The Impact of Wind upon the Pulse Technique Measured Airtightness of a Detached Dwelling

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ABSTRACT

The novel Pulse technique measures the building airtightness in a dynamic approach, involving a low-pressure pressurisation process, typically in 1-10Pa. It is known that the wind effect is one of the main sources of uncertainty for airtightness testing. The literature review revealed that the wind impact on measuring building airtightness has been explored in relation to the steady pressurisation method (i.e., the blower door), while there is limited research investigating the validity of the Pulse measurement under various natural wind conditions. In this study, in total, 423 Pulse tests were performed to measure the building airtightness of a five-bedroom dwelling located at the University of Nottingham, UK, under natural wind conditions. The viability of the Pulse technique for delivering airtightness measurements under different wind conditions was assessed, including the impacts of the wind speed and the wind direction on the Pulse measurements. Based on the measured air leakage rates, the threshold of maximum wind speed that led the Pulse measurements to have repeatability greater than ±10% is 5.0m/s at 2.2m above ground level (i.e., approximately equivalent to the meteorological wind speed of 7.9m/s). On the other hand, the directional wind study showed that at lower wind speeds, the wind direction has a lesser influence on the Pulse measurement than the wind speed itself. Practically, multiple Pulse tests are recommended for minimising the wind impact on building airtightness measurement when adverse wind conditions are present.

KEYWORDS

Building airtightness, The Pulse technique, Unsteady approach, Wind impact, Wind speed, Wind direction

NOMENCLATURE

Symbol

C_t	Constant
n_s	Terrain surface characteristic
P	Pressure (Pa)
$P(t)$	Transient air pressure in the compressor tank (Pa)
$Q_P\{t\}$	The volumetric airflow rate in the compressor tank (m^3/s)
$q\{t\}$	Building air leakage rate (m^3/s)
R	Gas constant (J/kg·K)
T	Temperature (K)
v	Velocity (m/s)
V	Volume (m^3)
V'	Air receiver volume (m^3)
z	Reference height (m)
z_0	Surface roughness length (m)

Greek letter

ρ	Air density (kg/m^3)
γ	Specific heat ratio

Abbreviations

ALR	Air leakage rate
RPD	Relative percentage difference

Subscripts

i	Internal
0	Initial

1 INTRODUCTION

1.1 Background

Building airtightness is defined as the resistance to inward or outward air leakage through unintentional leakage cracks or gaps across the building envelope, which indicates how well the building envelope is sealed [1]. Considering its associated impact on the energy efficiency, indoor environment and building durability, it is necessary to measure the building airtightness in order to gain a quantitative understanding of this physical property as visual observations can not quantify or detect all gaps and cracks in the building envelope. Additionally, building envelopes could have tortuous leakage pathways and obscured gaps in internal architectural facings or external cladding [2]. Typically, the building airtightness is measured by a pressurisation test using a large calibrated fan to establish a pressure difference between the inside of the building and the outdoor environment; *alias* fan pressurisation test [3]. In the fan pressurisation test, the reference pressure is 50Pa, which is most commonly used [4], although alternative reference pressures can also be used, for example, 1Pa [5], 4Pa [6], 10Pa [7], 25Pa [8, 9] and 75Pa [10].

Nevertheless, the direct leakage measurement at 4Pa has been proved by Cooper, et al. [11], to be more realistic and accurate in indicating the infiltration potential of a building envelope. The novel Pulse technique has been developed as a dynamic approach involving a low-pressure pressurisation process, typically around 4Pa [12]. The technique was originally developed to address the issues of large net fluid flows and uneven pressure distributions associated with testing large buildings [13]. With the Pulse technique, the building airtightness can be determined by releasing a 1.5-second air pulse from a pressurised vessel to the test spaces, thus establishing an instant pressure increase [14]. The measurement of the building pressure is recorded continuously over a typical pressure range of 1-10Pa, which is different from the multiple-point tests over a pressure range with the steady pressurisation method [15]. From herein, the proper noun 'Pulse' is used to refer to the Pulse technique and 'pulse' refers to the actual physical air pulse release [16]. In terms of practicality, the integrity of the test building could be maintained as only a self-contained portable Pulse unit is required, and its installation does not penetrate the building fabric [17]. Pulse is adaptable for buildings in a variety of sizes, as multiple Pulse units can be employed for operation simultaneously [18]. Although Pulse is a relatively newly developed transient method, its fundamental principle has been verified from many aspects in studies [19-22].

The uncertainty of building airtightness measurement has been extensively explored [23]. Based on the review of the literature [24-30], the uncertainty of the airtightness testing is mainly associated with: building testing preparation, tester behaviours, instrumentation accuracies, weather conditions, and seasonal variation of building airtightness. For instance, the building pressure difference between the indoor and outdoor could be influenced by the dynamic nature of the wind and buoyancy effect, which would result in an imprecise measurement of the building airtightness [31]. The impact of outdoor weather conditions on the building airtightness measurement has been noted from both numerical and experimental work. Therefore, the testing weather condition is regulated in the standards for the fan pressurisation method. 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 the building location and surrounding environment [32]. Hence, low and steady wind conditions are preferable for measurements. According to the ISO 9972:2015 standard (Thermal performance of buildings-Determination of air permeability of buildings-Fan pressurisation method) [33], the overall uncertainty of a blower door test can be estimated using the error propagation calculation, which is lower than ±10% in calm conditions and ±20% in windy conditions. The influence of the weather condition leads to specific recommendations for wind velocity. For instance, Nevander [34] recommended a wind speed limit of 5m/s for building airtightness measurement based on the static wind loads and simplified load distribution models.

There are two common 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 [35]. Nevertheless, an agreed definition of wind speed (e.g., by means of height) is difficult to find in existing research of wind impact on the building airtightness measurement. Confusion may occur because of the different wind speed references, and significant differences could be noted for measuring or calculating wind speed as researchers employed different definitions of wind speed. For instance, Bailly, et al. [36] considered the wind speed at the height of the wall in their numerical study. They stated that the valid building airtightness measurement could be obtained under the wind speed <8m/s. Differently, Walker, et al. [37] directly used the wind data from the on-site meteorological towers. Furthermore, measurements of the wind speed are generally obtained only before implementation and after test completion, causing ignorance of the wind speed variation during the testing period. However, the wind condition could change dynamically during the measuring period, introducing precision errors in the measurement.

1.2 Understanding of the wind impact on Pulse

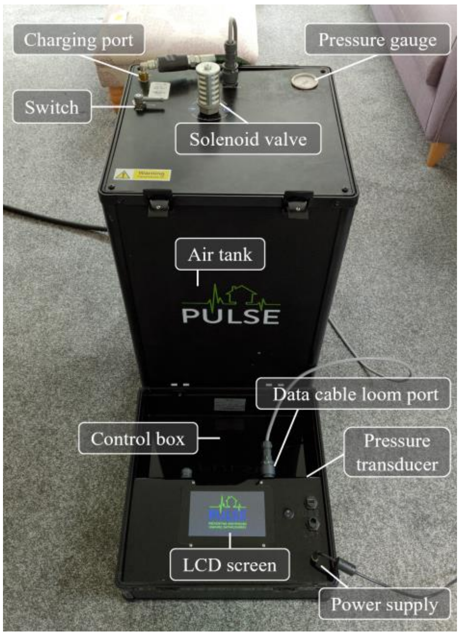
The wind impact is one of the main sources of uncertainty for airtightness testing, owing to its indefinite nature, which could influence the pressure difference across the building envelope, thus leading to an inaccurate building airtightness measurement. Many studies noted that the outdoor weather condition, particularly, the wind could greatly affect the measurement of building airtightness. For instance, the ISO 9972 standard [33] suggests a meteorological wind speed limit of 6m/s or 3m/s near the ground level for the fan pressurisation test. However, there is limited research considering the validity of Pulse under windy conditions. Cooper, et al. [38] found the Pulse testing repeatability was ±8% based on one-year repeated testing in a detached house. Zheng, et al. [39], [40] presented a Pulse repeatability assessment under artificially-imposed steady wind conditions. An uncertainty within ±3% was noted under the wind speed <3.5m/s at 1.5m above ground level, while the maximum uncertainty of ±25.6% was obtained in the wind speed range of 4-9m/s at 1.5m above ground level. Currently, no relevant standards or regulations concerning wind conditions for the Pulse test are in place. On the other hand, most of the investigations addressing the wind impact on building airtightness measurement have been conducted for the fan pressurisation method, while very few studies are noted investigating the wind impact on the Pulse measurement.

In this study, 423 Pulse tests were implemented over seven days (March 2019) in a five-bedroom detached house located at the University of Nottingham under various natural wind conditions. 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. This paper extends the work originally presented at the 40th AIVC Conference [41], aiming to report what has been routinely conducted as part of the ongoing Pulse development, and the investigation presents results of testing using the latest Pulse equipment to address the aforementioned research gap.

