Evaluation of the Indoor Pressure Distribution During Building Airtightness Tests Using the Pulse and Blower Door Methods

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ABSTRACT

Building airtightness is a critical aspect for energy-efficient buildings as the energy performance of a building can be significantly reduced by poor airtightness. The Pulse technique has been regarded as a promising technology, measuring building airtightness at a low pressure of 4Pa. However, due to the rapid dynamic nature of the test, a frequently raised question concerns the uniformity of the pressure distribution across the internal space of the test building during the air pulse release. In order to investigate this point, experimental work was conducted in a five-bedroom dwelling. All the tests were conducted at wind speeds less than 0.45m/s to minimise the wind impact on the indoor pressure. The results show a pressure difference within the building during the Pulse test does exist, but considering the accuracy of differential pressure transducers, the deviation is not significant. In addition, a subtle variation is noted when the Pulse test was conducted at different locations on the ground floor, which may also be caused by variations in the environmental conditions. In terms of the airtightness measurement, a good overall agreement was found between the Pulse technique and the conventional blower door fan pressurisation method, which indirectly verified the uniformity of the indoor pressure distribution during both tests. Moreover, the error analysis demonstrated the validity of the measurement results for the two test methods in this study.

KEYWORDS

Building airtightness, The Pulse technique, Blower door, Pressure distribution, Unsteady approach, Energy efficiency

1 NOMENCLATURE

Symbols

C	Air flow coefficient ($m^3/s/Pa^n$)
C_t	Constant
ΔE	The measurement error of isentropic expansion
n	Air flow exponent
P	Pressure (Pa)
$P_{livingroom}$	The living room pressure (Pa)
P_{room}	The room pressure (Pa)
ΔP	The building pressure difference (Pa)
ΔP_{Room_Living}	The pressure difference between the room and the living room (Pa)
$P(t)$	Transient air pressure in the compressor tank (Pa)
Q	Air leakage rate (m^3/s)
Q_{in}	The net fluid flow rate of the test pace (m^3/s)
Q_{out}	The fluid leakage rate of the test pace (m^3/s)
ΔQ	The measurement error of air leakage rate
$Q_P\{t\}$	The volumetric air flow rate in the compressor tank (m^3/s)
$q\{t\}$	Building air leakage rate (m^3/s)
R	Gas constant (J/kg·K)
R^2	The coefficient of determination
T	Temperature (K)
V	Volume (m^3)
V'	The volume of air receiver (m^3)

Greek letters

δm	The measurement error of air mass
δQ_e	Overall error (%)
δQ_{bias}	Bias error (%)
$\delta Q_{precision}$	Precision error (%)
$\delta Q_{modelling}$	Modelling error (%)
ρ	Air density (kg/m^3)
γ	Specific heat ratio

Abbreviations

DBB	Duct Blaster series B (blower door unit)
RPD	Relative percentage difference
S1	The Step-one test in a three-step Pulse test
S2	The Step-two test in a three-step Pulse test
S3	The Step-three test in a three-step Pulse test

Subscripts

0	Initial
i	Internal

1 INTRODUCTION

1.1 Background

In recent years, energy-saving has attracted increased attention, especially in the domestic sector, as this sector alone accounted for 28% of the UK's energy consumption in 2017 [1]. Research shows that domestic energy consumption is dominated by several factors, such as household characteristics, building energy performance and electrical appliances. Building energy performance plays a critical role in energy conservation and it can be significantly affected by ventilation due to the impact of uncontrolled air leakages (i.e. air infiltration) across the building envelope [2]. Researchers have confirmed that thermal losses from the building envelope are mainly attributed to heat transfer and ventilation, including infiltration (e.g., Ref. [3-5]). Airtightness is regarded as the fundamental building property that impacts infiltration and exfiltration [6]. Due to the fact that building airtightness is a crucial factor for energy-efficient buildings, the influence of poor airtightness on the built environment has aroused wide concern since the 1970s. The impacts of poor airtightness have been widely discussed from different perspectives, such as interfering normal operation of mechanical ventilation systems, more building energy consumption, damage of building structures, cold draughts, poor indoor air quality and lower acoustical performance [7-12].

The increasing demand for more energy-efficient buildings and the need to demonstrate compliance with more stringent building regulation requirements in the future reveal the important role of airtightness in buildings [13, 14]. The blower door method is a well-known and widely accepted steady-state pressurisation method, which can be implemented by fan pressurisation in a range of pressure differences, usually in steps of 10–60Pa [15]. For the blower door test, a range of steady pressure differences across the building exterior is created with a blower door fan, and the corresponding air flow rate through the fan is measured simultaneously for establishing the pressure-leakage relationship of the tested dwelling. However, it comes with disadvantages due to high-pressure measurement, a requirement for skilful operation and not maintaining the building envelope integrity. To overcome some of the issues, efforts have been made to explore and develop alternative methods [16-18]. One of them is the Pulse technique, which measures the building air leakage at lower pressures. From herein, this technique is referred to under the proper noun ‘Pulse’, in contrast to ‘pulse’, which refers to the actual physical pulse of air released. Typically the test is performed in the range of 1-10Pa and reported at 4Pa, which has been regarded as a more precise indicator of the pressure level experienced by buildings under natural conditions than conventional steady-state measurements at 50Pa [19]. It measures the building air leakage by rapidly releasing a known volume of air (*air pulse*) into the test building, thereby creating an instantaneous pressure rise and quickly reaching a “quasi-steady” condition [20-22]. Theoretically, the underlying principle of Pulse is the establishment of a quasi-steady flow, which has been proved via the temporal inertial model as given in Ref. [23-25]. Pulse is capable of measuring the building airtightness dynamically within a short period, typically 11-15s. The quick measurements of the corresponding change in the indoor pressure and the pressure change in the air tank can be measured to obtain the building air leakage rate at 4Pa. Due to the short-time operation, Pulse minimises the effects of wind and buoyancy forces and has been proven to be highly repeatable and of great practical value as demonstrated in Ref. [26-28]. However, questions have often been asked by both industrial professionals and academic researchers in relation to the test viability due to the dynamic nature of the test. One of the frequently raised questions considers the uniformity of the pressure distribution across the internal spaces of the test building during the air pulse release. Experimental work is conducted in a five-bedroom detached house to verify whether a uniform indoor pressure distribution can be achieved during the Pulse pressurisation process. This distribution is also compared with that of a steady pressurisation test. In addition, the effect of the pulse release location on the building airtightness measurement is also investigated. This paper is an extension of work originally presented in 40th AIVC Conference [29]. The tests in this study are routinely done as part of the ongoing development of Pulse, and the investigation presents results of testing using the latest Pulse equipment as an answer to the aforementioned questions.

1.2 Theoretical Understanding

Some issues have been noted for building airtightness testing using the steady pressurisation method, for instance, the requirement of a large amount of airflow for pressurisation [30, 31]. It is considered impractical in most instances to apply the steady pressurisation method for large buildings, as a high-capacity fan system is needed to deliver the required amount of airflow (e.g., a pressurisation test at 50Pa for a typical large building of 100,000m^3, the required air flow rate is 1,000,000m^3/h). Although this can be limited by decreasing the pressurisation level, such as from 50Pa down to 25Pa or lower, measurements at low pressures may result in large errors due to wind and buoyancy effects [32]. To address the limitation, Pulse was developed to allow accurate testing at much lower pressures, while negating the need for large airflow delivery. During the Pulse test, a pulse in the internal pressure is created with the release of a short burst of air from a pressurised air tank into the indoor space and a period of quasi-steady flow is achieved accordingly. For context, a typical air tank would be of volume 40-Litre at 10 bar pressure for a 3 to 4-bedroom modern residential dwelling in the UK. Based on the previous investigations (e.g. Ref. [23, 33]), the unsteady flow only accounts for less than 1% of the overall flow within the quasi-steady period. During testing, the building pressure is monitored for three key stages, as illustrated in Figure 1, including the pressure variation during the quasi-steady period, the background pressures before and after the pulse [21].

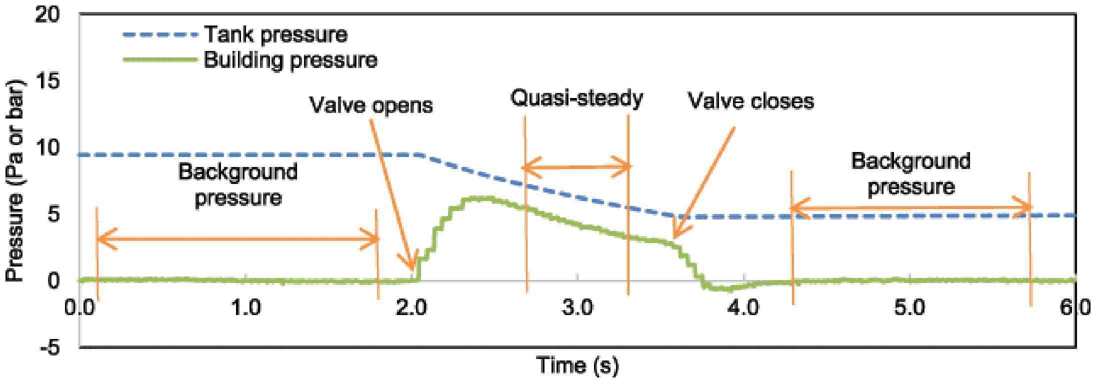


Figure 1: An example of the Pulse testing [21]

Another concern for using the steady pressurisation method for buildings of large volume is the difficulty of achieving an even building pressure distribution [32]. Different sources during the steady pressurisation testing may cause an uneven pressure distribution, such as the vicinity of the door unit where the blower door is installed. Pulse was developed to address such an issue, by measuring the building air leakage at various pressure levels in a dynamic manner [34]. Pressure variations in the building and tank are measured in order to establish the pressure-leakage relationship. Considering the background pressure variation, the adjustment method for the Pulse testing deducts the background pressure from raw data [21]. Peer researchers and practitioners have questioned the reliability and accuracy of Pulse, mainly due to the likelihood of an uneven pressure distribution over a short test period. Therefore, there is a necessity to provide insight into exploring the indoor pressure distribution during the Pulse pressurisation process.

Uneven pressure distributions could result in an error to the calculation of leakage area at a reference pressure, inaccurate quantification of required air flow rate, and thus inaccurate building airtightness measurements. Being conscious that the actual pressure distribution is more complex, for the ease of understanding the authors uses Figure 2 to illustrate a simplified diagram to describe the mathematical problem regarding the uneven pressure distribution in a test space with two different pressure levels established by a net fluid flow rate Q_{in}. Q_{out} is the rate of the airflow leaking out of the test space. The sensor is placed in the central zone giving a pressure reading of P_2 to represent the pressure in the whole zone, and the actual pressure in the outer zone is represented by P_1. Therefore, based on the assumption of a uniform indoor temperature, the measurement error of air mass (δm) within the test building can be described by eq. (1) using the continuity equation and ideal gas law:

$$\delta m = \frac{P_2 - (\frac{P_1V_1 + P_2V_2}{V_1 + V_2})}{\frac{P_1V_1 + P_2V_2}{V_1 + V_2}} = \frac{|P_2 - P_1\,|V_1}{P_1V_1 + P_2V_2} \tag{1}$$

Where V_1 and V_2 are volumes of the outer zone and the centre zone, respectively.

