Experimental insights into the airtightness measurement of a house-sized chamber in a sheltered environment using blower door and pulse methods

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ABSTRACT

This paper introduces a comparison study of measuring the airtightness of a house-sized test chamber using the novel pulse technique and a low range blower door method in a sheltered environment. Eight different testing plates were prepared and applied to the improvised envelope of the chamber to establish different leakage characteristics. Each testing plate has a unique opening in its centre, achieved by obtaining different combinations of shape and thickness of the opening. By using the sheltered environment, the vagaries of the natural condition when testing within buildings have been reduced providing a more robust testing environment. This investigation focuses on how the air leakage rate calculated from the measurements made by both techniques compare with each other. Comparable results (0-5.3%) under most scenarios have been obtained. Larger discrepancies (14.6% and 21.8%) were observed in the two airtight scenarios due to insufficient pressure range achieved in a standard pulse test. This finding guided further improvement on the testing performance. Further pulse tests under different scenarios, involving the use of an internal barrier and various location of the pulse unit were also performed to investigate the uniform pressure distribution and resilience to external interferences. It showed the internal barrier and location had minor impact (1.62% to 4.65%) on the test results.

KEYWORDS

Building airtightness, Blower door, Pulse, Sheltered environment

Nomenclature

Symbol

A	Area of opening (m^2)
a, b	Coefficients of quadratic equation for the pressure-flow relationship
B	Constant determined by the shape of the cross-section of the opening.
C	Flow coefficient ($m^3/s\cdot Pa^n$)
C_i	Constant
d	Diameter of opening (m)
$\frac{dq}{dt}$	Building pressure change rate (Pa/s)
ΔE	Measurement uncertainty of second term on the right of eq.(4) (m^3/h);
l_e	Effective length of opening (m)
L	Depth of opening (m)
n	Pressure exponent in eq.(3)
p_i	Building indoor pressure, Pa;
$P(t)$	Transient pressure of air in the compressor tank
$P(\dot{t})$	Change rate of building air pressure (Pa/s)
P_0	Initial pressure of air in the compressor
ΔP	Building pressure (Pa)
$\Delta p\{t\}$	Real time building pressure, (Pa)
Q	Air leakage rate (m^3/s)
Q_4	Air permeability at 4 Pa ($m^3/h\cdot m^2$)
Q_{50}	Air permeability at 50 Pa ($m^3/h\cdot m^2$)
ΔQ	Measurement uncertainty of air leakage rate (m^3/h);
$Q_p\{t\}$	Volumetric tank air flow rate, (m^3/s)
$q\{t\}$	Building air leakage rate, (m^3/s)
T_0	Initial temperature of air in the compressor
V	Building volume (m^3)
V'	Volume of air receiver (m^3)

Greek letter

μ_i	Viscosity ($Pa\cdot s$)
ρ_i	Indoor air density, (kg/m^3)
γ	Ratio of specific heat

1. INTRODUCTION

1.1. Context

As concerns related to carbon emission and climate change grow on a daily basis, there has been increased focus on the energy use in the buildings as it contributes up to 50% of global energy consumption in the developed countries [1-3]. The relative proportion of energy losses associated with air infiltration has increased as the building thermal insulation has been improved over the last few decades. Air tightness fundamentally determines the level of infiltration occurring through building fabric and affects the building ventilation. The term, air leakage, defined as the air movement through cracks, gaps or other adventitious openings in the building envelope, is also often referred to as ‘unnecessary ventilation’. It has been widely acknowledged that building air leakage is a great contributor to building energy loss in the regions where heating and cooling is required. A study [4] estimated unnecessary ventilation accounted for over 60% of the energy wastage in commercial and residential buildings, through the loss of conditioned air. A good building airtightness is desirable considering the fact that building energy consumption caused by air infiltration takes 13%-30% of the overall heating energy, 4-14% of cooling load [5-7]. A good airtightness also makes it easy to control the indoor environment and achieve effective and efficient ventilation, while a poor airtightness not only leads to high infiltration heat losses but also impacts the lifespan of building structure by allowing the unconditioned air to penetrate through building fabric, condense in the building envelope and deteriorate the building fabric. It also establishes a suitable environment for the growth of mould, which is potentially another source of contaminant to indoor environment.

Airtightness has long been recognised as a concern primarily for building energy efficiency and led to the setting up of the Air Infiltration Centre in 1979 [8, 9] and later formalisation in building standards in many countries. It is important to consider the airtightness in the norm of building qualitative evaluation considering its contribution to building energy loss and the fact that the energy consumption in the building sector represents a large contingent in overall global energy use. Hence, the demand for cutting the global carbon emission drives policy makers in the building sector to set a number of carbon reduction targets. For instance, the recent ‘emission reduction plan’ [10], as the national action set by the UK government to limit temperature change to around 2 °C, emphasizes the importance of focusing on cutting carbon emission in multiple sectors especially the building sector because it has larger potential for further reduction. This policy reflects the UK’s efforts to support the more ambitious international action: ‘Paris Agreement’, which was reached in December 2015 [11]. It aims to limit the rise in global temperatures to well below 2°C, to pursue efforts to hold it to 1.5°C and to reach net zero emissions in the second half of the century.

The most commonly used method for measuring building airtightness and diagnostics is the fan pressurisation technique, which is implemented by creating a steady pressure difference across the building envelope and simultaneously measuring the corresponding airflow through the fan that is used to exert the airflow. This technique was firstly used in Sweden around 1977 [12, 13] as a ‘blower window’ by Ake Blomsterberg, who then continued his research in Princeton University in 1979. This paved a foundation to wide developments and acceptance of the blower door test. The blower door technology has gone through significant developments from early bulky and heavy version, which was made of materials like plywood and Formica to the latest lighter and more compact version made of an adjustable metal frame and lightweight fabric door panel with advanced instrumentation. A large number of scientific research related to the blower door technology has been carried out, covering unregulated or temperate/hot climate countries [14-16], modelling/infiltration [17, 18] building characterization [14, 16, 19, 20] retrofitting [19], measurement uncertainty [20], indoor air quality [21] and other relevant aspects [22, 23]. However, the technology comes with its own shortcomings, which include change of building envelope (i.e. the blower door is positioned in an opening in the building fabric, such as a door way), testing pressure differentials, which are significantly higher than those experienced in the ambient condition, coarse interpretation of wind effect and demand for skilful training. Such issues provided early motivation for finding alternative methods for measuring building airtightness, such as AC method [23-25], decay method [24, 27-29], Pulse method [30-37] and acoustic method [7, 38-44].

One of the main challenges in the measurement of building airtightness lies in accurately measuring low pressures that a building experiences under natural conditions. This pressure is typically in a range of 1-4 Pa [8, 12, 45] and difficulties in measurement exist at this level due to the uncertain nature of wind and buoyancy effects. Pressure changes due to external influences need to be accounted for in the measured pressure difference across the building envelope in order to obtain the actual pressure difference that the building is subjected to when either pressurised or depressurised by mechanical means i.e. a fan positioned in an opening of the building fabric. One of the approaches to overcome this issue is to perform a test at higher pressures in order to negate the wind and buoyancy effects. The most commonly accepted method is to use the aforementioned steady fan pressurisation method. In doing so, the impact of these natural low-pressure variations is much reduced as the test airtightness result is given at a much higher pressure compared to the ambient. However, various issues surrounding this approach have been discussed in scientific studies and evidence in practical use [34, 46-52]. The convenient use of setting an airtightness metric at elevated pressures compared to the ambient is widely accepted; however, this does not necessarily preclude the use of a test at low pressures such as 4 Pa. Nevertheless, one must consider the increasing impact of environmental influences upon the accuracy of the result at 4 Pa. In fact in a number of countries, including North America and many European countries the test measurement must be made over a range of high pressures and quoted at 50 Pa for regulatory requirements.