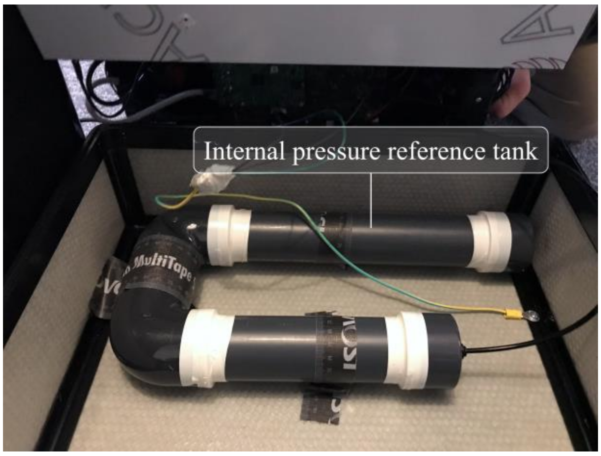
2 METHODOLOGY

2.1 Equipment

In this experimental study, a PULSE-60 unit was employed, as shown in Figure 1(a). It is mainly comprised of a 58.5-litre lightweight aluminium air tank and an oil-free compact air compressor. To release the compressed air from the air tank into the building indoor spaces, a ¾ inch (BSP) solenoid valve was installed at the outlet of the PULSE-60 unit. Additionally, the test data, including the chamber and tank pressures/temperatures, were recorded and analysed by the on-board control box and displayed on its LCD screen. Uniquely, an internal pressure reference tank was constructed inside the control box, as shown in Figure 1(b). An automated valve was installed on the internal pressure reference tank, which normally is kept open to equalise its internal pressure with the ambient environment and closes once the test starts to provide a reference pressure.



(a)



(b)

Figure 1: Photos of (a) PULSE-60 unit and (b) internal pressure reference tank of PULSE-60 unit

As all experimental tests were performed under natural outdoor conditions, an ultrasonic anemometer (as seen in Figure 2) was installed to measure the outdoor wind condition at the height of 2.2m above ground level in the backyard and a distance of 12m away from the perimeter of the test building, with no significant obstructions in its vicinity. A platinum RTD sensor was installed beside the anemometer to measure the ambient temperature. In terms of the data acquisition, a Datataker DT85 was employed at a sampling rate of 4Hz, with an accuracy of ±0.1%.

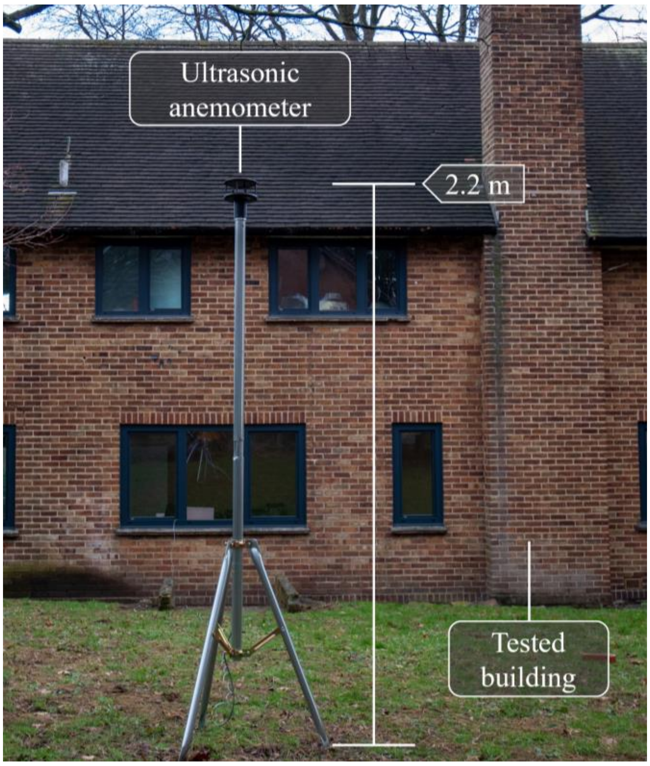


Figure 2: Photo of ultrasonic anemometer

All tests were conducted under similar conditions with a temperature difference of approximately 5℃ between the indoor and outdoor. Table 1 summarises the experimental instrumentation in this study, with their respective accuracies.

Table 1: List of test instrumentation with accuracies

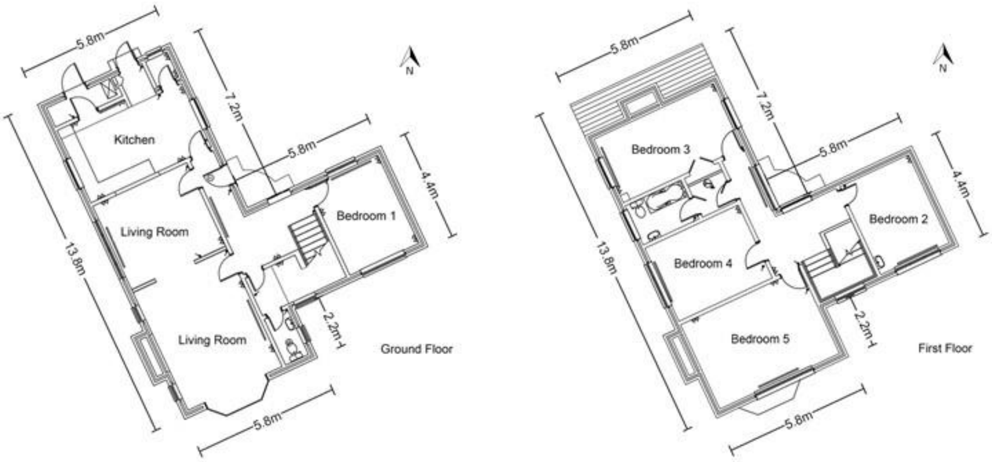
No.	Test Instrument	Accuracy
1	Pressure transducer (PULSE-60 unit built-in)	±0.40%
2	Temperature sensor (PULSE-60 unit built-in)	±0.08℃
3	Ultrasonic anemometer (WindSonic^{TM})	±3.0%
4	Temperature sensor (PT100 RTD)	±0.2℃
5	Data logger (Datataker DT85)	±0.10%

2.2 Dwelling

The test building is a five-bedroom detached dwelling located at the University of Nottingham, as shown in Figure 3, and floor plans are shown in Figure 4. The house has one bedroom, one living room, one kitchen on the ground floor and four bedrooms on the first floor.

Front view Back view

Figure 3: Photos of the tested dwelling



Ground floor First floor

Figure 4: Building plans of the tested dwelling

Referring to the English Housing Survey [42], the majority of dwelling types have a mean volume below 300m^3, and the category of the detached house has a mean volume of 381m^3. The building parameters of the tested dwelling are provided in Table 2. The test house has a volume of 447m^3, which is above the average volume of detached houses. Therefore, the size of this house is large enough to represent the worst-case scenario, providing a good case for investigating the wind impact on the Pulse test. The dwelling was retrofitted in 2018 for improved building energy efficiency, and the chimney was sealed off.

Table 2: Test dwelling parameters

Dwelling	Wortley 5 - University of Nottingham, University Park, Nottingham
Type	Five-bedroom detached house
Year	Built in 1950 and retrofitted in 2018
Volume (m^3)	447m^3
Envelope Area (m^2)	416m^2

2.3 Experimental setup

The Pulse testing preparation was conducted according to the guidance presented in the ISO 9972 standard, and the PULSE-60 unit was placed in the living room on the ground floor, as seen in Figure 5(a). During the testing, all heating, ventilation, and air conditioning systems were turned off. All windows, doors and trapdoors in the building envelope were closed, while the interconnecting doors were kept open for establishing a homogeneous pressure within the indoor spaces. All the intentional openings for natural and mechanical ventilation were closed and sealed with TechnoSol sealing tape, as seen in Figure 5(b).

(a)

(b)

Figure 5: (a) Setup of PULSE-60 unit in the test dwelling and (b) sealed vents during testing

Figure 6 presents the overall layout of the test equipment, including the PULSE-60 unit, temperature sensors and the ultrasonic anemometer.