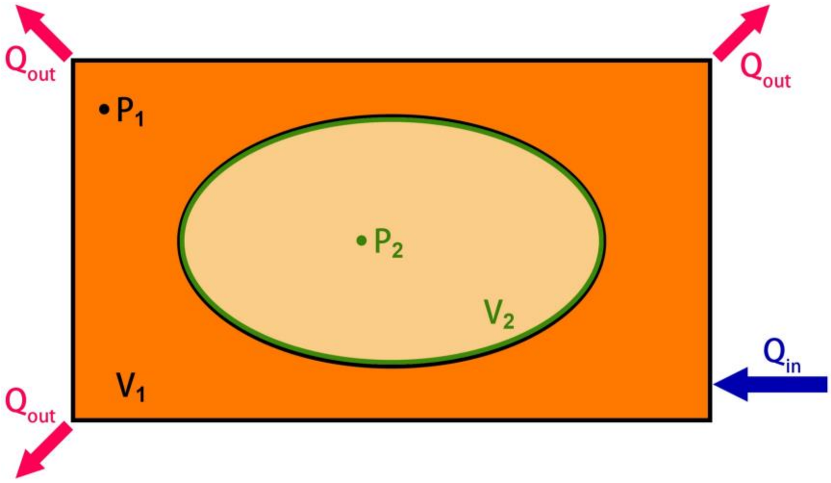


Figure 2: Diagram of uneven pressure distribution in building under pressurisation

As seen, the error is determined by the pressure difference between P_1 and P_2, and the volume V_1. It thus indicates that a uniform pressure distribution within the test space could contribute to minimising δm. Figure 3 presents examples of how the uneven pressure distribution (represented by $\frac{P_1}{P_2}$) and the different size of V_1 (represented by $\frac{V_1}{V_2}$) influences the measurement of the air mass. It can be noted that the measurement error increases remarkably as the size of V_1 increases, and the impact is greater at a larger pressure difference. Hence, evaluation needs to be given to the level of the error produced by various levels of pressure uniformity, which can be obtained according to the achieved uniformity in both the Pulse and blower door tests. The corresponding error in the calculated building air leakage can then be provided. This evaluation can be done according to two different scenarios, different sizes of V_1 and the different percentage differences between P_1 and P_2.

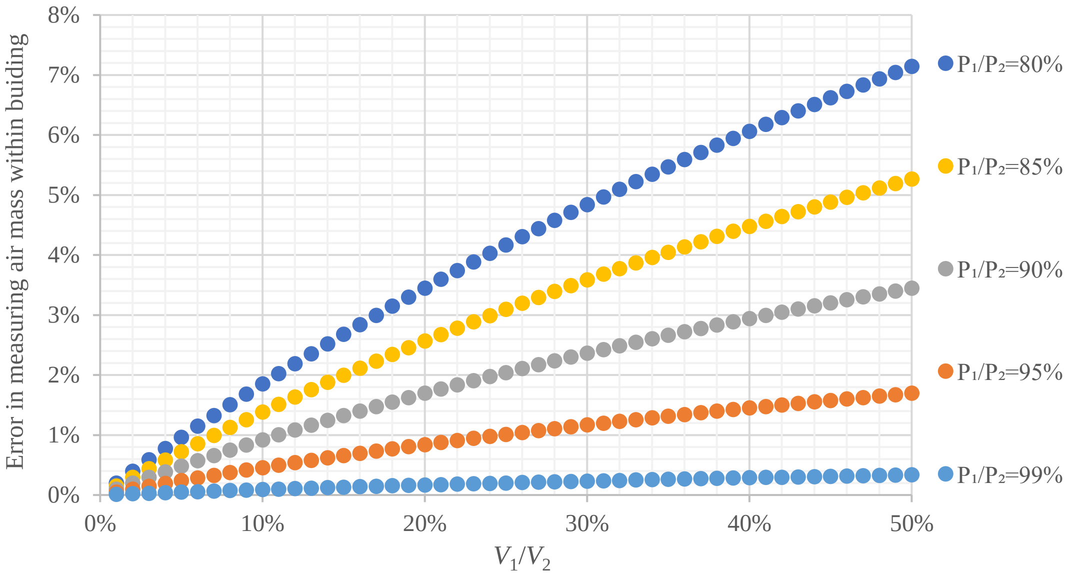


Figure 3: Measurement error of air mass increases with different percentages of V_1 and pressure differences between P_1 and P_2

2 METHODOLOGY

2.1 Dwelling

According to the English Housing Survey, the average (mean) usable floor area of English dwellings in 2018 was 94m^2 [35], and if multiplied by a typical floor to ceiling height of 2.5m, the average property volume is about 235m^3. Figure 4 shows the mean usable floor area by dwelling type, based on the English Housing Survey [36]. It can be seen that the majority dwelling type have a mean volume below 300m^3, while the detached house has a mean volume of 381m^3.

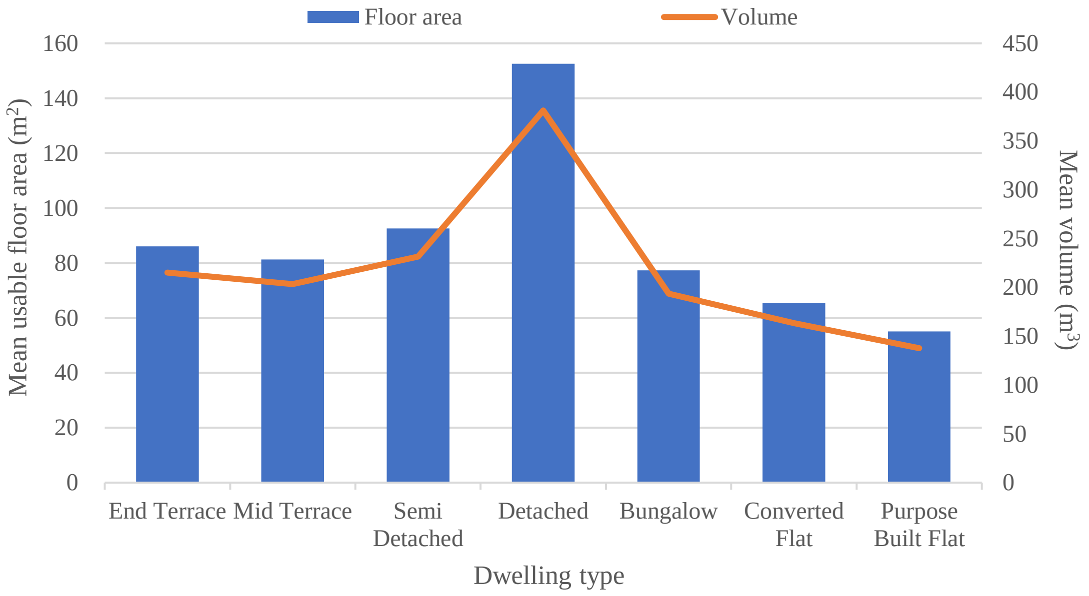


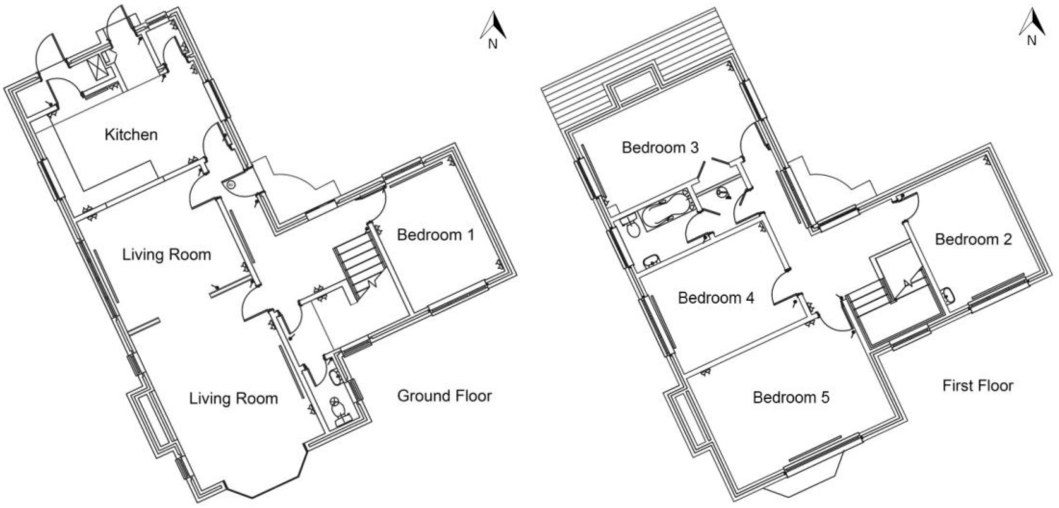
Figure 4: Mean usable floor area by dwelling type [36]

In this study, a five-bedroom detached house located on the University of Nottingham's University Park campus was chosen as the test building. Figure 5 shows the front and back views of the dwelling, and Figure 6 presents the floor plans. The house has one bedroom, one living room, one kitchen on the ground floor and four bedrooms on the first floor.

a

b

Figure 5: Tested building (a) front view and (b) back view



a b

Figure 6: Tested building (a) Ground floor plan and (b) First floor plan

The building parameters are listed in Table 1. This house has a volume of 447m^3, which is above the average volume of detached houses, as seen in Figure 4. Therefore, the size of this house is large enough to represent the worst-case scenario, providing a good case for the investigation of the uniformity of pressure distribution during the Pulse test.