In this study, a novel low-pressure technique is used to measure the airtightness of an enclosed chamber in a sheltered environment for comparison against the standard blower door technique. Previous studies [32-35] have shown the pulse technique is a promising alternative for air leakage measurement, when applied to physical dwellings. In order to provide greater verification to the underlying pulse principle this study is performed in a sheltered environment to provide comparable testing, with near eliminated external effects due to wind etc.

The air leakage test technique, known as ‘Pulse’ rapidly measures air tightness at building pressure differentials typically much below 10 Pa and reports a result at 4 Pa. The pulse technique is a low-pressure process (typically around 4 Pa) whereby the airtightness of a building is determined through the release of a 1.5 second pulse of air from a pressurised vessel. The rapid measurement of the consequential change in internal pressure of the building and tank can be used to calculate a flow rate through the building envelope at 4 Pa. The underlying principle is that of a quasi-steady flow, which can be shown to exist via the temporal inertial model and further detail is given by Cooper [46-48]. In this study, the pulse technique is compared to the results delivered by the blower door test. Blower door results are reported in two scenario’s; 4 Pa and 50 Pa. The difference in error between the 4 Pa and 50 Pa blower door test result is not investigated explicitly in terms of causation, but both measures are used to compare against the pulse technique.

A recent study by Remi [53] using the blower door method shows an uncertainty of 6%-12% can be caused by steady wind in a range of 6-10 m/s combined with other sources of error in a steady state test at 50 Pa. Given the low operating pressure (around 4 Pa) of the pulse technique the wind could be considered the foremost important environmental factor due to its direct impact on the building pressure. In this study, the pulse and blower door units are used to measure the air leakage rates of the enclosed chamber installed with 8 different testing plates, each having a different opening geometry. Overall with some modification of two of the test plates provides 11 testing scenarios. The test chamber is housed inside another large building and therefore the ambient external condition is more stable than that of real houses. This test arrangement allows both the blower door and the pulse technique to measure leakage at low pressures directly.

1.2. Description of the pulse technique

Figure 1 shows the schematic diagram of the pulse technique. A standard pulse unit consists of a compressor, main air tank, control box, valves and sensors. The main air tank is charged by the compressor to a maximum working pressure of 10 bar. In a pulse test, compressed air is released into a test space via a solenoid valve (V1) over a short period of time (typically 1.5 seconds). The pressures of tank and test building are monitored by a pressure transducer and differential pressure transducer respectively, which are mounted in the main air tank (near the pressure gauge in Figure 1) and the ATT (Air-Tightness Testing) control box. The building pressure is measured by the differential pressure transducer with the assistance of an internal pressure reference. The internal pressure reference tank is an airtight vessel one end of which is connected to the differential pressure transducer via pressure tube, the other end is connected to an airtight solenoid valve (as indicated by V2 in Figure 1). The valve is normally open to allow the pressure in the reference tank to equalise with surrounding and closes a couple of seconds before test starts to provide a useable pressure reference for measuring pressure change in the building when it is subject to air pulse released from the main air tank via the main valve (V1). The ATT control box controls the opening and closing of V1, records the measurements of tank and building pressure and analyses the data to display on the LCD screen instantly.

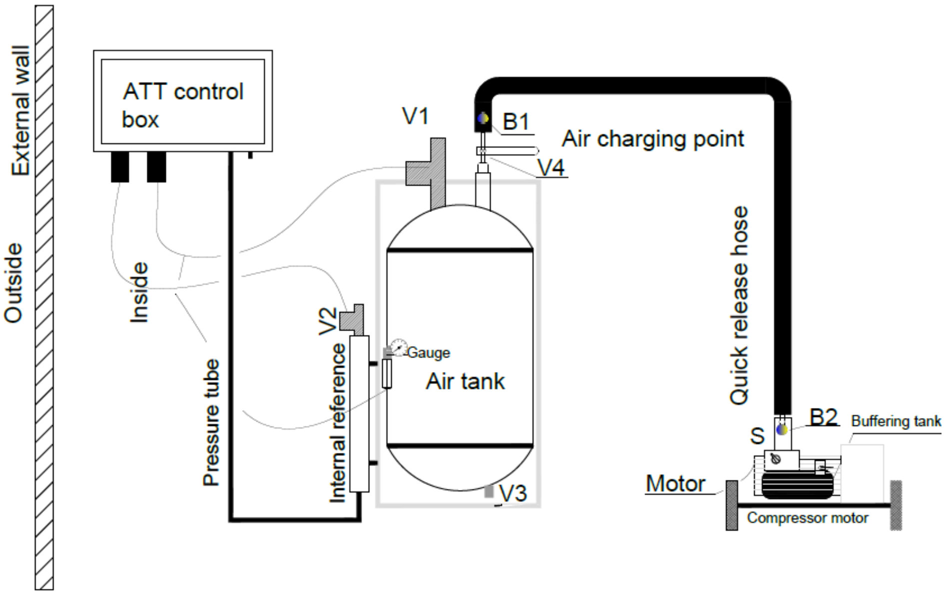


Figure 1 Schematic diagram of the pulse technique

The pulse technique measures the building airtightness at low pressures by releasing an known volume of air into the test building over 1.5 seconds from an air tank to create an instant pressure rise within the test building and reach a “quasi-steady” flow, where the pressure variations in the building and tank are monitored and used for establishing a correlation between leakage and pressure. The method used for the adjustment, which accounts for changes in background pressure, is achieved by deducting background pressure from the raw data. This is described in previous papers [32, 46]. A typical pulse test measurement is shown in Figure 2. The readings of building pressure consist of three key stages, pressure variation during quasi-steady period and background pressures before and after the pulse.

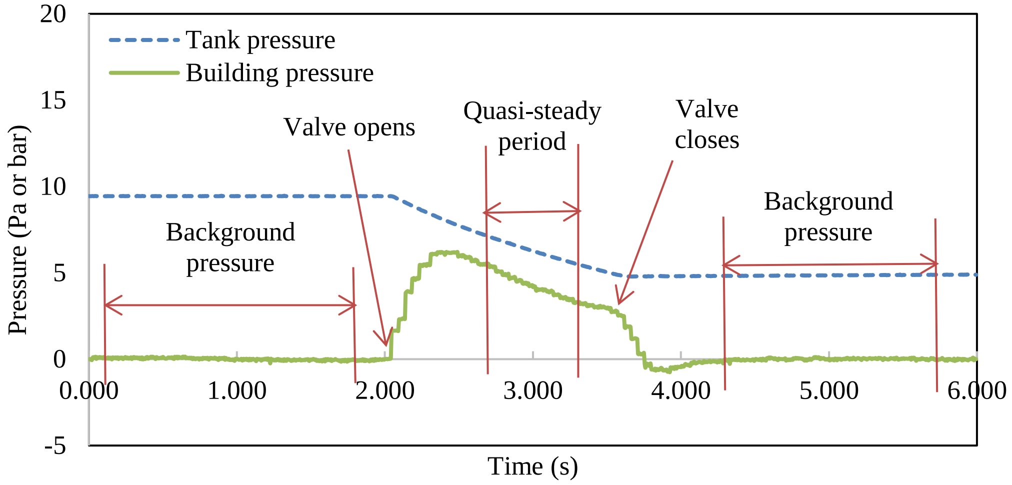


Figure 2 A typical pulse test by a pulse unit with 60 l tank (tank pressure measured in bar, building pressure in Pa)

The pulse technique measures the building leakage at various pressure levels similar to leakage measurements in a blower door test process. However, the pulse technique measures in a dynamic manner instead of taking each individual readings at a steady pressure level. The advantage of this technique is that the test can be done in 11-15 seconds. The challenge lies in the occurrence of the inertia effect of air that flows through openings, which then adds uncertainty to the measurement [54]. This type of flow is addressed herein as unsteady flow. The percentage of unsteady flow in the quasi-steady period, isolated and evaluated using a momentum equation [46], is used to account for that inertia effect. The momentum equation is described by eq.(1).

$$\Delta p\{t\} = aq\{t\}^2 + bq\{t\} + \rho_i \frac{l_e}{A}\frac{dq}{dt} \tag{1}$$

Where, $a = \frac{\rho_i B}{2A^2}$ and $b = \frac{\mu_i CL}{2d^2 A}$ are determined by the geometry (size and shape) of the opening, l_e the effective length of the opening. Where, μ_i is the kinematic viscosity of the internal air; A, L and d are the effective area, length and hydraulic diameter of the opening; Assuming a simple 2-D crack for typical building leakage pathways [55], the values of coefficients B and C are 1.67 and 96 respectively; l_e is taken to be related to the geometry by $l_e = L + 1.67d$.