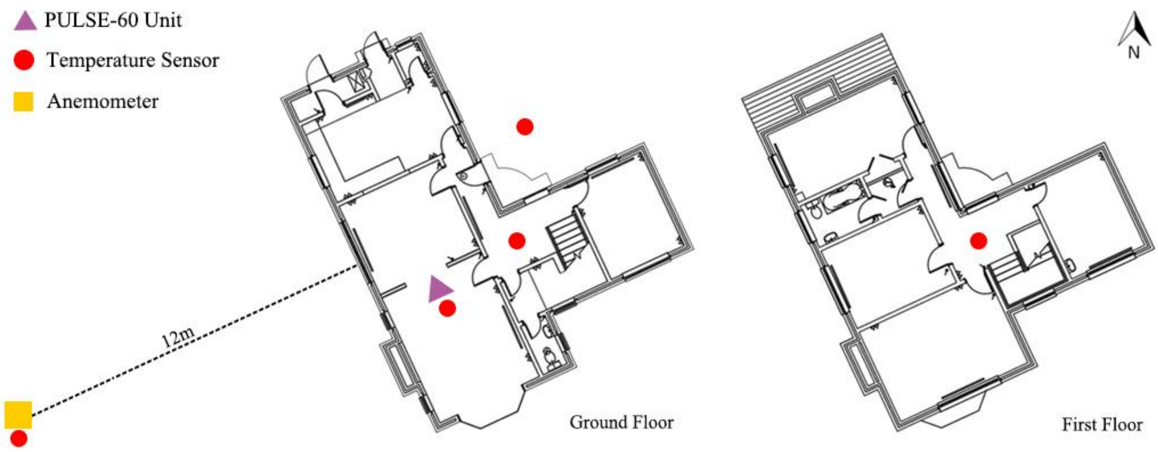
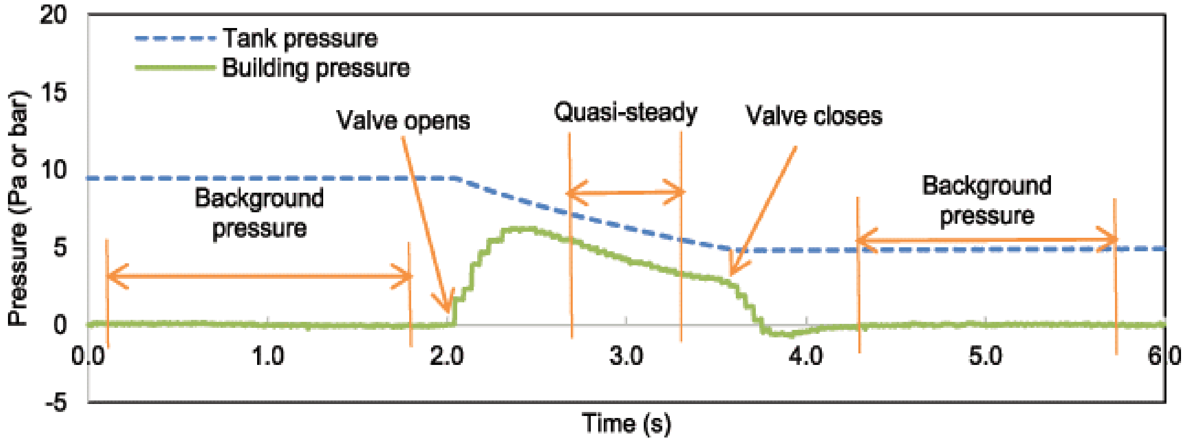
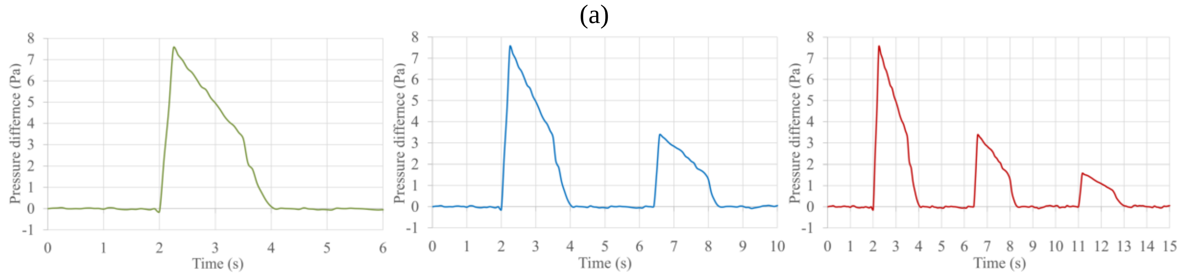


Figure 6: Illustration of the setup locations of test equipment

During the Pulse test, the mass flow rate from the nozzle can be derived by measuring the transient pressure in the air receiver, while the building pressure response is measured by a differential pressure transducer with the aid of an internal pressure reference [38]. The pressure variations in the test building and tank during the Pulse test are recorded simultaneously to determine a correlation between the leakage and pressure. Typically, the building pressure readings contain three key stages: the background pressure before the air pulse release, the quasi-steady period, and the background pressure after the air pulse release [38]. In particular, the quasi-steady period is selected for examining the building airtightness. Figure 7(a) illustrates the pressure variation throughout a typical one-step Pulse test; it can be seen that the quasi-steady period takes place in the middle part of the Pulse test. A complete Pulse test could contain a single air pulse release, two air pulse releases or three air pulse releases, as shown in Figure 7(b). The PULSE-60 unit employed for this experimental work allows up to three pulse releases in one complete Pulse test. Therefore, three-step Pulse testing was adopted in this study. It is also noteworthy that the reduction in the building pressure is attributed to the decreasing tank pressure as there is no charging of the tank between successive pulses. The testing duration of a three-step Pulse is about 15 seconds.



(a)



(b)

Figure 7: (a) Pressure variation with time for a typical Pulse test [12] and (b) pressure profiles during the one-step, two-step and three-step Pulse test

Over the 7-day testing period, in total, 423 tests were performed with around 60 Pulse tests implemented each day, and the break time between two adjacent tests was about 6 minutes. According to the weather data released by meteoblue.com [43], during March 2019 when the experiment was performed; the average exterior air temperature during the testing period (i.e., 9th March to 15th March 2019) in Nottingham was around 6.3°C, the average meteorological wind speed was approximately 9.3m/s, and the highest meteorological wind speed was 19.1m/s, thereby providing a wide range of wind conditions. In this study, all tests have been completed within a short period of time for minimising the impact of other variables.

Raw data consisting of continuous records of both the tank and building pressures during the entire Pulse testing period were recorded in the control box, and meanwhile, the wind speed and direction were measured by the ultrasonic anemometer. Figure 8 provides photos of the surrounding environment of the ultrasonic anemometer; there were no significant obstructions within a radius of 12m of the anemometer in the open backyard, except for sparse tree branches and grass on the ground. From herein, the mentioned wind speed refers to the wind speed measured at 2.2m above ground level unless specified. Overall, the monitored natural wind condition of 423 tests has the wind speed range of 0-10m/s, and wind direction degree ranged from 60° to 300°. The viability of the Pulse measurement under different wind conditions is evaluated. Referring to criteria for test validity of the fan pressurisation method in the ISO 9972 standard, the test result validity for each Pulse test at 4Pa is examined in this study based on the three main criteria: (1) the maximum recorded quasi-steady-state pressure >4Pa and the recorded minimum quasi-steady-state pressure <4Pa; (2) the air flow exponent (n) in the range 0.5 to 1, and (3) the coefficient of determination (R^2) in the log-log plot >0.98. The impacts of the wind speed and the wind direction on the Pulse test are analysed respectively based on the experimental data. Additionally, the necessity of implementing the multiple Pulse tests is discussed to minimise the wind impact on the Pulse measurement in practical testing scenarios.

Figure 8: Photos of surrounding environment of the installed ultrasonic anemometer

3 RESULTS AND ANALYSIS

3.1 Impact of wind speed

Due to a large number of test results, analysis is conducted by grouping these tests into a few wind speed ranges (i.e., 0-3.5m/s; 3.5-6m/s and 6-10m/s) for better clarity. In this section, the analysis is focused on the wind speed impact, while the wind direction impact is investigated later in Section 3.2. During the entire period of each test, the outdoor wind speed was continuously recorded, and the highest wind speed during a test was selected as the corresponding wind speed of the test. The reasons for selecting the highest wind speed of each test for analysis are: (a) representing the threshold value of the wind speed during the entire test and (b) taking into account the occurrence of gusty winds during the test period. Therefore, 133 tests have their highest wind speeds in the range of 0-3.5m/s, with 173 tests in 3.5-6m/s and 117 tests in 6-10m/s. The average wind speed of all the 423 tests is 4.76m/s.

A violin plot is presented in Figure 9, depicting the full distribution of the measured air leakage rate (ALR) of all 423 tests across different wind speed ranges. A marker for the median of the data (in blue colour) and a marker for the interquartile range (in green colour) are included. The shape of the distribution of the 423 tests demonstrates that the ALRs are centralised around the interquartile range. It can be clearly seen that the distribution shape varies significantly across the wind speed range with different median ALRs, which indicates that the wind speed affects the measurement of building airtightness. Detailed analysis of each wind speed range is presented in the following sections.

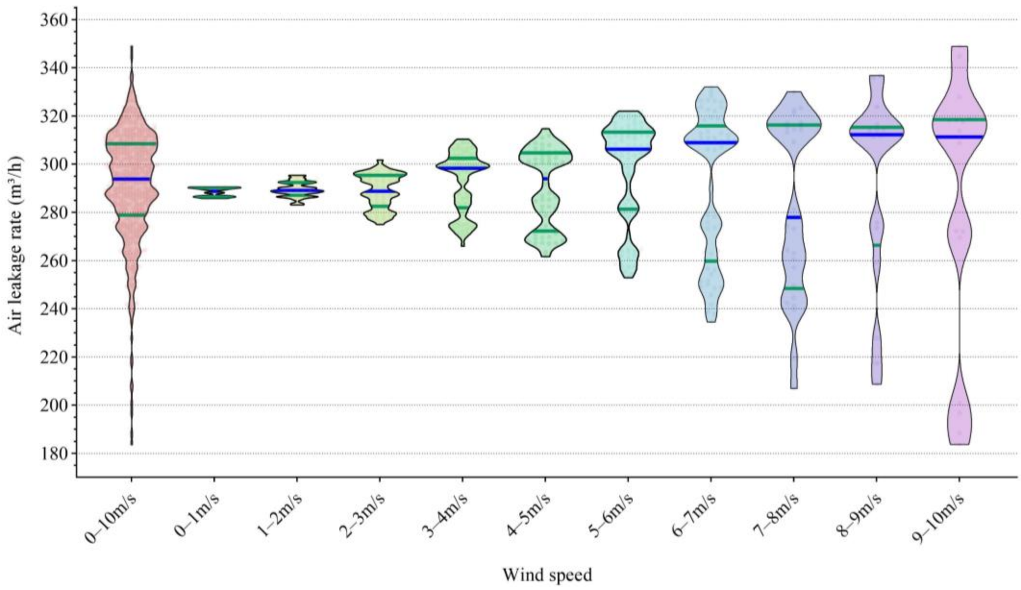


Figure 9: Violin plot of 423 tests

0-3.5m/s

Figure 10 shows the test results of ALR in the wind speed range of 0-3.5m/s. Among the total of 133 tests, three tests were performed at very low wind speeds (i.e., <0.5m/s), and the average outdoor temperature was around 6.3℃. The average ALR of the three tests is 288.02m³/h, which is used as the baseline ALR value in this assessment. Therefore, the relative percentage difference (*RPD*) is used to indicate the wind impact on building airtightness measurement, which is given by the relative difference between the ALR of every single test and the baseline ALR. The respective *RPD*s of the 133 tests are also provided in Figure 10. It can be clearly noted that the *RPD* becomes larger when the wind speed increases.