Table 1: Tested dwelling parameters

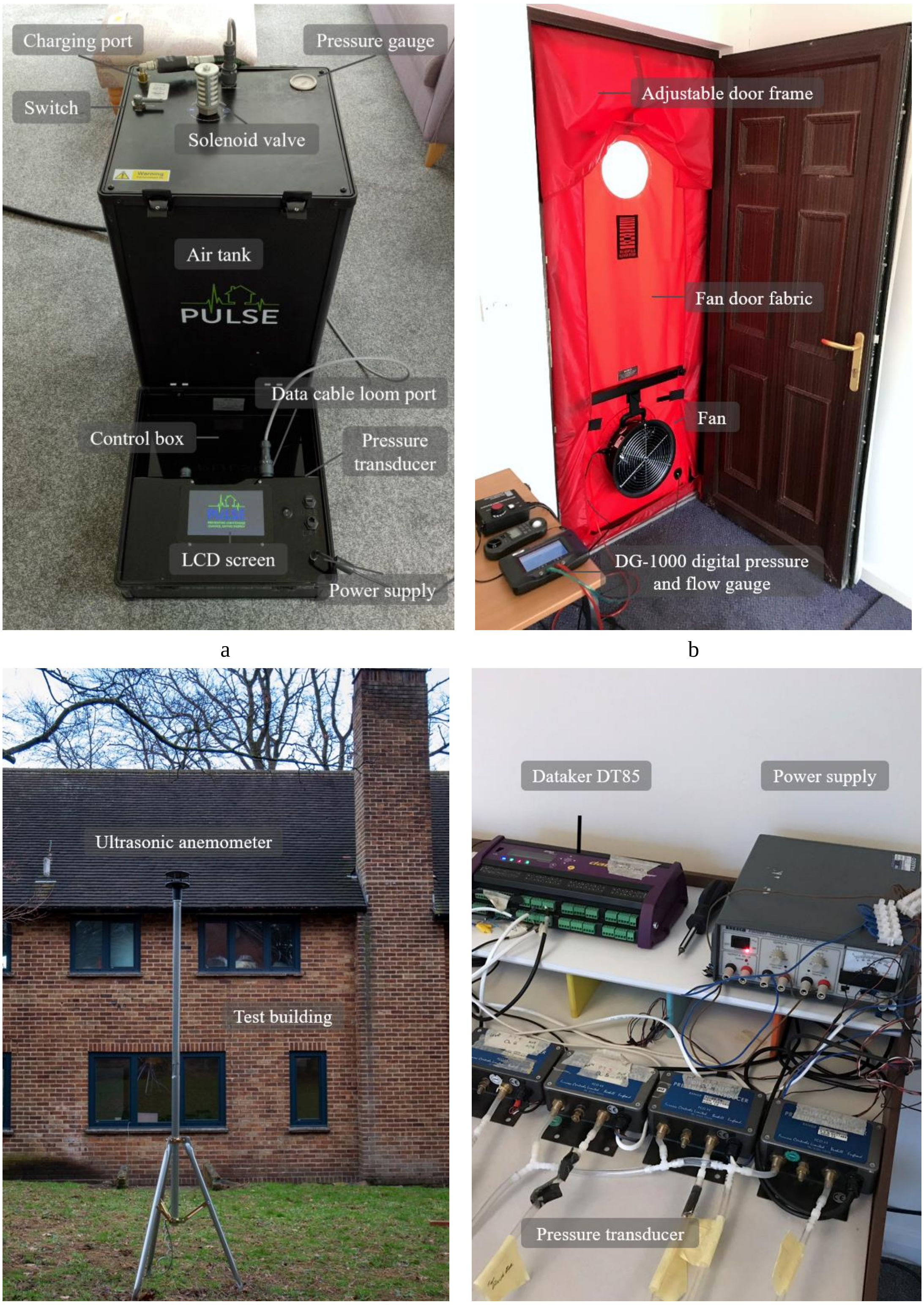
Dwelling	Wortley 5 - University of Nottingham, University Park, Nottingham
Type	Five-bedroom detached house
Year	Built-in 1950 and retrofitted in 2019
Volume (m^3)	447
Envelope area (m^2)	416

2.2 Equipment

A number of devices were used for this experimental work as listed in Table 2. A PULSE-60 unit (Figure 7a), which consists of a 58.5-litre lightweight aluminium air tank and oil-free compact air compressor, was used for the Pulse test. A ¾ inch (BSP) solenoid valve was installed at the outlet, allowing the release of compressed air from the air tank into the indoor spaces. In addition, the Pulse test data, such as the chamber and tank pressures, were recorded and analysed by the on-board PULSE-60 control box, with results displayed on the LCD screen, as seen in Figure 7a. In this study, a complete three-step Pulse test consists of three consecutive pulses, namely S1, S2 and S3 (i.e., three pulses are achieved from one compressed air tank without recharging). For the blower door test, Duct Blaster series B (DBB), which is manufactured by The Energy Conservatory (US), was employed. A photo of the DBB unit is presented in Figure 7b. The unit is mainly composed of an adjustable doorframe, a flexible canvas panel, a variable-speed fan and a DG-1000 digital pressure and flow gauge. In order to obtain the weather condition during testing, an ultrasonic anemometer was applied to monitor the outdoor wind condition (Figure 7c), with an accuracy of ±3% [37], and thermocouples were used to measure ambient temperature. Sensitive FCO44 differential pressure transducers (diaphragm-type), which are manufactured by Furness Controls Ltd, were adopted to measure the pressure level of the internal spaces (Figure 7d). A Datataker DT85 data logger was used for the experimental data acquisition, with an accuracy of ±0.1%. All employed instruments with their respective accuracies can be found in Table 9 and Table 10.

Table 1: List of test equipment

Airtightness	**Others**
PULSE-60	Ultrasonic anemometer
	FCO44 Differential pressure transducers
Duct Blaster series B (DBB)	Temperature sensors
	Datataker DT85



a b

c d

Figure 7: (a) PULSE-60 unit with control box; (b) Energy Conservatory Duct Blaster series B; (c) ultrasonic anemometer and (d) Differential pressure transducers and Datataker DT85

2.3 Setup and Test Arrangement

The DBB was installed at the main entrance door of the dwelling, and the pressurisation and depressurisation tests were performed sequentially. The PULSE-60 unit was placed in the living room on the ground floor. For both tests, the dwelling was prepared according to the ISO 9972 standard, therefore the interconnecting doors were kept open for establishing a homogeneous pressure within the house. Figure 8 shows the locations of the Pulse unit and the pressure transducers within the tested dwelling. During the testing, the outdoor wind speed was monitored continuously by the ultrasonic anemometer 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. In this study, all experimental tests were conducted separately but all under a wind speed less than 0.45m/s, which can be regarded as the calm condition based on the Beaufort scale [38]. The purpose of this arrangement was to minimise the wind impact on the indoor pressure distribution, so insights on the pressure distribution during the Pulse and blower door tests could be gained.

Furthermore, the corresponding test validity was examined with checks of the background pressure and zero-flow pressure difference. Five differential pressure transducers were utilised to measure the indoor pressure distribution, with a sampling rate of 4Hz. A higher sampling rate was not possible as the sampling rate of the Datataker DT85 reduces with the increasing number of connected transducers. Hence, a balance between the sampling rate and the number of monitored rooms was made. The accuracy of the differential pressure transducer is ±0.25%, and all five differential pressure transducers were calibrated by connecting to the same tapping point.

Figure 8: Setup locations of test equipment

Differential pressure transducers have two inlet ports, one for the reference pressure and the other connected to each room whose pressure is to be monitored. Figure 9 presents a flow chart for the arrangement of differential pressure transducers used in this study. The reference pressure was obtained by placing the pressure tubing in the attic space of the tested dwelling, giving the same pressure as that of the outdoor environment, but greatly minimising the impact of the varying outdoor weather conditions (e.g., rain, gust wind). The five pressure transducers connecting to the data logger are placed in the living room, and the pressure tubes connected to each room had the same specification in terms of material and dimensions (e.g., length and diameter).

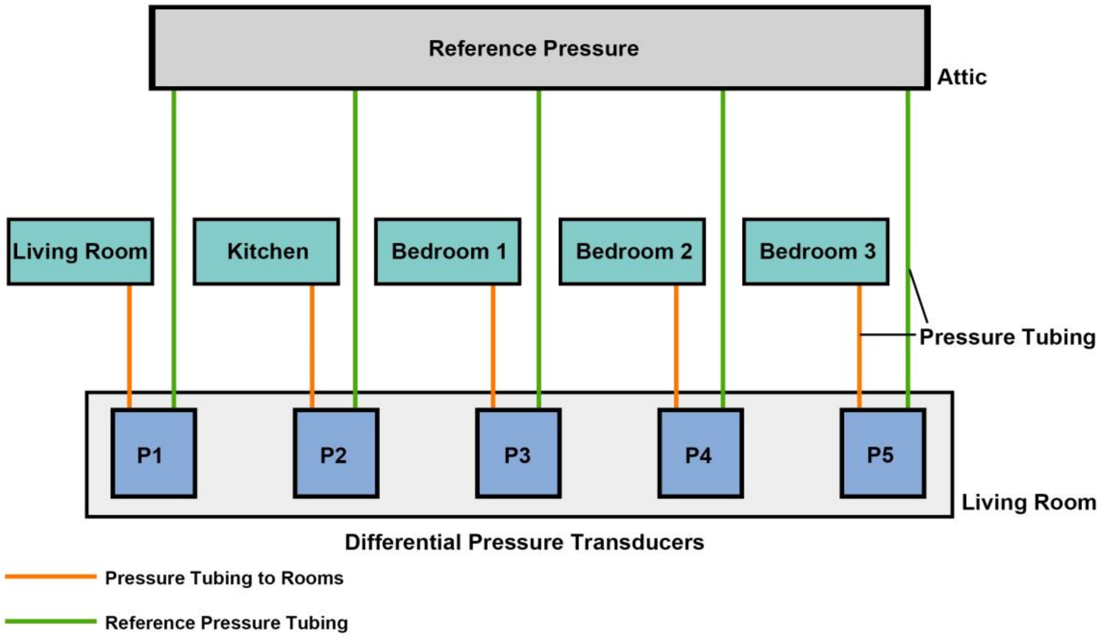


Figure 9: Arrangement of differential pressure transducers

3 RESULTS AND ANALYSIS

It is worth noting that the sampling rate of 4Hz is perhaps insufficient in capturing the complete profile of how the indoor pressures across the internal spaces might vary during the rapid and dynamic air pulse releasing process. However, it still allows us to gain an improved understanding of how the pressures across the building’s internal spaces respond simultaneously to the release of an air pulse in the Pulse test. The long pressure tubes, which were used to minimise the error caused by the equipment setup, also served as pneumatic low-pass filters for pressure readings and therefore an increased sampling rate would not achieve a significant improvement in the pressure readings. It is a limitation in this experimental study. Nevertheless, the experimental investigations on the impact of the pulse release location on the Pulse measurement and its comparison with the blower door measurement provide complementary validations for the uniformity of the pressure distribution from the testing perspective.

3.1 The Indoor Pressure Distribution During the Pulse Test

A series of Pulse tests have been conducted in the house to verify whether a uniform pressure distribution across the internal spaces of the test building can be achieved during the air pulse release so that the viability of the Pulse test for accomplishing building airtightness measurement at 4Pa in a very short period (i.e., typically 11-15s) can also be evaluated. The Pulse unit was located in the centre of the ground floor living room for testing, and the indoor pressure distributions for five rooms on both floor levels (i.e., the living room, the kitchen and the three bedrooms) were measured respectively during the pulse pressurisation process. Figure 10 displays the pressure variation in each room during the complete three-step of the Pulse test (i.e., S1, S2 and S3). A three-step Pulse test consists of three consecutive pulses, and therefore the 1.5-second pressure rise in the third pulse (S3) is much lower than that of the first one (S1) due to the declining tank air pressure. It can be noted that the curves representing the pressure responses in the five rooms are nearly identical, which indicates good uniformity of the pressure distribution across the five rooms during the pulse release. More discussions for each step of the Pulse tests are given in the following sections.