The first two terms of the right hand side of eq.(1) correspond to the momentum change and surface friction. The third term accounts for the inertia effect of the air that flows through the opening. For quasi-steady flow to occur, the inertia term in eq.(1) needs to be small enough compared to the other terms.
The percentage of unsteady flow is defined by eq.(2):

$$\frac{\left|\rho_i \frac{l_e}{A}\frac{dq}{dt}\right|}{|aq\{t\}^2 + bq\{t\}| + \left|\rho_i \frac{l_e}{A}\frac{dq}{dt}\right|} \times 100\% \tag{2}$$

The quasi-steady period, which has been identified in previous research [32, 46], lies in the latter part of the pulse. In order to allow "quasi-steady" flow to occur, the percentage of unsteady flow needs to be small enough compared to the other terms, usually less than a few percent.

Figure 3 shows an example of percentage of unsteady flow of a typical pulse test. Within quasi-steady period, the percentage of the unsteady flow is less than 1%. Hence, it can be concluded that a quasi-steady flow has been achieved in this test.

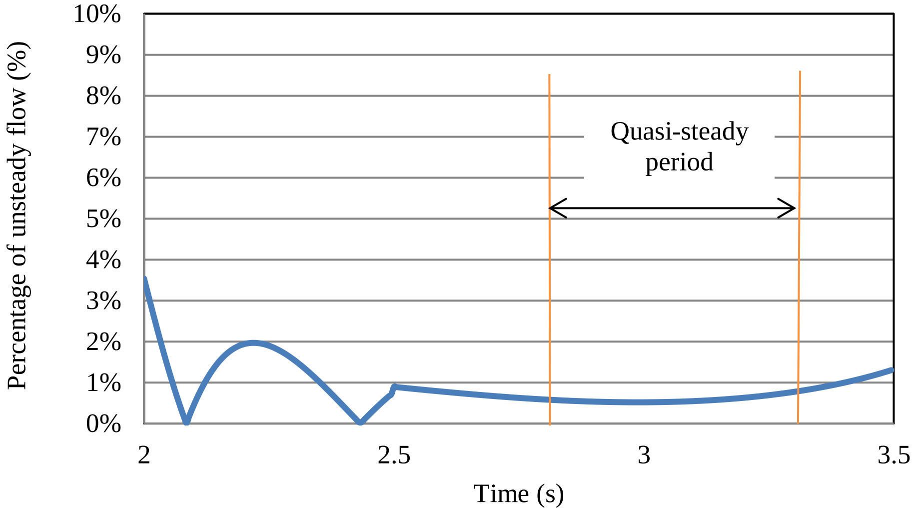


Figure 3 Percentage of unsteady flow of the pulse test in Figure 1

Figure 4 shows the results of both a pulse and blower door test in the same log-log graph. They can be presented in the same format using a power law relationship.

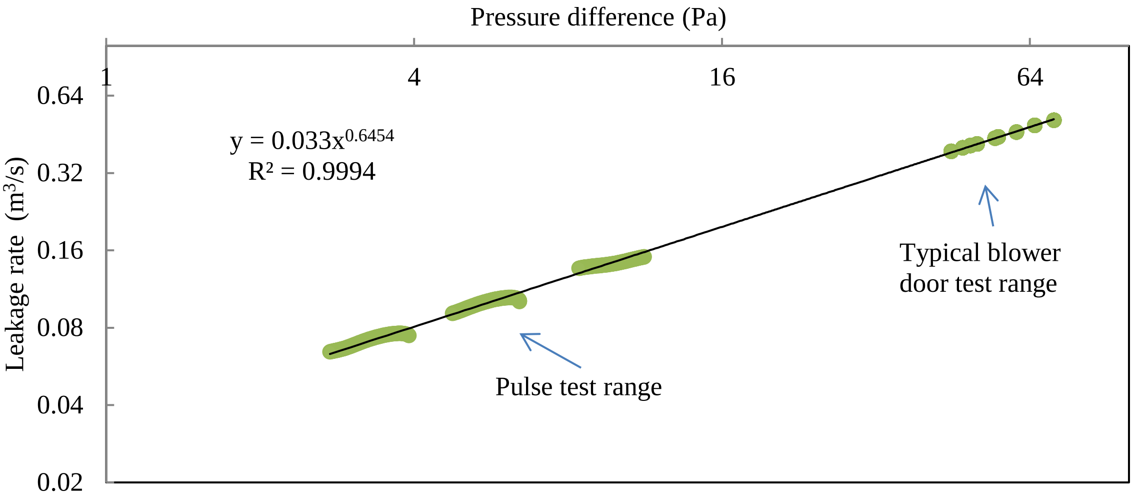


Figure 4 A log-log graph of pressure-leakage measured by APU and blower door in one building

1.3. Equipment

The blower door unit that is used in this study is a Duct Blaster B (DBB), manufactured by ‘The Energy Conservatory’ in the United States. It consists of an adjustable door frame, flexible canvas panel, a variable-speed fan, and a DG700 pressure and flow gauge, as shown in Figure 5. The DBB is calibrated to take reliable readings at lower pressures than the larger blower door units and is therefore used to carry out the comparative tests alongside the prototype PULSE-80 unit in this investigation.

Figure 5 Energy Conservatory Duct blaster B (DBB)

Figure 6 PULSE-80 and associated control box

The PULSE-80 unit incorporates an 80-litre light weight composite tank and oil free double piston compressor as shown in Figure 6. The outlet utilises a ¾ inch (BSP) solenoid valve to release compressed air from the air tank into the test space, which delivers a 1.5 second pressure rise. The data is recorded and analysed by the control box and results are displayed on the LCD screen of the control box. More technical details are introduced by Cooper [5]. It must be noted at this point that from a size and handling perspective, that the prototype 80l pulse used in this test, is somewhat larger than would ordinarily be required for testing of a chamber of this size and leakage (typically a unit of less than 40L would suffice for this arrangement). This was due to the need for a greater application of the prototype to other sized buildings beyond the scope of this particular investigation.

2. METHODOLOGY

2.1. Testing chamber

The tests were carried out in an environmental chamber (No.4) at the testing laboratories of BSRIA Ltd, UK. The chamber, built inside a large two-storey building, is made of insulated cold–store panels. The dimensions of the chamber are 6.01 m×4.64 m×7.20 m (L×W×H) with a 50 mm wall thickness, which give an envelope area and internal volume of 209 m^2 and 200 m^3 respectively. The spaces surrounding the chamber were left open during the tests. The chamber's air supply, extract and instrumentation holes were all sealed during the course of testing.

