Pins. 352-362.

ZHENG, X. F., COOPER, E., ZU, Y. Q., GILLOTT, M., TETLOW, D., RIFFAT, S. & WOOD, C. J. 2019b. Experimental Studies of a Pulse Pressurisation Technique for Measuring Building Airtightness. *Future Cities and Environment,* 5(1)**,** 10.