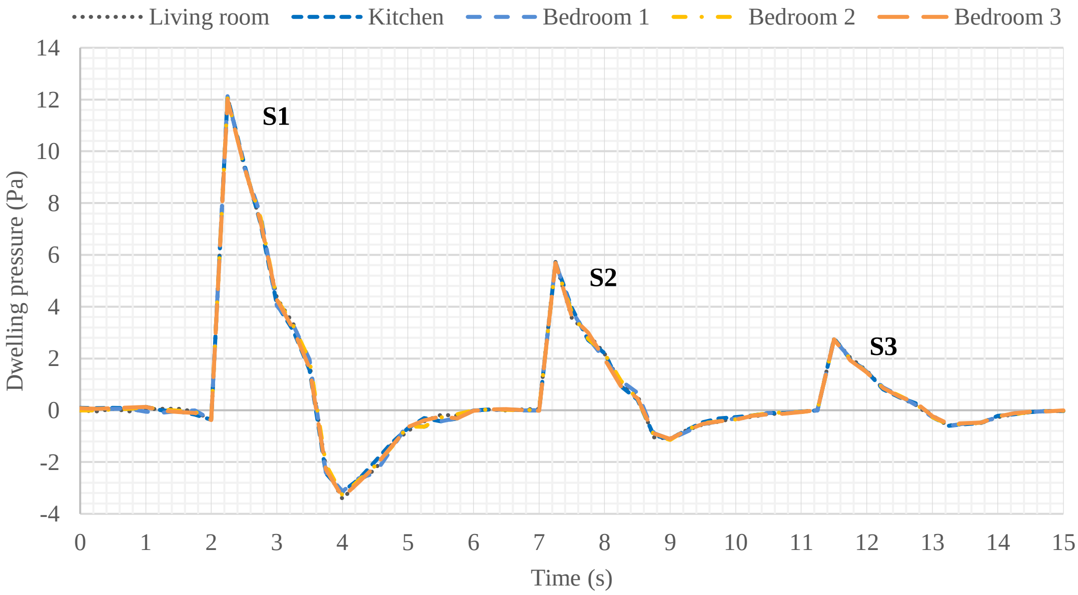


Figure 10: Pressure profiles in the five rooms during the complete Pulse test

Figure 11 shows the measured pressure distribution of each room during S1. Similar trends were observed in the five rooms, and the indoor pressure of every room reached around 12Pa at 2.25s, i.e., 0.25 second after the valve opened and released the compressed air from the tank into indoor spaces. Only slight differences were noted at the peak level. For the evaluation purpose, the Pulse unit was placed in the living room, and its pressure is regarded as the baseline against which the pressures of the other four rooms are compared. Therefore, the relative percentage difference (*RPD*) between the pressures in other rooms and the living room can be calculated using eq. (2).

$$RPD = (\Delta P_{Room\_Living})/P_{livingroom} \tag{2}$$

Where $\Delta P_{Room\_Living} = P_{room} - P_{livingroom}$, ΔP_{Room_Living} represents the pressure difference between the room pressure (P_{room}) and the living room pressure ($P_{livingroom}$).

As seen in Figure 11, *RPD* is only calculated for the pulse period during the air pulse release, but the pressures at the start and the end of the pulse release are not considered due to being unstable as the valve opens or closes. For S1, the highest *RPD* is approximately 0.83%, which was observed in Bedroom 3 with a pressure level of 11.99Pa in comparison to 12.09Pa in the living room.

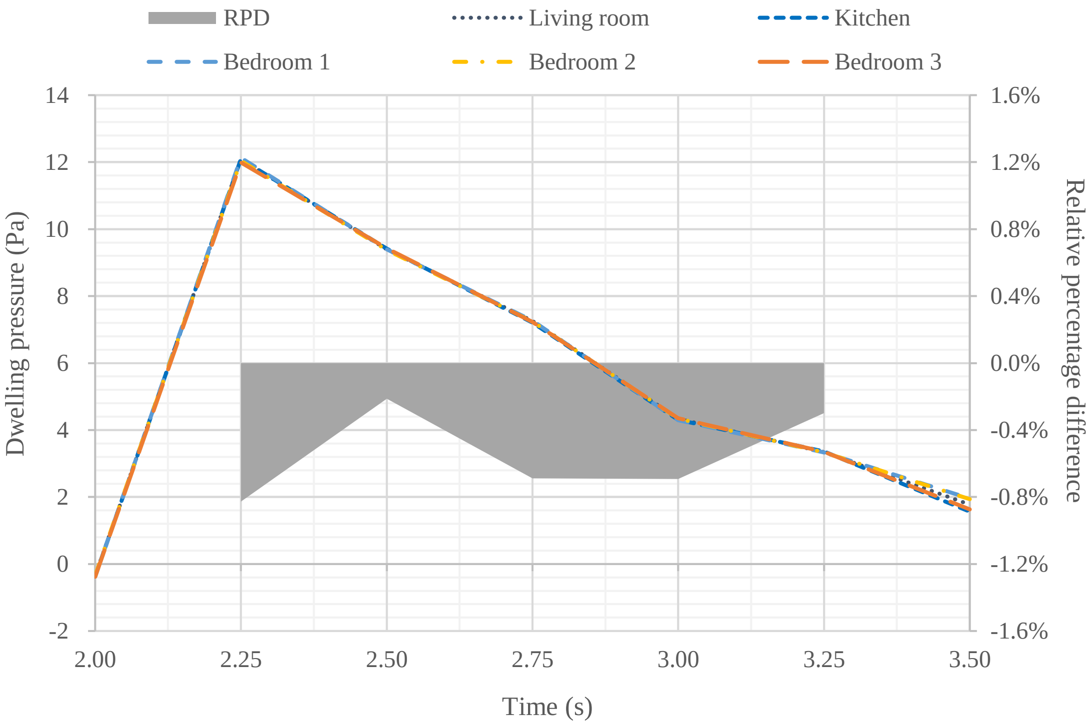


Figure 11: Pressure profiles in the five rooms during the S1 test

The results of pressure distribution in the five rooms for S2 are presented in Figure 12. At 7.25s, 0.25 second after the pulse of air was released into the interior rooms, the maximum pressure level was obtained for each room, ranging from 5.65Pa to 5.73Pa. Compared with the curves of the S1 test in Figure 11, some differences were seen among the five pressure curves of S2. The maximum *RDP* for S2 is around 1.40%, between Bedroom 2 with a room pressure of 5.65Pa and the living room of 5.73Pa, which is higher than that of S1.

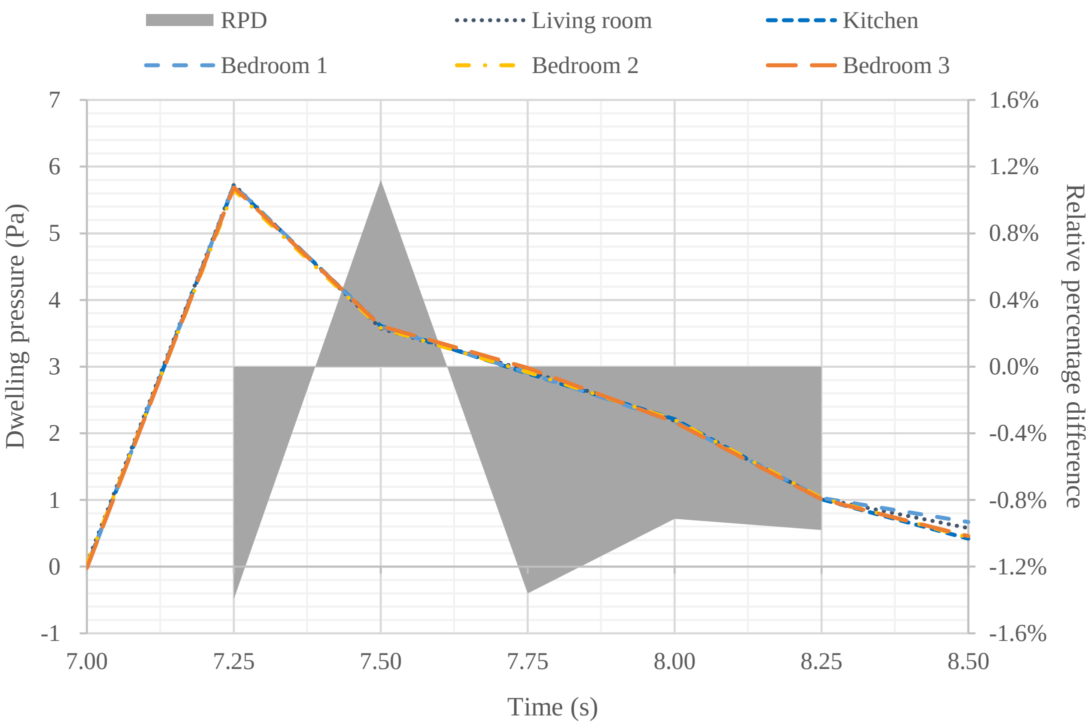


Figure 12: Pressure profiles in the five rooms during the S2 test

Figure 13 demonstrates the pressure distributions in the five rooms during S3. The pressure in each room peaked around 2.7Pa at 11.25s, 0.25 second after the release of air pulse. The highest *RPD* 1.45% was observed between Bedroom 1 (2.72Pa) and the living room (2.76Pa), which is slightly higher than that of S2.

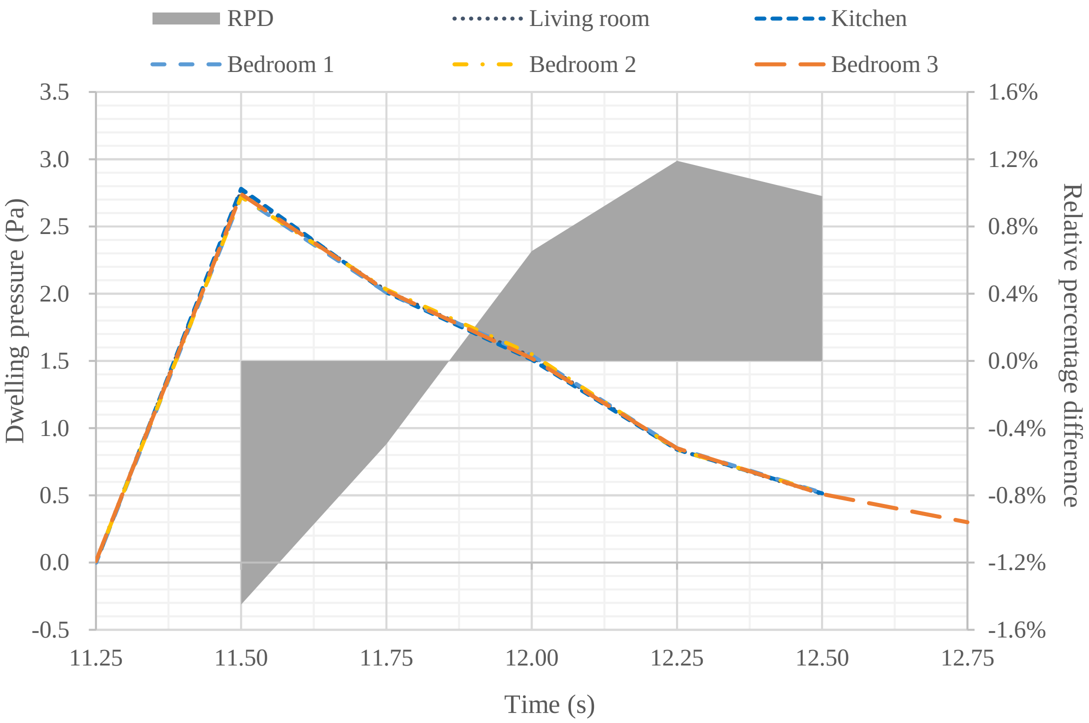


Figure 13: Pressure profiles in the five rooms during the S3 test

Table 3 lists the detailed data for the measured pressure level in each room during the S1, S2 and S3 tests. It can be seen that the *RPD* is within ±1.5% for the three Pulse tests, which thus confirms the uniformity of pressure distribution during the Pulse testing.