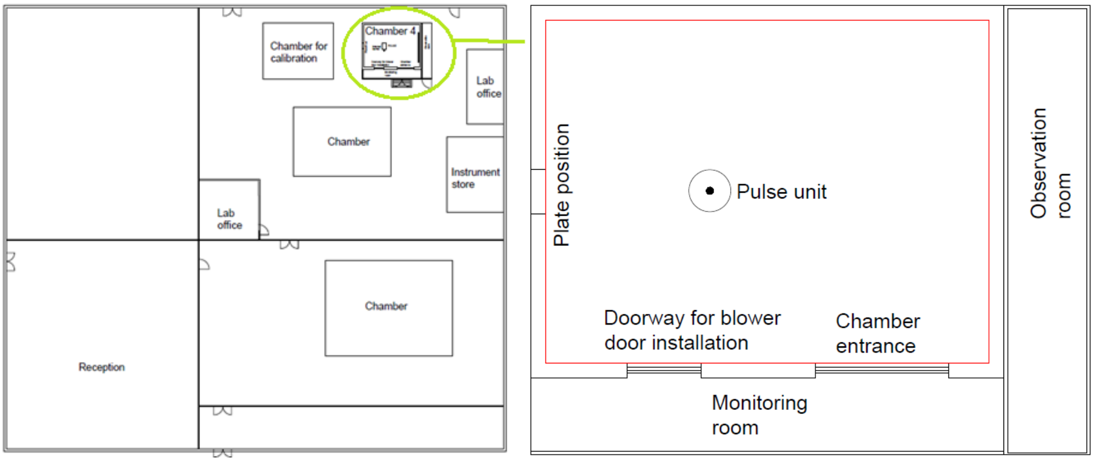


Figure 7 Environmental chamber for testing inside outer building (left) and test enclosure inside the chamber (right)

As shown in Figure 7, the chamber has a main entrance door and two smaller doors. One of them was used to install the DBB and the other was replaced by a compressed-fibreboard (MDF) sheet where plates with different openings were installed individually and at different times to provide a series of tests. The plan of the environmental chamber is shown in Figure 7, in which the red rectangle represents the test space. The chamber is a cuboid space where the pulse unit is placed in the middle during testing, as shown in Figure 8. When the pulse tests were carried out, the blower door unit was not in-situ in the door opening and the door was closed.

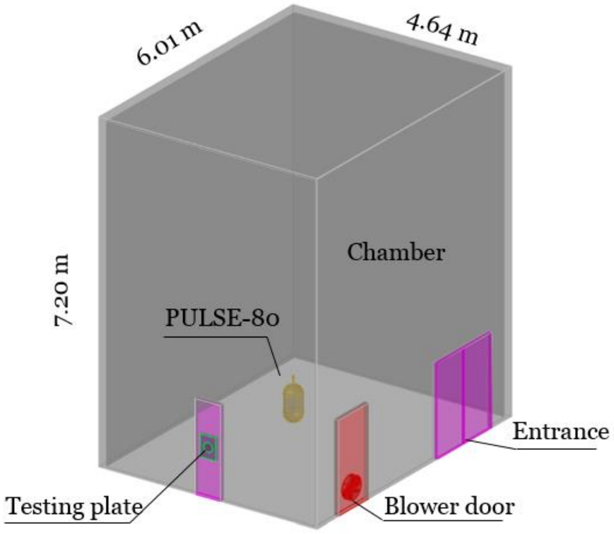


Figure 8 Setup of the test equipment in the chamber

Table **1** lists the three test approaches for measuring the air permeability of the chamber. It can be seen that there were two separate tests for the blower door, one following the ATTMA technical standard L1, with pressure range readings typically in the range of 10-60 Pa and a non-standard route where the readings were taken down to much lower levels of 4Pa. This non-standard approach was also taken as the readings at the lower level over-lap the region of pressure, which is measured by the pulse technique and therefore results reported at 4Pa could be directly compared.

Table 1 Three testing approach

Equipment	DBB		PULSE
Test approach	Standard	Non-standard	PULSE-80

Standard test: carried out in accordance to ATTMA technical standard L1, typically in 10-60 Pa;
Non-standard test: carried out mainly in accordance to ATTMA technical standard L1, but in 4-60 Pa.

This investigation had the following aims:

- To compare the measurements of Q_4 (air permeability at 4 Pa, $m^3/h \cdot m^2$) using DBB and PULSE-80 for various opening geometries in place in the chamber envelope.
- To investigate the behaviour of pulse and the building pressure response for different opening arrangements.
- To compare the difference between the Q_4 measured by DBB using standard and non-standard testing procedure.
- To investigate the impact upon the Q_4 result of moving the pulse unit into different positions within the test space and also to observe the effect of any internal physical barriers in the near location of the pulse unit.

2.2. Testing plates with different opening geometries

In order to achieve various leakage characteristics in the envelope of the enclosure, 8 fibre-board plates of two thicknesses were cut to provide various openings of known geometric area as shown together with their associated photograph in Table 2. It was originally intended to make openings with the same geometric area in plates 2-8; however due to fabrication discrepancy, this was not possible. Nevertheless for the purpose of individual test comparison of both test methods per plate this does not present any issue. In addition to the 8 plates and their associated tests, three more testing scenarios were created by modifying plates 2 and 3. Plate 2 was modified by adding a long air duct, plate 3 had three of the four square openings taped over with just one remaining and then plate 3 was further modified adding tightly packed straws to the remaining hole. The details for these modifications are listed in Table 3, therefore giving 11 plate test scenarios overall.

Table 2 Details of the testing plates

Test	Plate No.	Thickness (mm)	Description	Measured Area (cm^2)
1	1	18	Blank plate	0
2	2	18	Circle	318.10
3	3	18	Four squares	314.76
4	4	18	Slots	230.04
5	5	50	Circle	307.91
6	6	50	Four squares	306.56
7	7	50	Slots	328.73
8	8	50	Angled circle	381.44

Plate 1	Plate 2	Plate 3	Plate 4

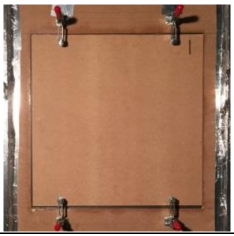
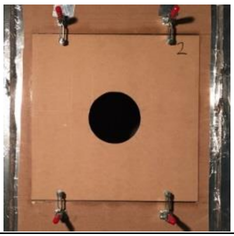
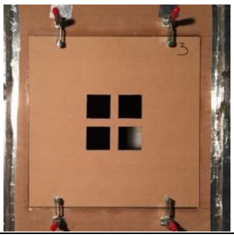
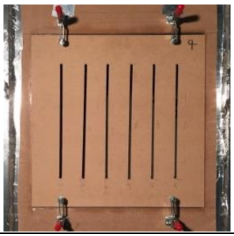

			

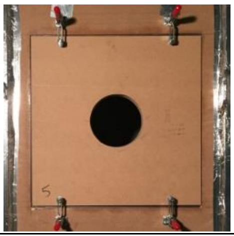
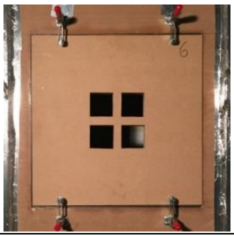
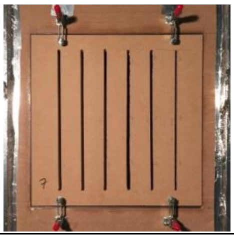
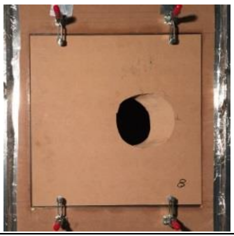
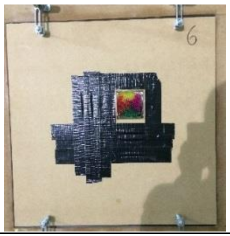
Plate 5	Plate 6	Plate 7	Plate 8
			

Table 3 Additional testing arrangements with modifications made to plates 2 and 6

Plate No.	9	10	11
Test	9	10	11
Modification	A 410 mm circular duct is added	Three squares were sealed	Straws in one square with others sealed



The plates were installed over a square opening (Figure 9), which had been cut into the MDF panel affixed to the door opening. In order to eliminate or minimize the leakage difference caused in each assembly of the testing plate, a rubber gasket was applied to the edges of the opening. The plates were installed by compressing the test plate against the gasket by means of four lateral press type clamps, as shown in Figure 9.