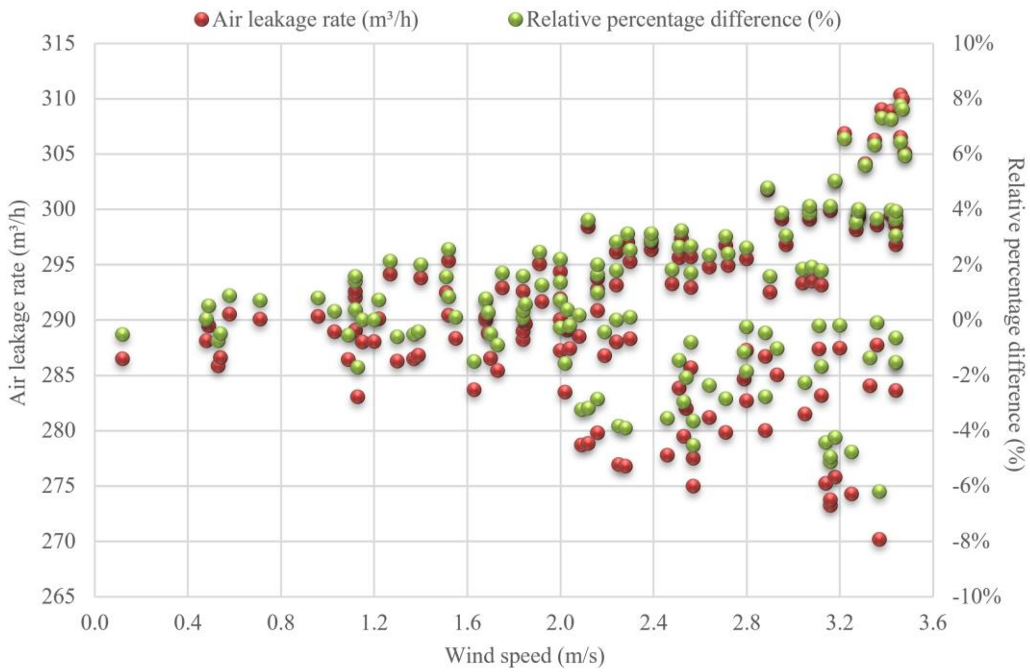


Figure 10: Test results in the wind speed range of 0-3.5m/s

For more detailed evaluations, the maximum *RPD* is about 2.54% for the wind speed varying from 1.69 to 2.0m/s, while in the wind speed range of 3.25-3.37m/s, the maximum *RPD* is 6.54%. Compared to the baseline ALR, similar ALR results were noted under the wind speed <2.08m/s, with the maximum *RPD* within ±3%. Also, it can be noted that the *RPD* fell outside ±5% when the wind speed was higher than 3.14m/s. The results reveal that a more precise Pulse measurement could be achieved under the wind speed below 3.14m/s. The highest *RPD* of 7.7% was observed among all the 133 tests in the assessed wind range, i.e., 0-3.5m/s. Table 3 summarises the corresponding wind speed limit with the *RPD* based on the obtained results.

3.5-6m/s

There are, in total, 173 tests that have been performed at the wind speed ranging from 3.5 to 6.0m/s. Figure 11 provides the measured ALR results and the *RPD* of each test. Similar trends are seen; as the wind speed increases, the deviation of the measured ALR from the baseline ALR becomes higher. It can be noted that the *RPD*s are higher than those in the aforementioned lower wind speed range, and the highest *RPD* is |-12.19%| in this wind speed range.

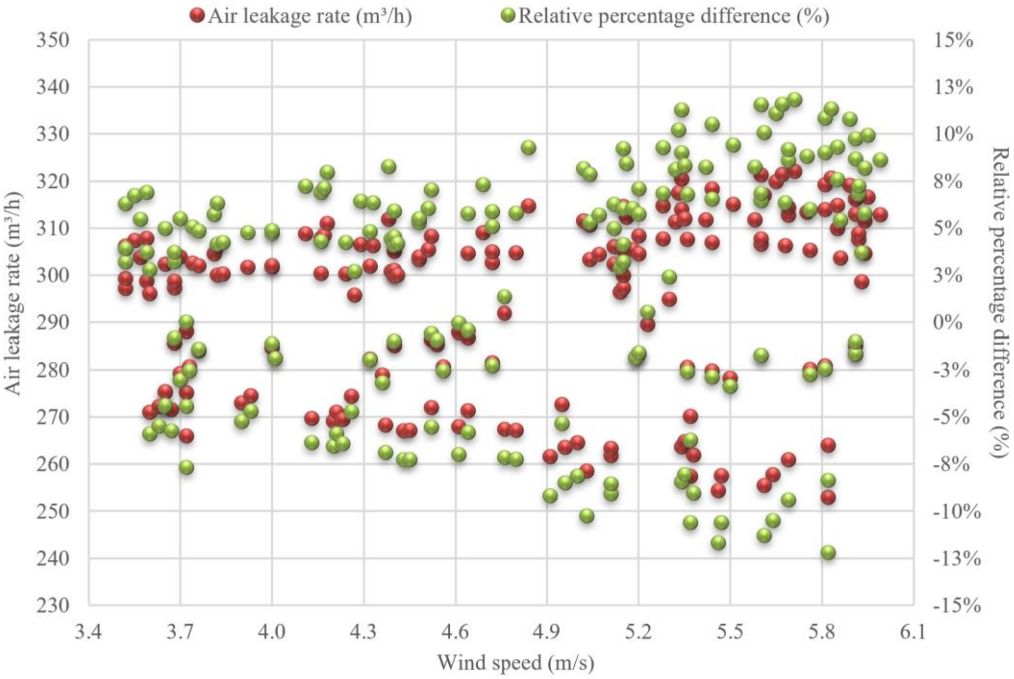


Figure 11: Test results in the wind speed range of 3.5-6m/s

There are different wind speed limits regulated in the available standards for the fan pressurisation testing. For example, the suggested ground wind speed limit is 2m/s as stated in the ASTM E779-19 standard (Standard Test Method for Determining Air Leakage Rate by Fan Pressurization), and a wind speed limit of 3m/s at ground level or meteorological wind speed limit of 6m/s is regulated in the ISO 9972 standard. Differently, based on the obtained test results, a more significant deviation of the Pulse measurement (i.e., *RPD*>|±10%|) could occur when the wind speed exceeded 5.0m/s at 2.2m above the ground level.

6-10m/s

For the wind speed range of 6-10m/s, 117 tests have been carried out. Figure 12 shows the corresponding ALR measurements and the *RPD* of tests. A larger difference against the baseline ALR (288.02m³/h) was observed. For example, at the wind speed of 9.3m/s, the ALR reached 348.95m³/h, while 183.67m³/h was obtained at a wind speed of 9.7m/s, with a significant deviation of -36.23%.

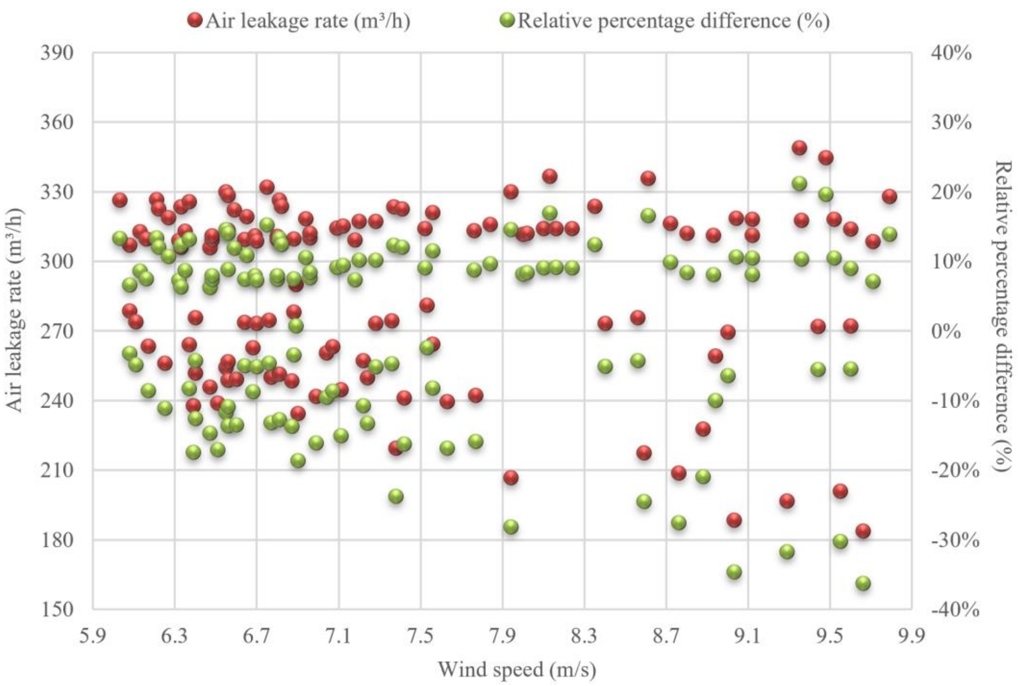


Figure 12: Tests results in the wind speed range of 6-10m/s

As shown in Figure 12, even for the wind speed ranging from 6.0 to 6.4m/s, the maximum *RPD* reached approximately 13.39%, and the *RPD* rose beyond ±20% when the outdoor wind speed was higher than 7.4m/s. Therefore, the results indicate that for the Pulse testing, the wind impact should be taken into account under the high wind speed condition as the measured building airtightness could vary considerably, most likely affected by other characteristics of dynamic winds, leading to inaccurate results.