Table 3: Maximum pressure level in each room for the S1, S2 and S3 tests

	Living room	**Kitchen**	**Bedroom 1**	**Bedroom 2**	**Bedroom 3**	***RPD****
S1	12.09 Pa	12.09 Pa	12.13 Pa	12.04 Pa	11.99 Pa	-0.83%
S2	5.73 Pa	5.71 Pa	5.72 Pa	5.65 Pa	5.69 Pa	-1.40%
S3	2.76 Pa	2.78 Pa	2.72 Pa	2.72 Pa	2.74 Pa	-1.45%

*The maximum relative percentage difference between the living room and the other rooms

3.2 The Indoor Pressure Distribution During the DBB Test

Experimental work was also undertaken to investigate the uniformity of the pressure distribution within the house during the blower door testing. Due to the limited measurement range (±20Pa) of the differential pressure transducers used in the Pulse unit, the uniformity of the pressure distribution was only investigated at 10Pa and 15Pa. Figure 14 and Figure 15 present the respective results. The overall measurement lasted about 15 seconds after the building pressure became steady. For evaluation herein, the relative percentage difference (*RPD*) is also calculated based on eq. (2).

As seen from both figures, the overall trends of the pressure variation in each room are similar. For a test at 10Pa, the pressure difference between the living room and other rooms pressures is about 0.05Pa, with a relative percentage difference of 0.50%, while only 0.03Pa of the pressure difference is observed for testing at 15Pa, with an *RPD* of 0.13%. Considering the accuracy of the pressure transducers (i.e., 0.25%), a uniform pressure distribution across the internal spaces has been demonstrated for the fan pressurisation test.

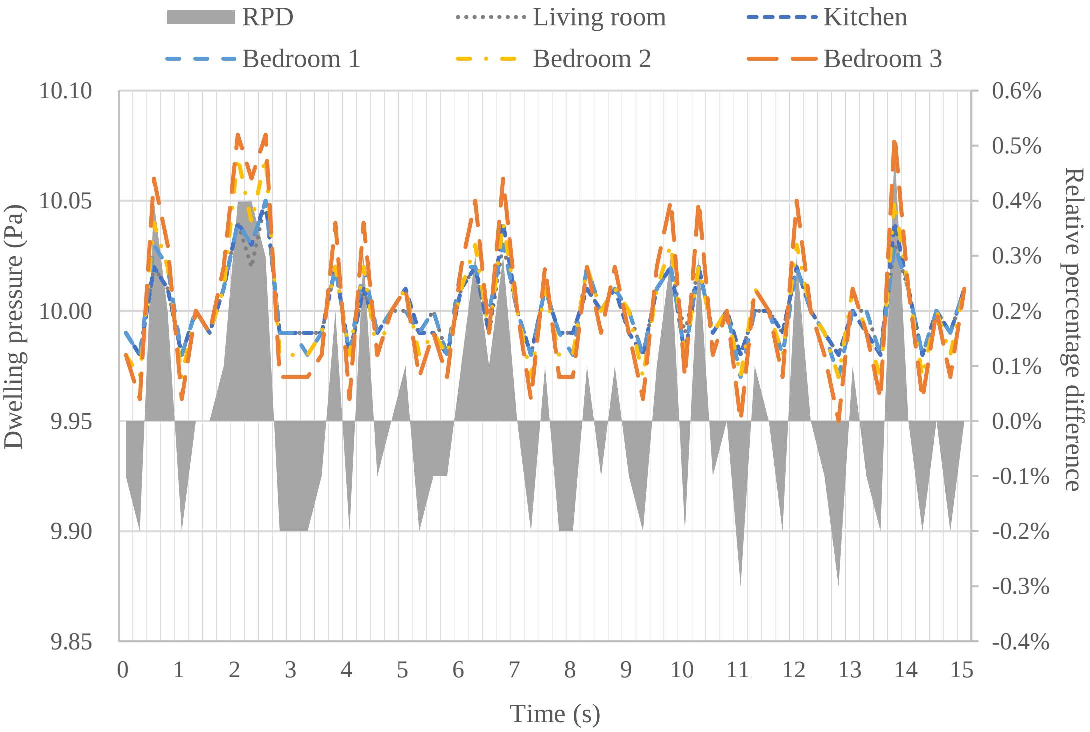


Figure 14: Pressure profiles in the five rooms during the DBB test at 10Pa

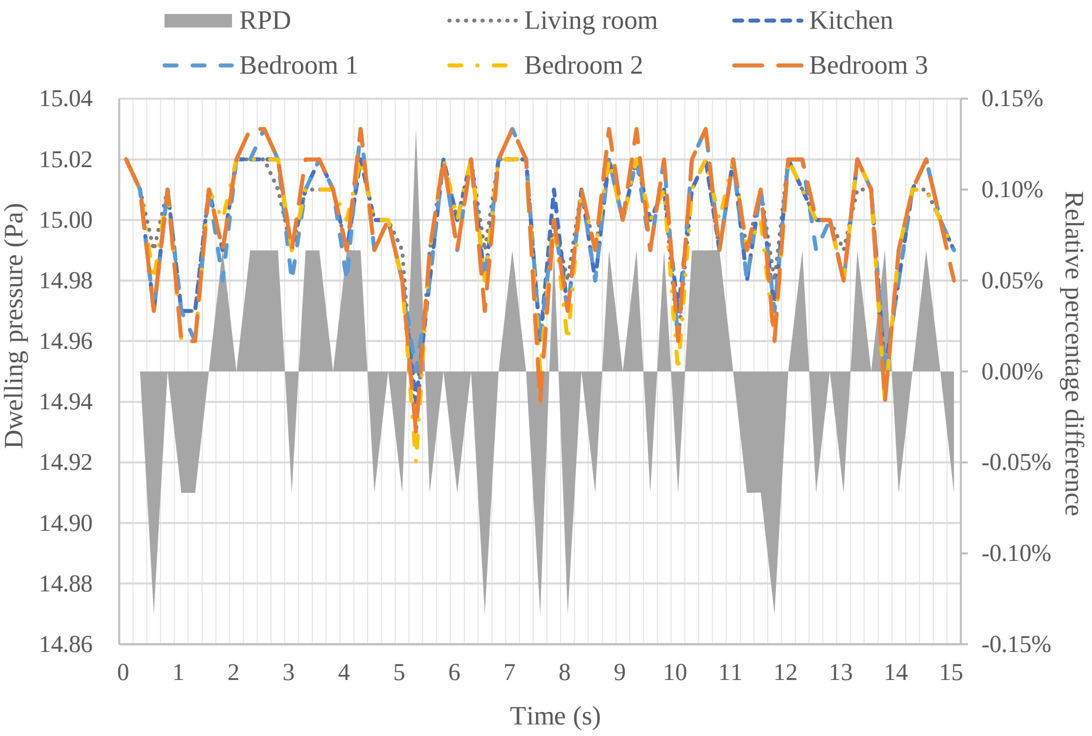


Figure 15: Pressure profiles in the five rooms during the DBB test at 15Pa

Table 4 below lists the detailed data for the measured pressure level in each room during the blower door tests.

Table 4: Maximum pressure level in each room for the DBB tests at 10 Pa and 15Pa

	Living room	**Kitchen**	**Bedroom 1**	**Bedroom 2**	**Bedroom 3**	***RPD****
DDB 10 Pa	10.03 Pa	10.04 Pa	10.03 Pa	10.05 Pa	10.08 Pa	0.50 %
DDB 15 Pa	14.93 Pa	14.94 Pa	14.95 Pa	14.92 Pa	14.93 Pa	0.13 %

*Relative percentage difference between maximum and minimum

3.3 Effect of the Pulse Release Location

Investigations were made to understand any potential effect of the specific pulse release location on the building airtightness measurement by performing tests at various locations within the building. Figure 16 illustrates the floor plan of the dwelling with marked test points. In total, six locations on the ground floor were selected, including the living room, the living room corner, Bedroom 1, the Bedroom 1 corner, the kitchen, and the kitchen corner.

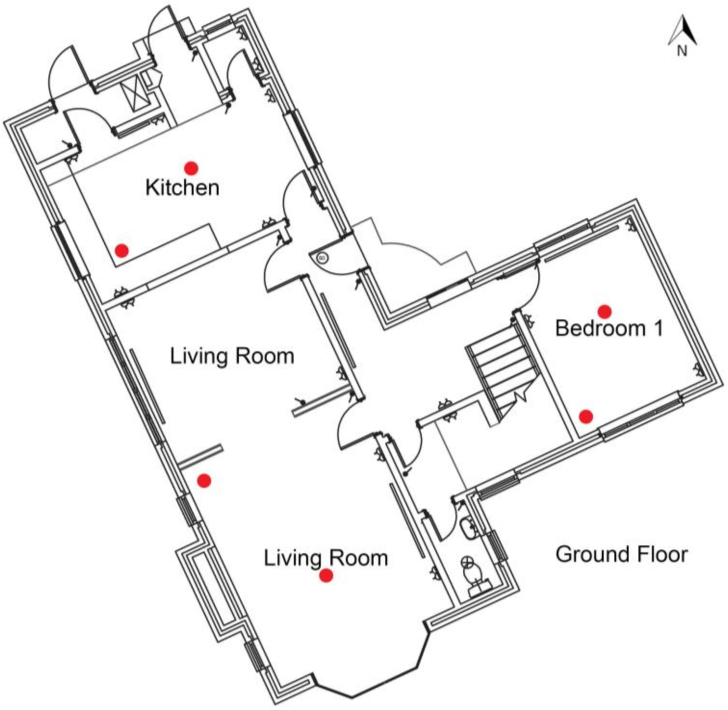


Figure 16: The Pulse test locations

At each test location, five repeated tests were implemented under calm weather conditions. Figure 17 presents the building airtightness measurement results for the 30 tests at the different pulse release locations with the results listed in Table 5. The average building permeability value is calculated based on the five tests for each location. As seen, the average permeability for the pulse release in the living room, the living room corner, Bedroom 1, the Bedroom 1 corner, the kitchen and the kitchen corner are 0.725, 0.721, 0.721, 0.728, 0.731 and 0.716 $m^3/h/m^2$, respectively. A subtle difference in the average building permeability is noted with a variability of 1.05%, which can be considered acceptable due to intrinsic measurement uncertainty. Therefore, the obtained results reveal that the Pulse test location in this study has little effect on the building airtightness measurement. This is in line with similar observations, which have been reported in previous experimental investigations in Ref. [20, 22].