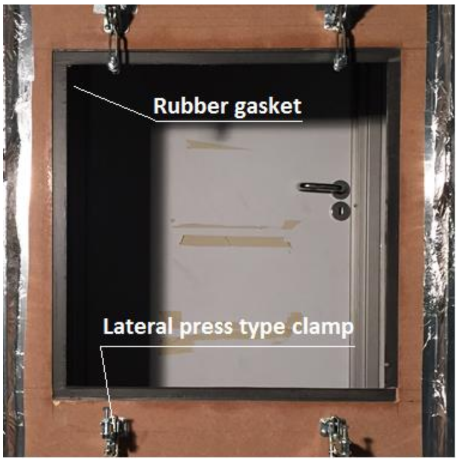


Figure 9 Frame design for assembling the plates

2.3. Basic testing process

The comparison tests were carried out under the assumption that due to the tests being performed in a sheltered environment that any difference in environmental conditions over the course of testing is insignificant. (This assumption was tested by observation of background pressure differentials before testing commenced.) The DBB tests were conducted by a qualified BSRIA compliance engineer and the testing procedure followed the Air Tightness Testing & Measurement Association technical standard L1 [56]. The DBB tests to all the plates were carried out consecutively in the pressurisation state and then followed by the pulse tests. In this paper the air permeability measured by both the DBB and PULSE-80 is compared at 4 Pa, but a discussion to the comparison at 50 Pa is also made. In order to predict Q_4 and Q_{50} (air permeability at 4 Pa and 50 Pa, $m^3/h\ m^2$), the power law equation is used, as shown in eq.(3):

$$Q = C \times \Delta P^n \tag{3}$$

Where Q is the air leakage rate (m^3/s), C is the flow coefficient ($m^3/s \cdot Pa^n$), ΔP is the building pressure (Pa) and n is the pressure exponent.

3. RESULTS AND ANALYSIS

The environmental chamber where the comparison test was performed was housed in a two-storey large building to obtain a sheltered environment where the outdoor weather condition has a reduced impact on the pressure in the environmental chamber. In the test, the impact of outdoor weather condition on the chamber pressure was not explicitly studied. However, the pressure difference between the chamber and the large building was measured by a pressure gauge (accuracy: ±1% of reading) when taking the zero-flow pressure readings in the blower door tests. It was found the pressure difference during the testing period was consistently lying in the range of 0-0.1 Pa. Therefore, it can be considered that the outdoor weather condition had negligible impact on the chamber pressure in the experimental study.

3. 1. Air leakage testing

In a number of countries including the United Kingdom, the air permeability at 50 Pa has been used in the standards as the metric for building airtightness [14, 57]. It is obtained by normalising the building air leakage rate with the area of building thermal envelope. In countries where the air change per hour at 50 Pa is used e.g. Germany, it is obtained by normalising the building air leakage rate with the volume enclosed in building thermal envelope.

In this study, the air permeability at 4 Pa (Q_4) is used as the metric for comparing the results of both techniques to avoid the error caused by extrapolating pulse results to a higher pressure. For the 11 testing plates, the Q_4 results are shown in Table 4 with achieved pressure range (ΔP). All the plates were tested by each approach consecutively. For the pulse tests, ideally the ΔP needs to cover 4 Pa so as to avoid any extrapolation, however, in some of the pulse tests, the ΔP doesn't cover 4 Pa but is in close proximity. Considering the hydraulic similarity at low pressures, minor extrapolations are made to the results close to 4 Pa in order to calculate Q_4, all the pulse tests that cover or are in close proximity of 4 Pa are used in this comparison study.

Table 4 Air permeability at 4 Pa (Q_4) of pulse and DBB tests ($m^3/h \cdot m^2$)

Test	1	2	3	4	5	6	7	8	9	10	11
Standard (DBB) Q_4 ($m^3/h \cdot m^2$)	0.5	1.24	1.27	1.1	1.28	1.33	1.48	1.01	1.51	0.79	0.57
ΔP range (Pa)	25-60	25-61	25-57	26-59	27-57	27-57	25-56	29-63	27-55	23-60	26-50
Non-standard (DBB) Q_4 ($m^3/h \cdot m^2$)	0.48	1.31	1.34	1.23	1.34	1.36	1.51	1.08	1.59	0.73	0.55
ΔP range (Pa)	4.5-60	4.0-61	4.2-57	4.2-59	4.0-57	4.0-57	4.0-56	4.0-63	4.0-55	4.4-60	4.4-54
PULSE-80 Q_4 ($m^3/h \cdot m^2$)	0.41	**N/A**	1.34	1.22	1.36	1.39	1.43	1.08	1.57	0.73	0.67
ΔP range (Pa)	5.8-8.4	**N/A**	3.3-4.9	3.1-4.5	3.3-4.5	3.2-4.2	2.8-4.6	4.7-9.0	1.6-3.5	6.1-11.2	6.7-8.2

ΔP range stands for the achieved pressure range in which the leakage is measured.

N/A stands for the fact that the test was unable to be performed due to time constraints.

The air leakage vs building pressure of all tests measured by DBB and PULSE-80 is plotted on the log-log scale graph, as shown in Figure 10. The PULSE-80 and DBB tests of the same plate are plotted with the same colour with a trend line added to each DBB test. It can be seen that the pulse measurement of plates 3 to 10 lie closely to the trend line of each corresponding DBB measurement. Note that, unfortunately a pulse test on plate 2 was not done due to time constraints.