Overall

Table 3 summarises the wind speed limit (i.e., at 2.2m above the ground) with the corresponding *RPD* based on the obtained results.

Table 3: Test result summary for the wind speed range of 0-10m/s (at 2.2m above ground level)

Wind Speed	Number of Tests	Wind Speed Limit (m/s) with Maximum *RPD* (%)						
0 - 3.5m/s	133 tests	< |±1%|	< |±2%|	< |±3%|	< |±4%|	< |±5%|	< |±6%|	< |±7%|
		1.1m/s	1.2m/s	2.1m/s	2.6m/s	3.1m/s	3.2m/s	3.4m/s
3.5 - 6.0m/s	173 tests	< |±8%|	< |±9%|	< |±10%|	< |±11%|	< |±12%|	< |±13%|	
		4.4m/s	4.8m/s	5.0m/s	5.3m/s	5.8m/s	6.0m/s	
6.0 - 10.0m/s	117 tests	< |±14%|	< |±18%|	< |±19%|	< |±24%|	< |±29%|	< |±35%|	< |±37%|
		6.4m/s	6.9m/s	7.4m/s	7.8m/s	9.0m/s	9.6m/s	9.8m/s

To better understand the indication of the findings in this study, the wind speed limits obtained in Table 3 are then converted to the corresponding meteorological wind speed based on the test location. It is known that the wind speed rises with the increasing height above the ground level. To estimate the vertical wind speed profile, two approaches are commonly used, including the log law (eq. 1) [44] and the power-law (eq. 2) [45].

$$v_2 = v_1 \cdot \frac{\ln \frac{z_2}{z_0}}{\ln \frac{z_1}{z_0}} \tag{1}$$

Where, z is the reference height and z_0 is the surface roughness length.

$$v_2 = v_1 \cdot (\frac{z_2}{z_1})^{n_s} \tag{2}$$

Where, n_s is the terrain surface characteristic based on the typology.

Manwell, et al. [44] listed the values of surface roughness length for various types of terrain, and Dalila, et al. [46] reported various terrain surface characteristics. In accordance with the urban environment in the field tests, z_0 is chosen as 0.1m (i.e., few trees) for log law extrapolation, and n_s is chosen as 0.3 (i.e., a small town with some trees) for power law extrapolation. In the field tests, measurements of the wind speed were also taken at various heights (i.e., at 0.5, 1, 1.2, 1.5 and 2m). By comparing measured data with the extrapolated values using the two approaches, the power law profiles matched well with the measured data.

Based on the calculation, Table 4 summarises the corresponding meteorological wind speed limit with the *RPD* ranges. It shows threshold value of the meteorological wind speed is approximately 7.9m/s for the *RPD* within ±10%.

Table 4: Test result summary for the meteorological wind speed range of 0-16m/s

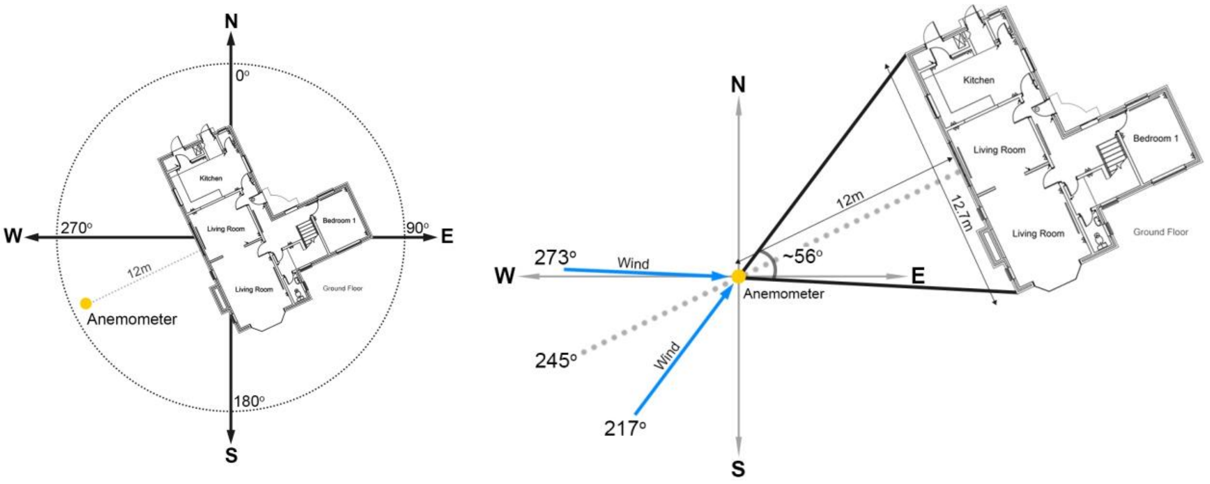
Meteorological Wind Speed	**Number of Tests**	**Wind Speed Limit (m/s) with Maximum *RPD* (%)**						
0 - 6m/s	133 tests	< |±1%|	< |±2%|	< |±3%|	< |±4%|	< |±5%|	< |±6%|	< |±7%|
		1.7m/s	1.9m/s	3.3m/s	4.0m/s	4.9m/s	5.0m/s	5.3m/s
6 - 10m/s	173 tests	< |±8%|	< |±9%|	< |±10%|	< |±11%|	< |±12%|	< |±13%|	
		6.9m/s	7.6m/s	7.9m/s	8.4m/s	9.2m/s	9.4m/s	
10 - 16m/s	117 tests	< |±14%|	< |±18%|	< |±19%|	< |±24%|	< |±29%|	< |±35%|	< |±37%|
		10.0m/s	10.8m/s	11.6m/s	12.4m/s	14.2m/s	15.1m/s	15.4m/s

Different wind speed limits for the fan pressurisation method are available in different standards, such as the ground wind speed <2m/s in the American standard ASTM E779 [6], meteorological wind speed<5.5m/s in the Canadian Standard [47] and meteorological wind speed <6m/s in the European Standard EN 13829 [48]. The experiment work of the 423 tests provides insights into whether these wind speed limits could also be applicable to the Pulse testing.

Based on the research by Zheng, et al. [40] using a multi-gear portable trailer fan to provide various artificially imposed steady wind conditions, they found the test conditions were under the steady wind speed below 3.5m/s at 1.5m above ground level with a fixed wind direction for the *RPD* within ±3%. Differently, according to the observations in this study, the wind speed limit was noted as 2.1m/s (i.e., meteorological wind speed of 3.3m/s) with the *RPD* < |±3%|, and the test is advised to be performed at <5.0m/s (i.e., meteorological wind speed of 7.9m/s) for the *RPD* within ±10%. Both studies investigated the wind speed limit that allowed Pulse to produce repeatable and accurate measurements (e.g., within ±3%), and a different pattern in the airtightness variation is shown between the two studies when the wind level was beyond the limit, for instance, a noticeable decrease in the obtained airtightness values with the increased wind speed was found in [40], while the measurement results in this study were more diverse and scattered in a wide range. This might be attributed to: (a) the different building configurations, i.e., the small-size outdoor chamber compared to the five-bedroom dwelling; (b) the test building leakage level and distribution are different from each other; (c) two different experienced wind conditions, i.e., the fix-direction steady wind conditions in contrast to the natural wind conditions with unprecedented wind directions and fluctuations; (d) the analysis presented in this section does not consider the wind direction impact; and (e) the occurrence of wind gust during the test period, which may influence the building airtightness measurement, but was not able to be precisely captured by the anemometer, due to the time delay caused by the distance between the anemometer and the test building, as well as the dynamic nature of the gusty wind.

3.2 Impact of wind direction

As introduced in Section 2.1, an ultrasonic anemometer was installed in the backyard of the tested dwelling at the height of 2.2m above ground at a distance of 12m away from the nearest perimeter of the test building to record the wind speed and wind direction during the testing period. In terms of site analysis, the test dwelling orientation is shown in Figure 13(a). Considering the anemometer orientation and building geometry, for the wind blowing to edges of the façade facing the backyard, the corresponding wind direction degree measured by the anemometer ranges from 217° to 273° as illustrated in Figure 13(b).