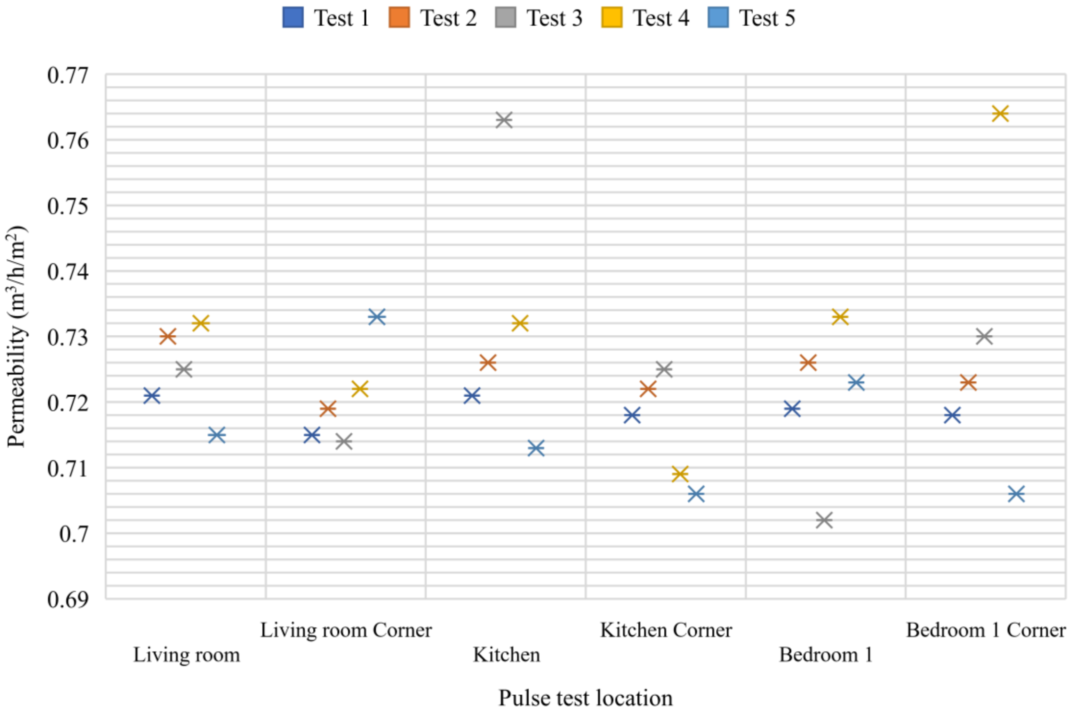


Figure 17: Results of 30 Pulse tests at different pulse release locations

Table 5: Measurement results of the building permeability ($m^3/h/m^2$) for the Pulse tests at different locations

	Living room	**Living room Corner**	**Kitchen**	**Kitchen Corner**	**Bedroom 1**	**Bedroom 1 Corner**
Test 1	0.721	0.715	0.721	0.718	0.719	0.718
Test 2	0.730	0.719	0.726	0.722	0.726	0.723
Test 3	0.725	0.714	0.763	0.725	0.702	0.730
Test 4	0.732	0.722	0.732	0.709	0.733	0.764
Test 5	0.715	0.733	0.713	0.706	0.723	0.706
Average	0.725 (±1.38%) *	0.721 (±1.66%)	0.731 (±4.38%)	0.716 (±1.40%)	0.721 (±2.64%)	0.728 (±4.95%)
Overall Average	0.724					
%**	0.15%	0.40%	1.03%	1.05%	0.40%	0.65%

* Highest relative percentage difference between each test and average
** Relative percentage difference between location average and an overall average

3.4 Comparison Between the Pulse Test and Blower Door Test

The blower door test is implemented at high pressure, with a large flow rate continuously supplied by the fan to maintain the desired indoor pressure. Based on the previous blower door tests at 15Pa, the pressure difference of each room is only 0.50%. Comparatively, for the Pulse test at low pressure (i.e., 4Pa), a uniform pressure distribution within the tested dwelling is also noticed with the maximum difference of 1.45%. This suggests that both methods are able to achieve a uniform pressure distribution during the stage of test implementation. Therefore, for the same tested house, the measurements obtained by both testing methods should follow the same trend when factors that might lead to a significant difference in envelope leakage are minimised. To provide insights into that, a more comprehensive comparison between the two test methods is conducted based on the obtained data, which are generated in the tests conducted consecutively, thereby being subjected to similar environmental condition.

Figure 18 presents the building air leakage rate based on the Pulse test in a pressure range of 3-10.6Pa. A three-step Pulse test was conducted to achieve measurements of leakage in a wide range of building pressure. Table 6 lists ranges of the pressure difference (ΔP) during the three-step Pulse testing. In this study, the largest achievable pressure rise during the quasi-steady period is about 10.6Pa within the dwelling (i.e., the S1 test).

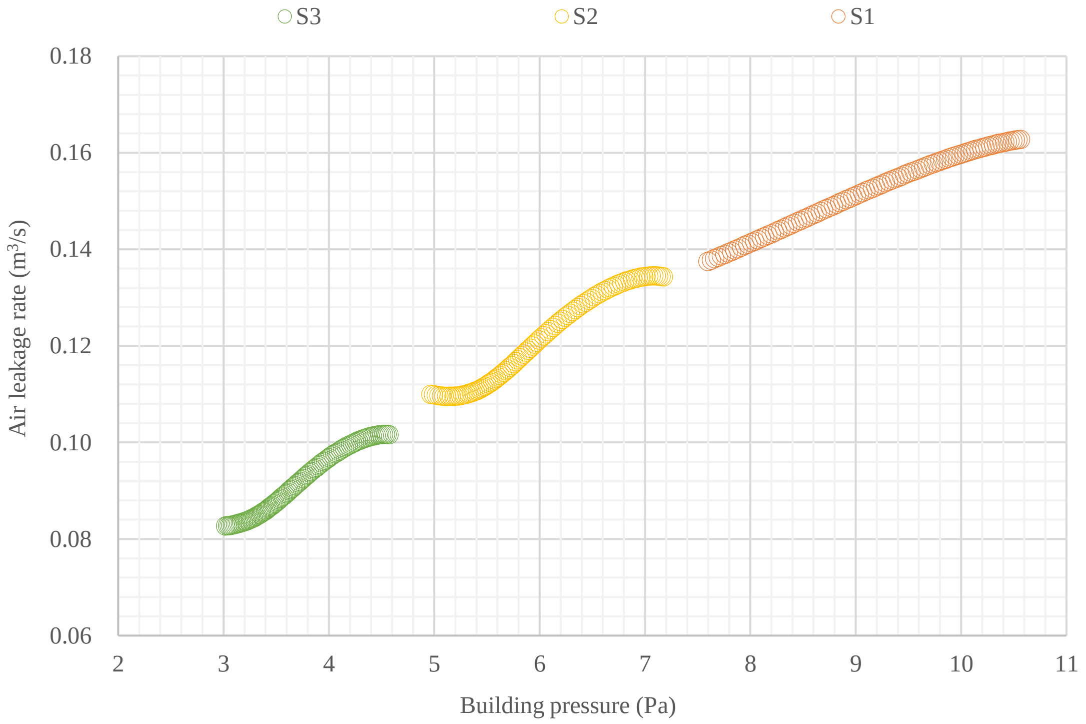


Figure 18: Air leakage rate-pressure curves for the Pulse tests

Table 6: Building pressure difference during the Pulse tests

Three-step Pulse	**ΔP Range (Pa)**
S1	7.6 ~ 10.6
S2	5.0 ~ 7.2
S3	3.0 ~ 4.6
Overall range	3.0 ~ 10.6

Figure 19 presents the measured building air leakage rate-pressure curves for the blower door tests. As listed in Table 7, the building pressure difference ranges from 6.9-72.3Pa for the pressurisation test and from 7.1-70.2Pa for depressurisation test.

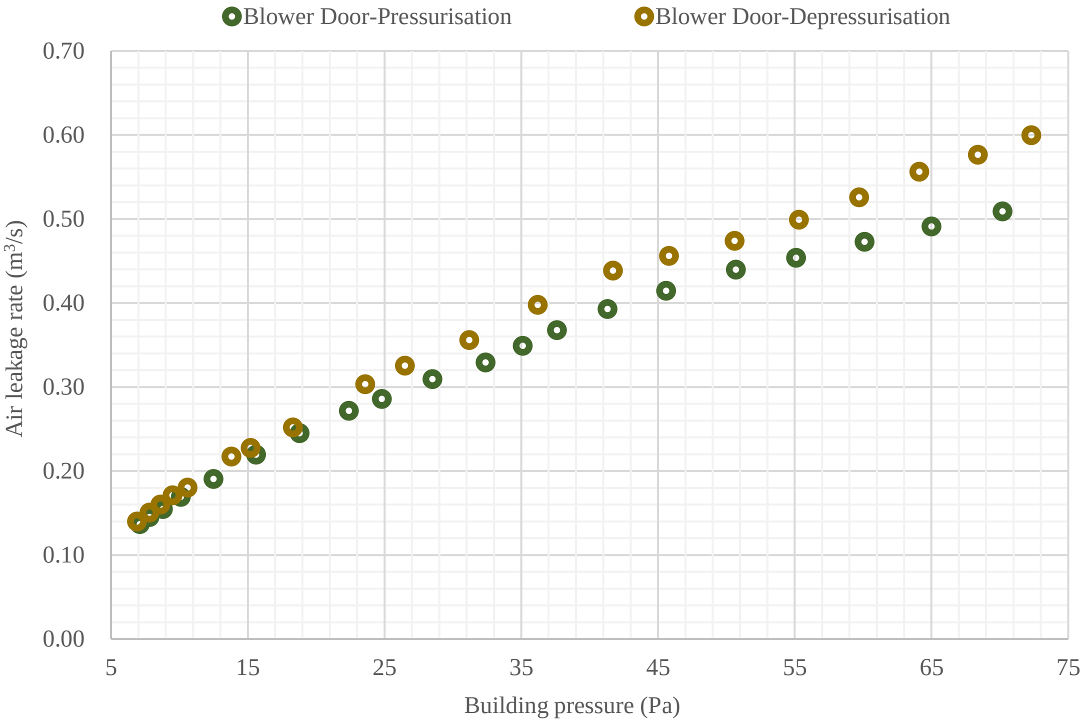


Figure 19: Air leakage rate-pressure curves for the blower door tests

Table 7: Building pressure difference during the blower door tests

Three-step Pulse	**ΔP Range (Pa)**
Blower Door - Pressurisation	6.9 ~ 72.3
Blower Door - Depressurisation	7.1 ~ 70.2

For comparison, Figure 20 presents the air leakage rate-pressure curves for both the blower door (pressurisation and depressurisation) and Pulse tests, covering the overlapped pressure range. Due to the different test approaches and the limitation in practical testing, the building pressure difference between the indoor and outdoor, where the tests overlap is from 7.1Pa to 10.6Pa. As seen, the power-law equation was fitted to the leakage-pressure curves. Details are listed in Table 8 with the measured air leakage rate, derived equation coefficients and the corresponding coefficient of determination. In Table 8, *C* and *n* are the air flow coefficient ($m^3/s/Pa^n$) and the air flow exponent, as described in the power law equation $Q=C\Delta P^n$, Q is the air leakage rate and R^2 is the coefficient of determination, representing the quality of curve-fit. The test validity was assessed by referring to the standard, for instance, n in the range 0.5 to 1, and R^2 >0.98.