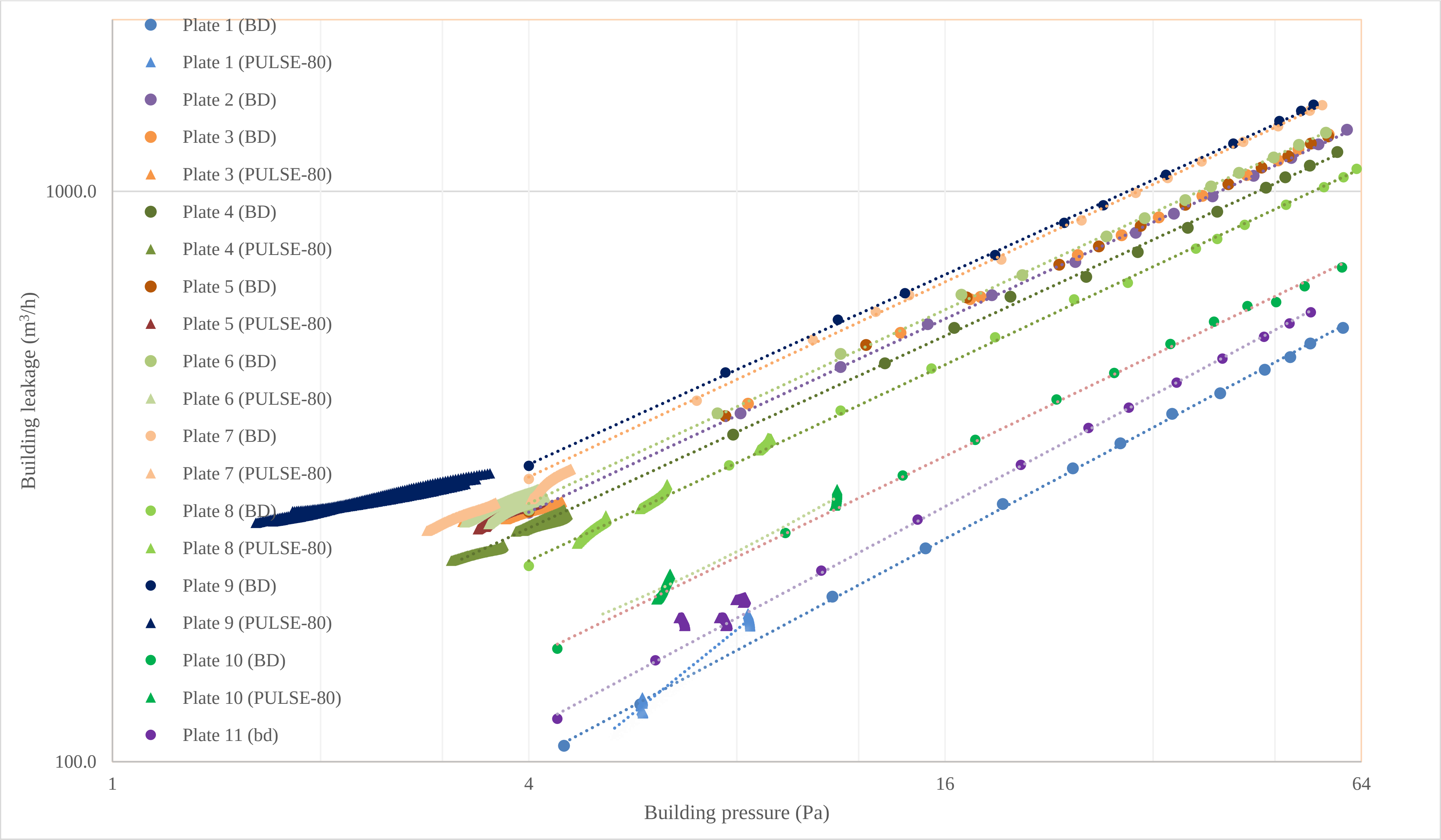


Figure 10 Log-log scale graph of leakage-pressure measured by DBB and PULSE-80

Figure 11 shows the percentage difference of Q_4 measured by PULSE-80 against both the standard and non-standard DBB approaches. It can be see that the difference in the Q_4 pulse results against the Standard DBB test lies in the range of 3.4%-18%, and 0%-21.8% for the non-standard DBB test. It can be observed that the relative percentage difference of the pulse result against non-standard DBB lies in the region of 0-5.3% except for plates 1 and 11. For plates 1 and 11, the relative percentage difference is much greater at 14.6% and 21.8%, respectively. Interestingly, this larger difference occurs where both test plates, 1 and 11 provide the lowest leakage rates of all the tests. To investigate why this may be the case, the building pressure measurements for plates 1 and 11 were examined against that for plate 5, which has a much larger opening. Figure 12 shows a comparison of the pulse shapes produced with plates 1, 5 and 11. It can be seen that the test chamber pressure response is much different for plate 5 compared to plates 1 and 11. For instance, the pulse peak is seen later with the more airtight chambers when plates 1 and 11 are used. Due to the fixed valve opening time for the release of air from the air tank, the quasi-steady period for the plate 1 and 11 is therefore much shorter than that of plate 5. Together with the slower decline of building pressure due to the chamber being more airtight, it leads to a measurement of leakage over a much smaller pressure range. This consequently contributes to a less accurate measurement of the leakage characteristics. This finding has now been accounted for in a further development of the pulse technique where the valve opening time and time range for analysis is made adjustable to allow longer period of measurement of building pressure drop in buildings with highly airtight envelopes in order to capture a wider pressure range.

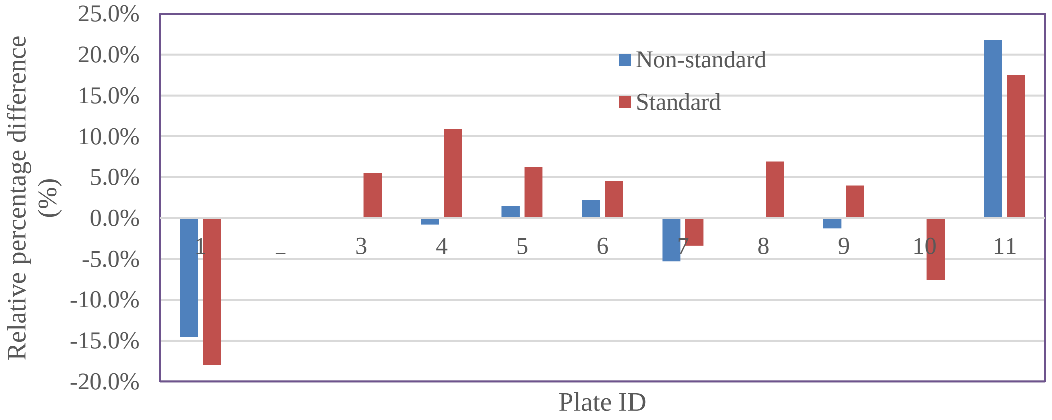


Figure 11 Percentage difference of Q_4 measured by PULSE-80 against that measured by DBB in two approaches (Plate 2 was not tested due to time constraints)

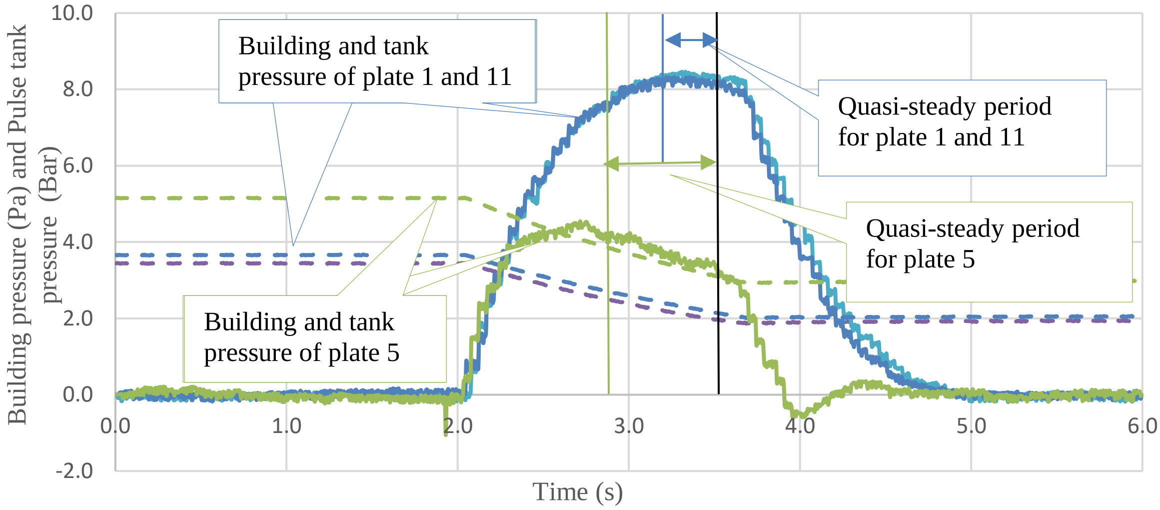


Figure 12 Comparison of building pressure of plate 1, 11 with plate 5 (broken line corresponds to tank pressure (Bar))

If it is now determined that the test performed with plates 1 and 11 are producing unreliable results due to test practicalities, then with these two tests excluded from the data set the percentage difference of Q_4 given by PULSE-80 and DBB (Standard) comes down to 3.4%-10.9% and 0%-5.3% for DBB (Non-standard). Therefore, in most of the testing scenarios, a good agreement has been achieved in the measurement of Q_4 using PULSE-80 and DBB. It is also seen that PULSE-80 has closer agreement with the non-standard DBB than the standard approach. This may suggest that the extrapolation error with the Q_4 obtained from the standard DBB could be responsible for this greater difference when compared to the PULSE-80 and non-standard DBB results.