(a) (b)

Figure 13: Illustrations of (a) test dwelling orientation and (b) anemometer orientation and wind directions with respect to test dwelling

In total, 423 Pulse tests have been conducted under different wind conditions. A wind rose plot is produced in Figure 14, to provide an overview of the wind condition distribution (i.e., wind speed and wind direction) of the 423 tests; the vertical axis represents the number of the Pulse tests. It shows most of the tests were conducted with the wind direction degree from 220 to 270°, which is mainly attributed to the prevailing west to south-westerly winds in the UK.

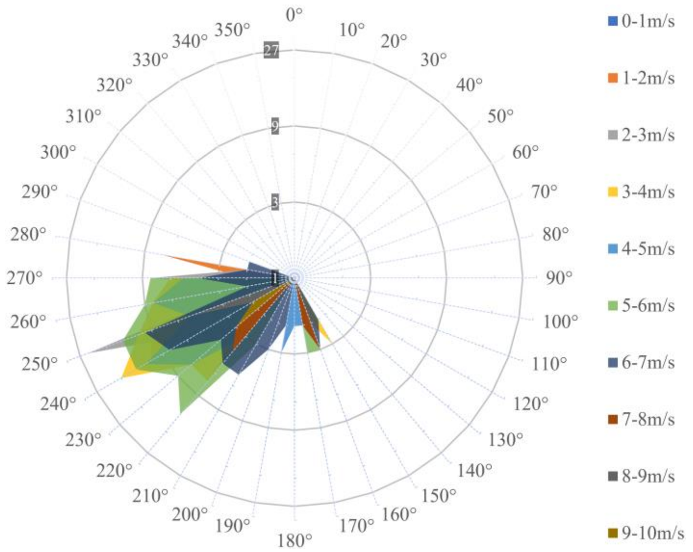


Figure 14: Wind rose plot of wind condition distribution of 423 tests

More specifically, the wind direction distribution and the associated number of tests is shown in Figure 15. The wind direction range for all the 423 tests is from direction degree of 60° to 300°, while no tests have been conducted with the wind direction from 300° to 60° due to climatic characteristics in Nottingham, UK during the test period. Comparatively, the wind direction degree of 250° has the greatest number of the Pulse tests, in total about 85 tests, accounting for around 20.1% of the total 423 tests, followed by the wind direction degree of 240° with 78 tests.

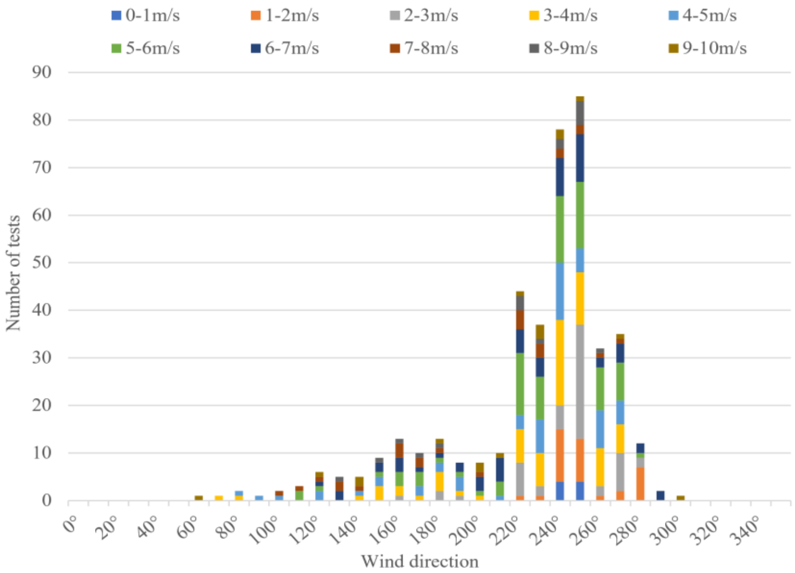


Figure 15: Wind direction distribution of 423 tests

For analysis, the 423 tests are categorised into three groups according to the wind direction degree, including Group A: 65°-217°; Group B: 217°-273° and Group C: 273°-65°. There are 101 tests in Group A, 301 tests in Group B, and 21 tests in Group C. Figure 16 depicts the respective wind direction categories experienced by the tested dwelling during testing, showing the windward/leeward façade of the house in different wind direction categories.

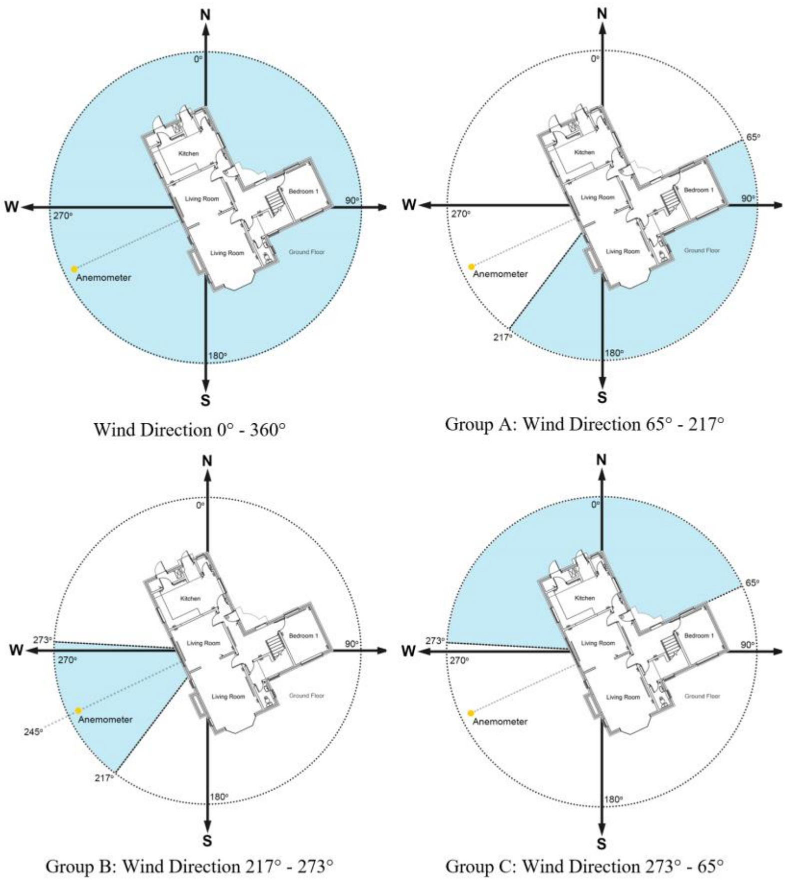


Figure 16: Illustration of different wind direction categories in relation to the test dwelling

The measured ALRs under different wind directions are plotted in Figure 17. Group B has the largest number of tests for the wind speed ranging from 0.1 to 9.8m/s (i.e., 301 tests), while the wind speed range of Group A is 2.0-9.7m/s with 101 tests, and less tests were implemented in Group C (i.e., 21 tests), with the wind speeds mainly fallen in the range of 1.1-2.7m/s and 5.7-6.8m/s. In the overlapped wind speed range (i.e., 2-3m/s), the tests in Group B provided ALR measurement results higher than those of Group A and C, with the average ALR of 294.64m³/h, 276.04m³/h for Group A and 281.36m³/h for Group C. The difference in the average ALR may be caused by the building geometry and orientation effect, for instance, the windward façade of the test building has a larger envelope area as well as a larger glazing area when the wind is in the direction range of 217-273° (i.e., Group B). In the wind speed range of 6-7m/s, larger differences among the three groups were noted, Group C has larger average ALR results (i.e., 328.13m³/h), which is approximately 5.74% higher than that of Group B (i.e., 309.31m³/h) and 21.84% higher than Group A (i.e., 256.47m³/h). It can also be seen from the figure, the tests in Group B provided measurement results that were less susceptible to the variation in wind direction, with the maximum difference of 22.15% in the ALR measurements over the tested wind speed range, while the maximum difference reached 55.53% for Group A.