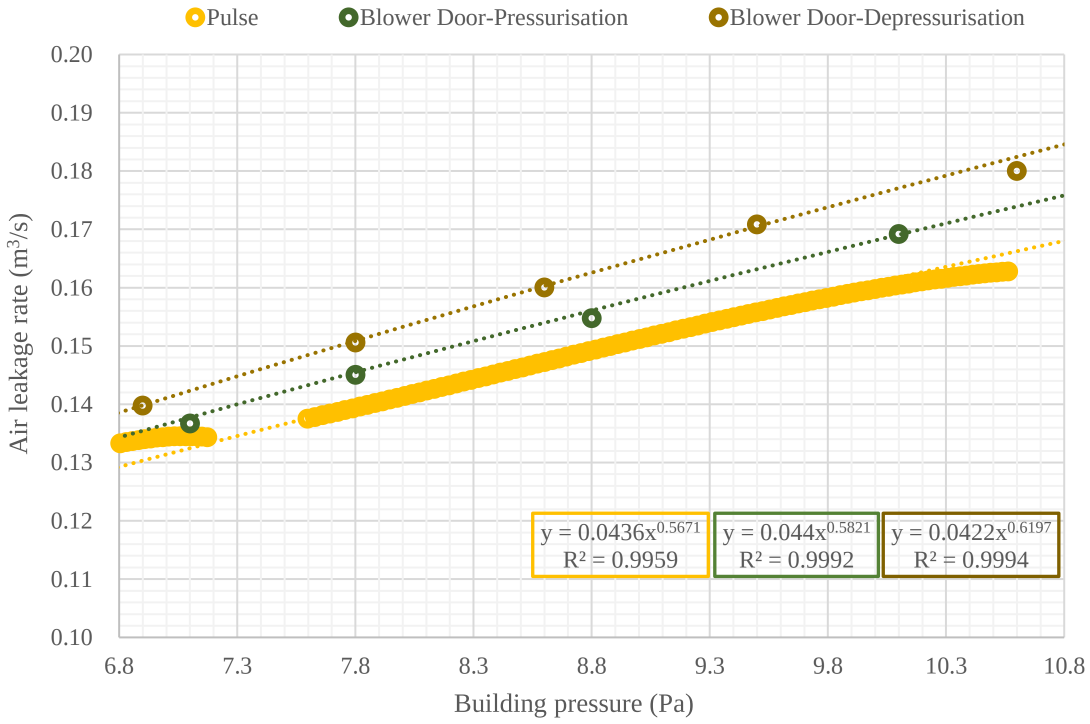


Figure 20: Relative percentage difference between the Pulse and blower door tests

Table 8: Airtightness measurement results and Power-law equations of the blower door and Pulse tests

		Pulse	Blower Door-Pressurisation	Blower Door-Depressurisation
ΔP Overlapped Range (Pa)		10.6 ~ 7.1		
Equation	***C***	0.0436	0.0337	0.0465
	n	0.5671	0.7135	0.5349
	R^2	0.9959	0.9709	0.9969

The relative percentage difference (*RPD*) between the blower door tests and the Pulse tests in the overlapped pressure range of 7.1Pa to 10.6Pa is calculated, as presented in Figure 21. Regarding the pressurisation test results of the two test methods, the blower door pressurisation result deviates from the Pulse result by 3.93% at 7.1Pa and 4.56% at 10.6Pa. Hence, a reasonably good agreement between the blower door and Pulse tests are obtained. It can be noticed that the obtained air leakage rate of the Pulse test is lower than that of the blower door pressurisation test. One of the reasons for this discrepancy may be because both pressurisation and depressurisation tests were conducted without sealing the door frame, i.e., leakage difference caused by the installation of the blower door unit. In addition, some drainage grooves in the door frame itself were observed and may contribute to the discrepancy, together with the valving effects of some building elements [39].

As recommended by the ISO 9972 standard, both pressurisation and depressurisation measurements have been implemented, and the average of the pressurisation and depressurisation test results was derived (as seen in Figure 21). Based on the measured air leakage rate, the difference between the pressurisation and depressurisation tests is also noted, i.e., 3.24% at 7.1Pa and 4.81% at 10.6Pa. The difference, albeit small, could be caused by the combination of valving effects in leaks under different flow directions, and biases in the two measurement procedures [40, 41]. Therefore, it is understandable that the pressurisation test result agreed with the Pulse test result slightly better than the depressurisation test result.

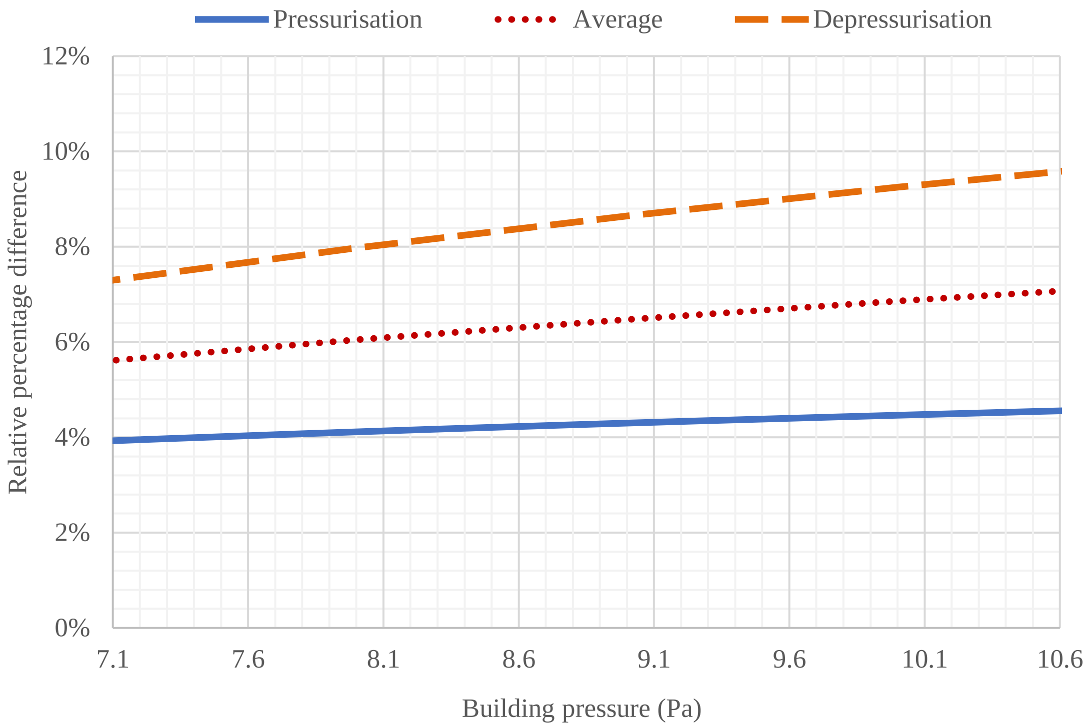


Figure 21: Relative percentage difference between the Pulse and blower door tests

4 ERROR ANALYSIS

The overall error (δQ_e) associated with airtightness measurements for Pulse and blower door tests is determined by taking three sources into consideration, including instrumentation accuracy for bias error (δQ_{bias}), environmental conditions for precision error ($\delta Q_{precison}$) and model specification for modelling error ($\delta Q_{modelling}$) [20, 42, 43].

$$\delta Q_e = \sqrt{\delta^2 Q_{bias} + \delta^2 Q_{precison} + \delta^2 Q_{modelling})} \quad (4)$$

It is known that the impact of the wind may be the most pernicious error source as both precision and bias errors can be caused. The ISO 9972 standard recommends the ground wind speed for valid testing should be less than 3m/s or smaller than 3 in Beaufort scale. To minimise the wind effect on measurements, measures have been taken in this study. For instance, all the tests were conducted under steady wind conditions (<0.45m/s, 2.2m above ground, 0 on Beaufort scale) with multipoint testing for the blower door method and multiple air pulse releases in the Pulse testing. In addition, based on the numerical study in Ref. [43], the steady wind-induced errors for pressurisation testing at reference pressures of 4Pa and 50Pa are minor and negligible in the wind speed range of 0-1m/s. Table 9 and 10 below lists the error sources for both the Pulse and blower door tests and the measuring instruments with their respective accuracies. For the uncertainty of building volume measurement, the reference value generally varies from 3% to 10% [38], and the highest value of 10% is considered herein.

Table 9: Error analysis for the blower door test

Error Sources	**Measurement Instrument**	**Unit**	**Precision**
Building parameter	-	m^3	±10%
Building pressure	DBB built-in pressure transducer	Pa	±0.9%
	Differential pressure transducer	Pa	±0.25%
Atmospheric pressure	Pressure transducer	hPa	±3%
Indoor air temperature	Indoor thermocouples	℃	±0.2
Outdoor air temperature	Outdoor thermocouple	℃	±0.2
Fan flow rate	-	m^3/h	±3.0%

Table 10: Error analysis for the Pulse test

Error Sources	**Measurement Instrument**	**Unit**	**Precision**
Building parameter	-	m^3	±10%
Building pressure	PULSE-60 built-in pressure transducer	Pa	±0.40%
	Differential pressure transducer	Pa	±0.25%
Indoor air temperature	Indoor thermocouples	℃	±0.08
Tank air pressure	Tank pressure transducer	Pa	±0.2%
Tank volume	-	Litre	±0.4
Tank air temperature	Tank thermocouple	℃	±0.08

The bias error analysis for the blower door test is conducted, with reference to Ref. [42], ISO [38] Annex C, [43] and [44], and a similar approach has also been discussed in Ref. [20]. The two independent errors are mainly from pressure and air flow measurements. On the other hand, the building air leakage measurement by the Pulse test can be expressed with a quasi-steady/temporal inertia model, solving a set of the continuity equation for the enclosed space and integral momentum equations for openings [20].

$$\frac{V}{\rho_i}\frac{d\rho_i}{dt} = Q_p\{t\} - q\{t\} \tag{5}$$

Where V is the building volume, ρ_i is the indoor air density, $Q_p\{t\}$ is the volumetric flow rate of the air released from the compressor and $q\{t\}$ is the building leakage rate. The isentropic expansion of the air is assumed as expressed in eq. (6):

$$\frac{P_i}{\rho_i^{\gamma}} = C_t \tag{6}$$

Where P_i is the building indoor pressure, γ is the specific heat ratio (1.4) and C_t is a constant.