Although the pulse test is designed to resolve the issues existing in the measurement of building air leakage at low pressures, it is frequently asked how it is compared with the blower door test at 50 Pa. The flow regimes at low pressure and high pressure levels are hydraulically dissimilar and therefore significant errors will occur in the prediction of air leakage rate from one level to the other. One of the issues with extrapolating the result at low pressure level to that at high pressure level is the absence of a higher data point, whereas an extrapolation downwards (as with the DBB tests) at least has the presence of the origin at the lowest point. Nevertheless, Q_{50} is predicted by using the pulse test data in various ways and compared with the DBB test, as listed in Table 5.

Table 5 Comparison of Q_{50} ($m^3/h{\cdot}m^2$) predicted by the pulse test using various methods against Q_{50} (standard method by DBB)

Plate	1	2	3	4	5	6	7	8	9	10	11
n	0.627	0.588	0.583	0.606	0.582	0.576	0.578	0.595	0.576	0.548	0.631
(DBB) Q_{50} ($m^3/h{\cdot}m^2$)	2.45	5.45	5.56	5.08	5.54	5.7	6.37	4.56	6.45	3.17	2.8
(Pulse) Q_{50} (n) ($m^3/h{\cdot}m^2$)	2.00	N/A	5.84	5.64	5.91	5.95	6.16	4.85	6.73	2.91	3.30
RPD (%)	-18.5	N/A	5.1	11.0	6.8	4.5	-3.3	6.4	4.3	-8.1	17.8
(Pulse) Q_{50} (0.66) ($m^3/h{\cdot}m^2$)	2.17	N/A	7.10	6.46	7.20	7.36	7.57	5.72	8.31	3.87	3.55

RPD (%)	-11.4 %	N/A	27.6	27.2	30.0	29.2	18.9	25.4	28.9	22.0	26.7
(Pulse) Q_{50} (Qua) ($m^3/h{\cdot}m^2$)	4.88	N/A	3.22	4.9	5.83	5.73	5.11	4.61	4.24	3.36	3.18
RPD (%)	99.2 %	N/A	-42.1	-3.5	5.2	0.5	-19.8	1.1	-34.3	6.0	13.6
(Pulse) Q_{50} (Pow) ($m^3/h{\cdot}m^2$)	4.91	N/A	2.11	4.98	5.33	3.84	4.71	4.94	2.99	3.57	1.83
RPD (%)	100.4	N/A	-62.1	-2.0	-3.8	-32.6	-26.1	8.3	-53.6	12.6	-34.6

RPD (%): relative percentage difference of Q_{50} predicted by using various methods using the Q_4 measured by PULSE-80 against the **(DBB) Q_{50}** measurement. **(Pulse) Q_{50}(n)** stands for the air permeability at 50 Pa predicted by the pulse test using the pressure exponent n given by DBB test. **(Pulse) Q_{50}(0.66**) stands for the air permeability at 50 Pa predicted by the pulse test using the empirical n value [58].**(Pulse) Q_{50}(Qua)** stands for the predicted air permeability at 50 Pa using quadratic equation based on the pulse test. **(Pulse) Q_{50}(Pow)** stands for the predicted air permeability at 50 Pa using power law equation based on the pulse test.

Compared with the Q_{50} measured by the DBB in the Standard tests, the percentage difference of Q_{50} predicted by PULSE-80 lies in the ranges of 3.3%-18.5%, 11.4%-30.0%, 0.5%-99.2% and 2%-100.4%, for the four different methods of calculating Q_{50} from pulse i.e. when ‘n’ value used is measured by DBB, when the empirical n value of 0.66 used, the fitted quadratic equation is used based on the pulse test and the power law equation based on the pulse test is used, respectively. The best prediction is the one using the n value measured by DBB, which gives predictions of Q_{50} within 18.5%. For the predictions using the empirical n value obtained by Orme [58], the percentage difference generally lies in the range of 11.4%-30%. It indicates the empirical n value is not representative of that of most of the testing scenarios. A possible explanation for this is due to the fact that the test environmental chamber, which is built differently from typical dwellings, is a single cell enclosure without the adventitious openings that are present in typical dwellings. For the predictions using either quadratic or power law equation based on the pulse test, the uncertainty range is larger than the previous two methods although for a few reasonable accuracy is seen. Therefore, similar with the findings reported by Cooper [5], the low-pressure pulse test does not always provide an accurate indication of Q_{50}. The measurement needs to be made over a wider pressure range in order to reduce the error in extrapolation if Q_{50} is calculated using the pulse test, but that would deviate from the primary purpose of the pulse technique that is designed to measure building air leakage at low pressures. Nevertheless, a more recent study by Wood [65] where pods with a volume of about 48 m^3 were tested in a wider range using both the blower door method and the pulse technique suggested a good agreement between them could be achieved when the impact of other factors such as blower door installation on the leakage level is minimized.

3.2. Pressure pulse

In Figure 13, the building pressure pulses generated by the PULSE-80 in the test chamber for each test are plotted together to show how the different plate openings affect the pulse shape. In order to achieve the required quasi-steady pressure readings from the chamber the pulse tank starting pressure was between 4 and 5 bar (g) for each test. However, for the test performed with plate 1, the starting pressure had to be reduced due to the fact that the plate is without any opening and a higher tank pressure would have created a pressure pulse within the chamber, which was too high. The test with plate 1 is therefore used as a comparative baseline. Figure 13 shows that the pulse shape varies between tests and can be approximately classified into three categories according to the shape and peak period of the pulse. The peak shape of the pulse generated with plate No.9 is sharp, whereas it is smooth for other plates. The most significant difference is seen where a 410 mm long circular duct is added to the opening in test plate No.2 (i.e. Plate No.9), which increases the leakage depth and alters the discharge coefficient. A rapid drop was subsequently seen after the pressure peak and this unique signature can be used to indicate the presence of such type of openings. The peak shapes of the pulses generated with other plates are relatively smooth. But the peaking time of the pulse generated with plate No.1 varies significantly from plates No.3-No.8. The trend shows that the more airtight the plate the later the pulse peaks, as shown in Table 7. According to the shape and peaking time of the pulse, the leak characteristics are categorized into three different types, as shown in Table 6. Therefore, the pulse shape could reflect the leakage level of the test building and possibly the type and location of leaks in the building envelope. One interesting point is that more airtight scenario (category 3) provides slower pressure decay after the valve closes. According to eq.(2), the percentage of unsteady flow during this period becomes smaller due to reduced value of $\frac{dq}{dt}$. However, the percentage of unsteady flow during decay is still higher than that in the quasi-steady period because air is supplied into the test space during the quasi-steady period.