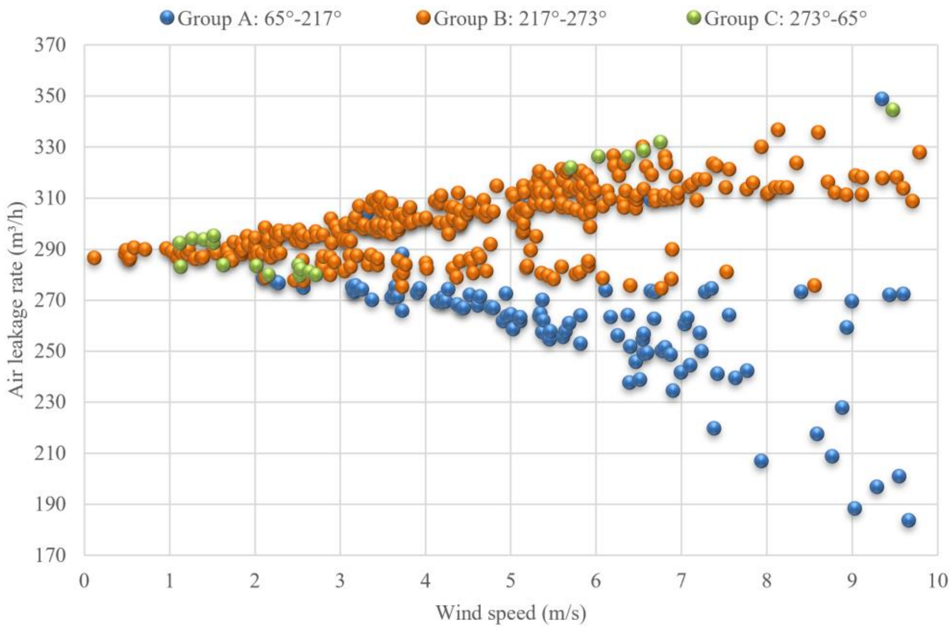


Figure 17: ALR measurements under different wind directions

This could also be observed in the violin plot in Figure 18, as the three groups have distinct distribution shapes. In addition, each group has different median ALRs and interquartile ranges. Comparatively, Group A and Group C have relatively larger dispersions of the ALR data, while the ALRs of Group B are more centralised in the interquartile range. In this study, Group B has the greatest number of tests (i.e., 71% of the total tests), owing to the UK's prevailing west to south-westerly winds, while 24% of the tests were in Group A, and 5% in Group C. Hence, based on the obtained data, the Pulse test is preferably performed in the tested dwelling, with the wind direction in the range of 217°-273°, for a reduced wind direction impact on the airtightness measurement. This finding may not be applicable to the Pulse testing in other buildings, as the building configuration and local wind characteristics vary; nevertheless, it provides insights into the wind direction effect on the Pulse test under natural conditions.

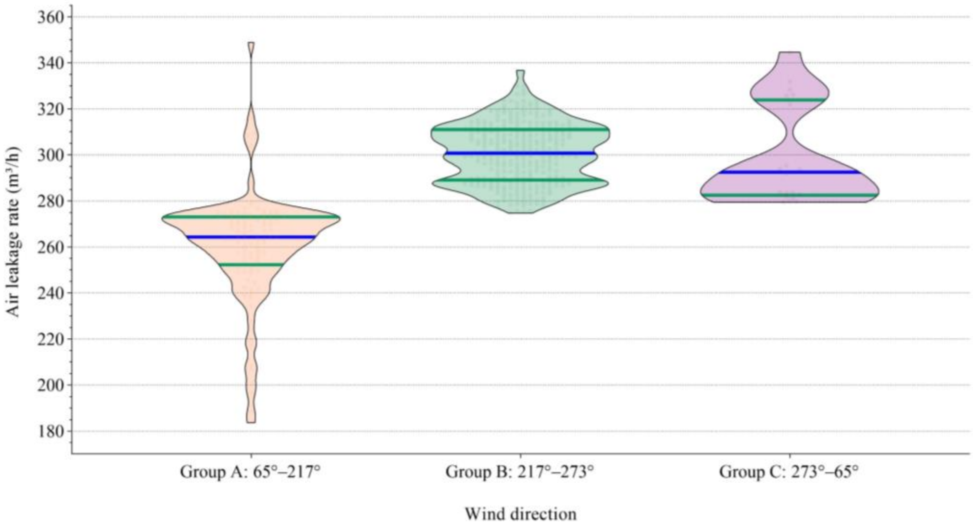


Figure 18: Violin plot of ALR results under different wind directions

Furthermore, the impact of the wind direction is less significant when the corresponding wind speed is at a low level. It can be noted from Figure 17, the average ALR measurement for tests in Group B is around 289.13m³/h in the wind speed range of 0-2m/s with a difference of 3% between the highest and the lowest measurements, while the discrepancy becomes more noticeable for the wind speed above 3m/s, with the maximum difference of 61.07m³/h in the wind speed range of 8-9m/s. Similar results are found when comparing different groups. For instance, the ALR of 292.48m³/h was measured at 1.5m/s in Group C, while the measurement of 290.40m³/h was obtained in Group B, with a difference of 2.07m³/h. However, the difference becomes much larger comparing the measurement of Group B with that of Group C at the wind speed of 6.8m/s, which is 57.27m³/h, and the difference between Group C and Group A at the wind speed of 9.5m/s reached up to 117.25m³/h. This is also because of the limited available tests in Group C. Therefore, a similar recommendation could be made, as discussed in Section 3.1, that the Pulse test is recommended at the calm wind condition (e.g., at lower wind speed level) for the building airtightness measurement with minimal wind impact. For example, the threshold wind speeds for *RPD* within 10% were different based on the measurements of the three groups, 5.0m/s at 2.2m above ground level for Group A, 5.32m/s for Group B and 5.71m/s for Group C. Furthermore, the results reveal that the degree of the wind direction impact on the Pulse measurement could be influenced by the building geometry and orientation, such as the envelope area of the windward façade and the location of the openings.

3.3 Impact of multiple tests

As the Pulse test is easy and quick to perform, conducting multiple tests could be a practical solution to minimising wind impact when the wind condition is adverse. While it is universally true that by performing multiple tests, the margin of error can be reduced, it is not always practical or cost-effective to do so in practice. Considering that the duration of the actual pulse test is short, it is practical to run multiple tests. In this section, an assessment is conducted to evaluate how multiple Pulse tests could contribute to minimising the wind impact on the Pulse measurement.

For more in-depth discussions, the total 423 tests are divided into 20 groups based on the wind speed interval of 0.5m/s (i.e., from Group A: 0-0.5m/s to Group T: 9.5-10m/s). Assessments are performed based on three cases to include all the practical testing scenarios, including: (1) single test, (2) multiple tests in each group and (3) the first three tests in each group. Table 5 lists the detailed results for Group A to Group T, with regard to the ALR for each case and the corresponding *RPD* by comparing with the baseline ALR.

Table 5: ALR results for the 423 tests

Test Group	Wind Speed (Ground Level)[1]	Number of Tests	Group Average ALR	First Three Tests Average ALR	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 Conditions 0 – 0.5 m/s (3 Tests)			**Baseline: Average ALR (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 baseline ALR.
3. The relative percentage difference of average ALR of each group to the baseline ALR.
4. The relative percentage difference of average ALR of the first three tests to the baseline ALR.

The results listed in Table 5 demonstrate that a minimised wind impact on the building airtightness measurement could be achieved with an increased number of the Pulse tests. For instance, for the single Pulse test conducted at the wind speed ranging from 5.0 to 5.5m/s (i.e., Group K), the maximum *RPD* was approximately |-11.69%|. By considering the first three tests in Group K, the *RPD* reduced to |-3.42%|, and the *RPD* was only around 1.84% when taking all the 43 tests in Group K into consideration. Although it would be impractical to conduct a large number of the Pulse tests in practical scenarios, running three Pulse tests could also make a difference. The difference became more significant under adverse windy conditions; for example, the *RPD* decreased by 6.6% in Group G (i.e., 3-3.5m/s), while the reduction in *RPD* was 17.8% in Group T (i.e., 9.5-10m/s).

On the other hand, the *RPD* of each group was within ±5% at the wind speed <8m/s, and the *RPD* of the first three tests fell within ±5% when the wind speed was below 6m/s. However, the recommended wind speed limit for a single Pulse test is about 3.1m/s for an *RPD* within ±5%, as discussed in Section 3.1. Therefore, in practical circumstances, the multiple Pulse tests could be a solution to obtaining the building airtightness measurement with a reduced wind impact under inevitable windy conditions.

The violin plot in Figure 19 shows the shapes of ALR distribution for the three cases, which clearly visualises the difference between the three cases. By conducting the multiple Pulse tests, the difference of ALR between different wind speed ranges is much less significant compared with the ALR that is obtained from a single Pulse test under various wind conditions. Although the median ALRs for the three scenarios are close, the interquartile range describing the range in values of the central 50% of ALRs differs widely, suggesting the benefit of performing multiple Pulse tests in minimising the wind impact on the Pulse measurement.

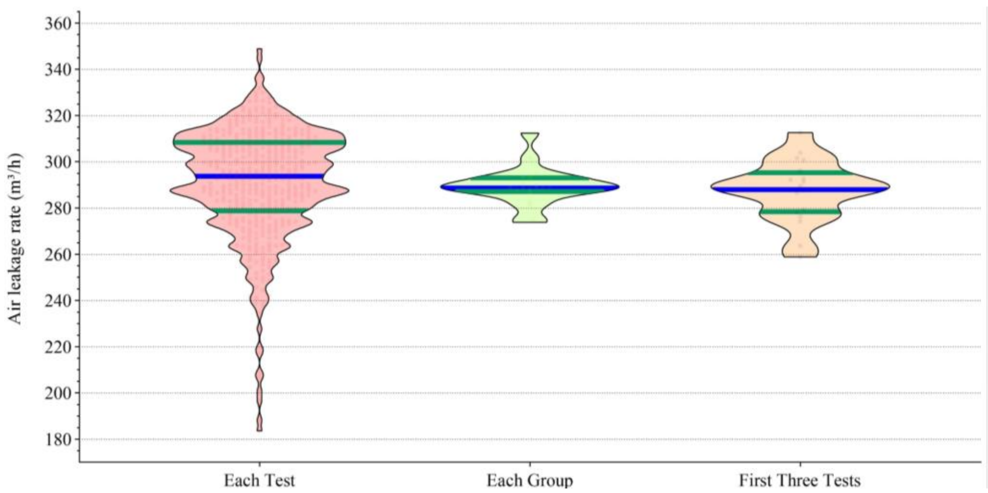


Figure 19: Violin plot of ALR results for the 423 tests, by each test, each group and first three tests

Besides evaluating the first three tests in each group, further investigations are conducted to provide insights into how the *RPD* reduces when comparing a single Pulse test with three-multiple tests that are randomly selected from all 423 tests. Theoretically, the total number of combinations for three-multiple tests is 12,525,171. The *RPD* distribution is provided with the corresponding number of combinations in Figure 20, and the *RPD* of +3% has the highest probability with the most combinations (i.e., 1,142,399 combinations, accounting for 9.12%). The pie chart in Figure 21 shows the detailed proportion of each *RPD* among all combinations over the entire wind speed range. It shows that the majority of the three-multiple Pulse tests (i.e., 97.07%) could achieve an *RPD* within ±10%, while the *RPD* < |±3%| accounts for 49.43%, and 71.80% of the combinations have an *RPD* < |±5%|. Only a very small proportion (i.e., 2.93%) has an *RPD* beyond ±11%. Therefore, the assessment shows that by performing multiple Pulse tests, the adverse wind condition impact on the Pulse testing can be significantly reduced.