Therefore, the building leakage rate can be expressed as:

$$q\{t\} = Q_p\{t\} - \frac{V}{\gamma P_i}\frac{dP_i}{dt} \tag{7}$$

The volumetric flow rate of the air released from the compressor can be derived by eq. (8):

$$Q_p\{t\} = -\frac{V'}{\gamma R T_0}\left[\frac{P(t)}{P_0}\right]^{\frac{1-\gamma}{\gamma}}\frac{P(t)}{\rho_i} \tag{8}$$

Where $P(t)$ is the air transient pressure in the compressor, P_0 is the initial air pressure in the compressor and. T_0 is the initial air temperature in the compressor. R represents the gas constant (287.058 J/kg·K), and V' is the volume of the air receiver.

The overall bias error of the measured building leakage rate can be expressed as:

$$\delta Q_{bias} = \sqrt{\Delta Q^2 + \Delta E^2} \tag{9}$$

Where ΔQ^2 relates to the measurement of air flow rate in the tank and ΔE^2 occurs in the measurement of isentropic expansion.

The precision error is calculated according to procedures described in Annex C in BS EN ISO 9972 [38]. Environmental variations during the tests are treated as the key source for the precision error. Model specification (or modelling) errors for the blower door and Pulse tests is calculated with reference to Ref. [20, 42, 43]. The key model specification error is related to the assumption that the flow can be extrapolated using a power-law formulation; thus, the error can be caused by extrapolating data beyond the measurement limits [45].

Based on the obtained data for the blower door and Pulse tests, Figure 22 shows the overall error for their overlapped building pressure testing range. Due to the different test approaches and limitation in practical testing, detailed results for both the tests are provided in Table 11. As it can be seen, the overall measurement errors for the Pulse test, the fan pressurisation and depressurisation tests are lower than 10% under the clam weather condition, which is in line with the expectation stated in the ISO 9972 standard. Hence it demonstrates the validity of the obtained measurement results in this study. Over the tested building pressure range, the average overall error is 1.60% for the Pulse test and 2.94% for the fan pressurisation test, with a small difference of the overall error (i.e., 1.34%). This also verifies the good overall agreement between the two pressurisation tests. In terms of the depressurisation test, the average overall error is about 7.46%. The larger overall error is attributed to the combination of the blower door frame leakage, valving effect of leaks and different component behaviours during the depressurisation testing.

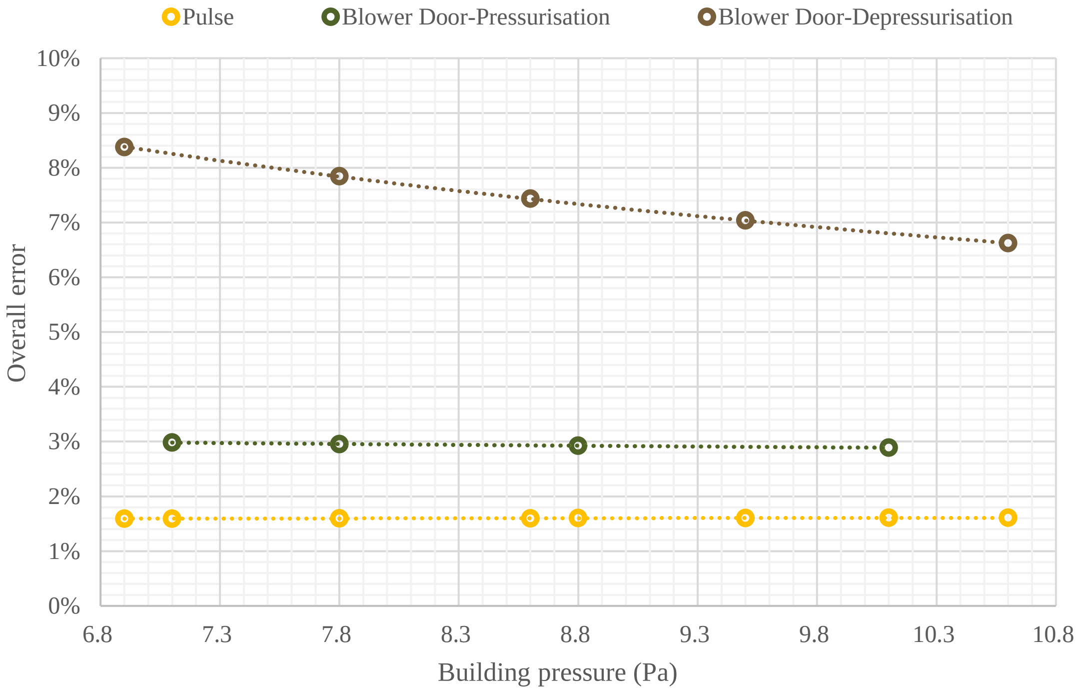


Figure 22: Overall errors of the Pulse and blower door tests for the overlapped pressure range

Table 11: Results of overall errors of the Pulse and blower door tests for the overlapped pressure range

Building pressure (Pa)	**Overall error**		
	Pulse	**Blower Door-Pressurisation**	**Blower Door-Depressurisation**
6.9	1.59%	--	8.83%
7.1	1.59%	2.98%	--
7.8	1.60%	2.96%	7.84%
8.6	1.60%	--	7.44%
8.8	1.60%	2.92%	--
9.5	1.60%	--	7.04%
10.1	1.61%	2.89%	--
10.6	1.61%	--	6.62%
Average	1.60%	2.94%	7.46%
Difference (between Pulse and blower door)	--	1.34%	5.86%

Comparisons of the overall error for the blower door and Pulse tests at 4Pa and 50Pa are presented in Figure 23. The overall error for Pulse testing is approximately 0.80%

at 4Pa and 1.83% at 50Pa, while the pressurisation test has an overall error of 3.19% at 4Pa and 1.46% at 50Pa, and depressurisation of 10.96% at 4Pa and 5.47% at 50Pa. As suggested by Sherman and Palmiter [42], to minimise the uncertainty within blower door testing, the low-pressure point should range from 10 to 20Pa, while the high-pressure point is in a range of 40-60Pa. The blower door tests in this study were conducted by following these rules, covering a pressure range of around 7Pa to 70Pa. Therefore, the average error of the blower door testing is less than 6% at 50Pa.

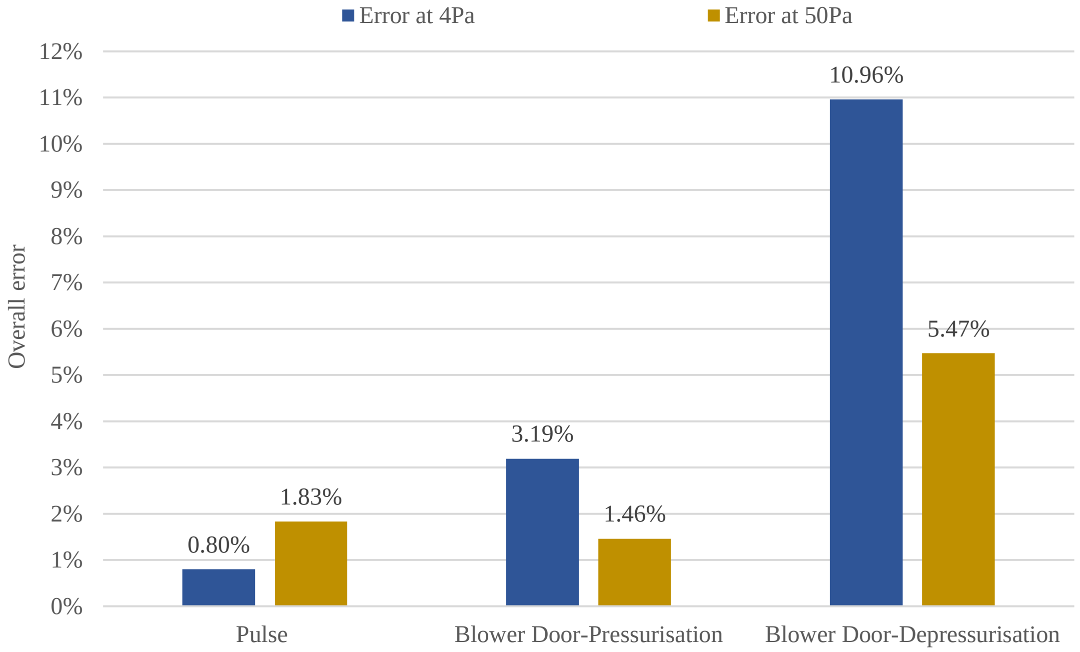


Figure 23: Overall errors for the Pulse and blower door tests at 4Pa and 50Pa

On the other hand, the error for the pressure distribution measurement during the blower door and Pulse tests is calculated by considering the error sources within the blower door and Pulse tests, the pressure measurement error, and the data logging error. The overall error for pressure distribution measurement is approximately 1.62% for the Pulse test and 2.95% for the blower door pressurisation testing at 10Pa and 15Pa. Therefore, the obtained data can reinforce the finding that a uniform indoor pressure distribution can be achieved during the pulse pressurisation process.

5 CONCLUSIONS

Pulse adopts an unsteady approach to measure building airtightness at low pressures. Due to the rapid dynamic nature of Pulse, the uniformity of the pressure distribution across the internal space of the test building during the pulse period has been frequently questioned. Based on the experimental investigations in a large UK detached dwelling under calm weather conditions, a uniform indoor pressure distribution has been observed during both the Pulse and blower door tests. In the complementary comparison test between the two test methods, a good overall agreement of building air leakage rate is noted, with deviations of 3.93% at 7.1Pa to 4.56% at 10.6Pa. This comparable measurement therefore supports the finding of the uniformity of pressure distribution during both tests. The error analysis also proves that the overall measurement error aligns with the officially cited range given by both testing methods, and thus the study provides a valid assessment. Furthermore, a minor impact of the Pulse test location on the building airtightness measurement was observed with a subtle variation (i.e., 1.05%) in building air permeability when the Pulse tests were conducted at different locations inside the building. The work extends the explorations of Pulse in practical aspects, providing a full image of the uniform pressure distribution within the building during the test and proving the applicability and reliability of the technique. The study is based on tests performed with a single Pulse unit in a five-bedroom dwelling of a relatively large volume, representing the worst-case scenario. Hence, the findings are also applicable to smaller buildings.

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