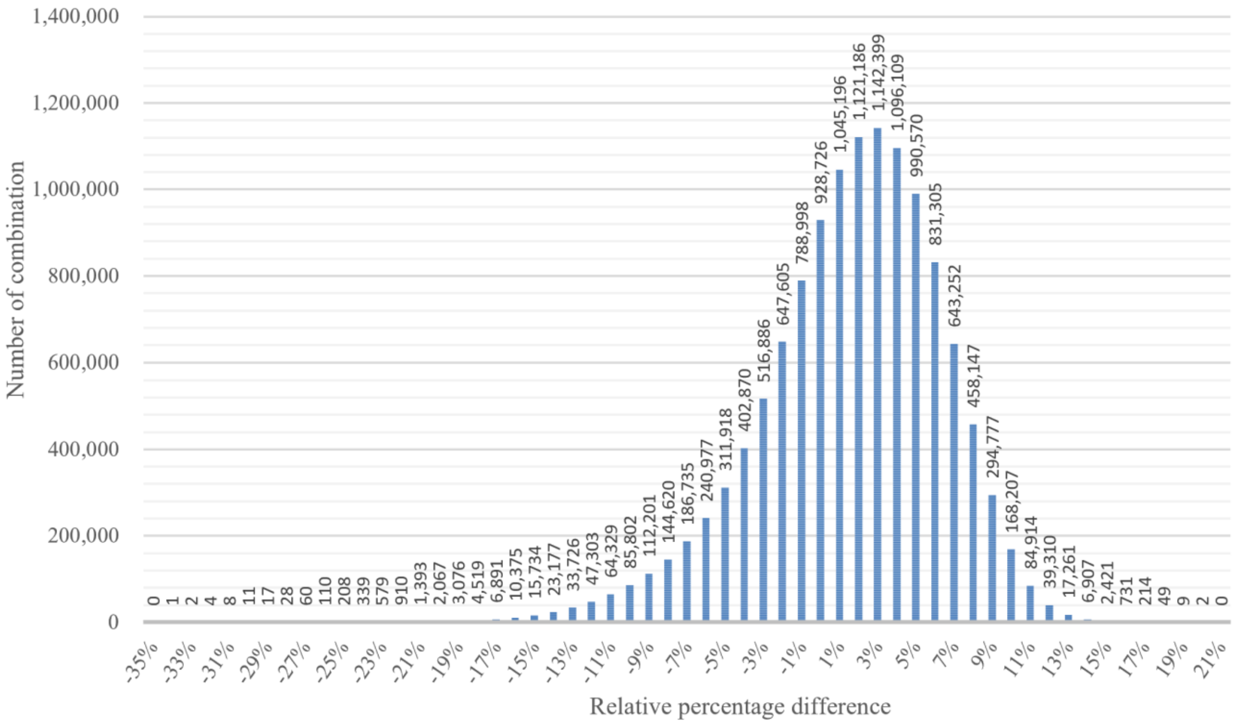


Figure 20: *RPD* distribution with the corresponding number of combinations

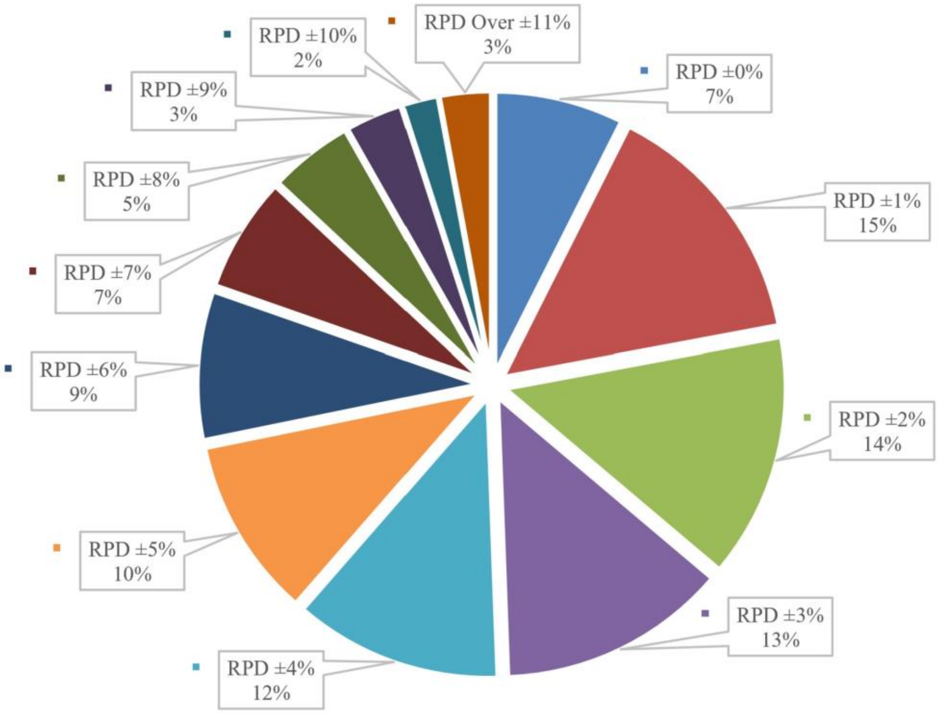


Figure 21: *RPD* distribution and the corresponding proportion

3.4 Discussions

The investigation in this study allows us to gain a general insight into the wind impact on the Pulse test under natural wind conditions. It is acknowledged that there are a few aspects that remain to be improved in future investigations to achieve an in-depth understanding. Due to the restricted site access and health/safety concern, the installation of the ultrasonic anemometer was limited to the ground level, thereby making it practical and ambient-representative to keep a distance (12 metres) between the ultrasonic anemometer and the house perimeter. It was not possible to fully eliminate the influence of temporal delay and spatial difference due to the uncertain nature of wind, but such impact is recognised and was accounted for in the analysis. In addition, the leakage distribution has a bearing on how wind might affect the Pulse test, which, however, was not considered due to various reasons, including technical barriers and time constraints. This type of in-situ study still remains under-investigated and should be a further area of research. Finally, the random nature of wind poses difficulty in fully isolating the impact of wind speed from the wind direction. Therefore, a model-scale experiment within a wind tunnel is recommended to evaluate the wind impact on the building airtightness measurement under more controllable wind speed conditions and with a more configurable building model to achieve various leakage scenarios (e.g., leakage type and distribution). Mélois [49] performed steady pressurisation tests with a scalable building model to investigate the effect of different configurations of leakage distribution between windward and leeward façades on the measurements under various steady wind conditions. Further work on a model-scale experiment is needed to achieve a thorough examination of how various wind factors and leakage factors (including distribution and type) affect the Pulse measurement.

4 CONCLUSIONS

The literature review has highlighted the gap of investigations of the Pulse test performance under different natural wind conditions and addressed the wind impact on the building airtightness measurement. In total, 423 Pulse tests were implemented to measure the building airtightness of a five-bedroom detached dwelling under natural wind conditions. A relative percentage difference (*RPD*) of each test was determined by comparing each measurement with the average building air leakage rate at low wind speed conditions (<0.5m/s) and used to evaluate the wind impact on the Pulse measurement. According to the measured air leakage rate results of the tested dwelling, the preferred test wind speed for the Pulse test was below 3.14m/s at 2.2m above ground level (i.e., approximately equivalent to the meteorological wind speed 4.95m/s based on the test location) if the *RPD* falls within ±5%. The observed threshold of wind speed that gave the Pulse measurements an uncertainty of ±10% is 5.0m/s at 2.2m above ground level (i.e., approximately equivalent to meteorological wind speed 7.9m/s based on test the location). When the wind speed is greater than 7.4m/s at 2.2m above ground level (i.e., approximately equivalent to meteorological wind speed 11.6m/s based on test the location), the resulted measurement uncertainty exceeds ±20%. On the other hand, the directional wind studies showed that at lower wind speeds (<5m/s at 2.2 above ground level), wind direction has a lesser influence on the Pulse measurement than the wind speed itself.

The findings of the suggested wind speed limit in this study could be used as supporting information for considering the wind impact when conducting the Pulse testing in practical conditions. In addition, the experimental results also imply the benefit of performing multiple Pulse tests in practical testing when adverse wind conditions are present.

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