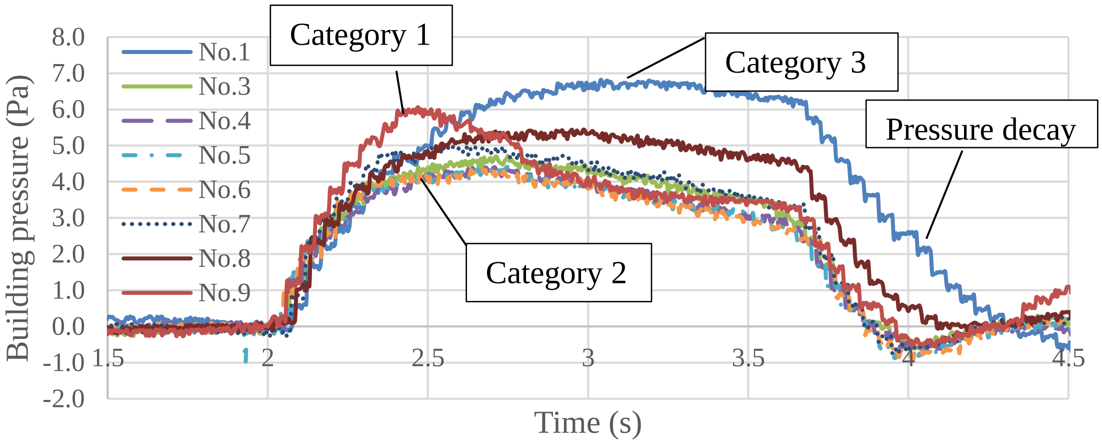


Figure 13 Shapes of the pulses generated with various plates

Table 6 Pulse shape category

Category	1	2	3
	Sharp peak	Smooth peak	Smooth and slow peak
Plate	No.9	No.3-No.8	No.1
$Q_{4,}$ (m^3/h·m^2) (Non-standard DBB)	1.59	1.08-1.51	0.48
Peak time (s)	2.47	2.545-2.985	3.04

Table 7 Pulse peaking time vs Q_4

Plate	1	8	4	5	3	6	7	9
Q_4 (m^3/h·m^2)	0.48	1.08	1.23	1.34	1.34	1.36	1.51	1.59
Peaking time (s)	3.04	2.985	2.705	2.715	2.75	2.67	2.545	2.47
Note: The plate are listed in the order of the leakage level.								

3.3. Comparison between DBB Standard and Non-standard

As discussed previously, two testing approaches, including the Standard and Non-standard DBB tests, were employed to carry out the steady state tests, which were then analysed to give the result of Q_4. The results of Q_4 measured by the two approaches for the same plates are compared to see the impact of extrapolation to the value of Q_4. Considering the influence of wind and buoyancy is insignificant due to the experimental arrangement then, theoretically, Q_4 given by the Non-standard approach should be more reliable than the Standard approach considering it did not involve any extrapolation in most cases. In other cases where 4 Pa was not directly measured, extrapolations were made only over a short pressure range (less than 0.5 Pa).

Prior to the discussion on the results, it is important to give some background introduction on the mathematical representation of the pressure-flow relationship. The most popular and widely used form is the power law equation, as described by eq.(3). It has been found to give a reasonably good empirical description of the flow-pressure relationship [50]. But it does not model the behaviour of adventitious openings because it conflicts with the fundamental law of fluid mechanics [59] and therefore the quadratic equation was preferred by Etheridge [59, 60]. The debate on the advantage of one over the other had been ongoing for a number of years [32, 59-64]. Walker [62, 63] compared the two equations on extrapolating the results measured at high pressures down to low pressures and found the power law better represented the relationship between pressure and flow for buildings with small cracks only, combinations of the small building envelope cracks and large holes (a furnace flue) and laboratory measurements of furnace flues. It was also mentioned that the power law equation is appropriate for developing flow in cracks and therefore work well for the building envelope leakage. Chiu [61] was in opposition to this claim and concluded from a numerical study that power law provides a good fit at high pressures but not so at low pressures and there were significant differences between the two equations at low pressures. Nonetheless, the similarity shared by the two is that they were both based on flows through adventitious openings. In this study, most of the test plates have well-defined openings except plate No.1, therefore the flow is supposed to be more developed than that in normal buildings during testing.

Table 8 lists the C and n values obtained only in the Standard DBB tests to the eleven testing scenarios to provide clean comparison with other standard blower door tests. It shows all the n values are much smaller than the average n value (0.66) obtained from a large data set of blower door tests undertaken in a number of countries [58]. The biggest n value was given by the test plate No.11, which had straws installed in the opening and made the flow less developed than other plates. Nevertheless, the flows experienced in all the testing scenarios are more developed than that occurred in typical buildings.

Table 8 C and n value measured in standard DBB tests

Test plate	1	2	3	4	5	6	7	8	9	10	11
C	44.1	114.4	118.6	99.3	119	125.3	138.7	92.9	141.9	95.6	49.5
n	0.627	0.588	0.583	0.606	0.582	0.576	0.578	0.595	0.576	0.613	0.631

In the analysis, the Q_4 given by the Non-standard approach is used as the baseline to present the percentage difference of Q_4 given by the standard approach, as shown in Figure 14. Overall this difference between the two approaches lies in the range of 2.0%-10.6%. In 8 out of 11 testing scenarios, the standard approach underestimated Q_4. Hence, it is seen that by measuring the building leakage according to the standard procedure in a sheltered environment, the DBB test can produce a significant deviation when calculating Q_4. Considering the tests were undertaken in a sheltered testing condition, it is reasonable to think that this discrepancy is more likely caused by performing the extrapolation down to a lower pressure. Sherman [20] pointed out the likelihood of incurring modelisation error in extrapolation using the power law equation. Cooper [32] stated direct measurement of Q_4 can reduce the uncertainty by a factor of three or more. It can therefore be seen that much of the disagreement of Q_4 between the pulse results and the standard DBB test can also be seen between the standard and non-standard DBB tests. Therefore extrapolating standard DBB results to be reported at 4 Pa is contributing to error at this level. This might also stand true when quadratic equation is used in the extrapolation. However, the comparison on the uncertainty of extrapolation using the two equations is not within the scope of this paper but will be reported in future based on the same data set.

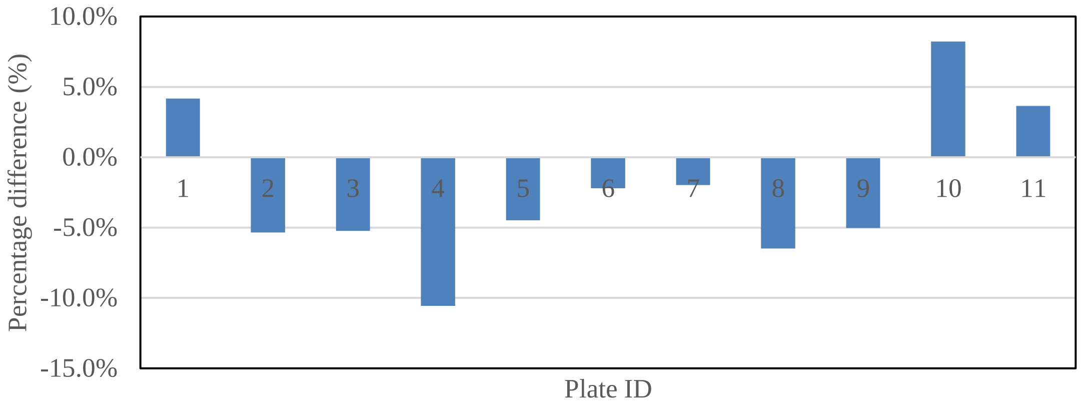


Figure 14 Percentage difference of Q_4 measured by DBB in Standard and Non-standard approach

3.4. Impact of Pulse unit location and use of internal barriers

As explained earlier, the pulse technique measures the building airtightness at low pressures by rapidly releasing a known volume of air into the test building, thereby creating a rapid pressure rise that quickly reaches ‘quasi-steady’ conditions. Therefore, the pulse technique relies on achieving an instant and uniform pressure rise throughout the whole internal space of the test building due to the nature of the short time operation. Hence, questions are frequently raised on how an even pressurisation in a test building could be achieved in a short time or when internal barriers are present in the vicinity of the ejecting air flow from the nozzle, or openings. Theoretically, the released air pulse would send a pressure wave travelling at the speed of sound throughout the building. This pressure wave would diffract around objects and rapidly equalise in a typical domestic building.

The following tests involved the same facility as described in the earlier test arrangement, but in this scenario the PULSE-80 was placed at various different locations inside the chamber in conjunction with setting an internal barrier. For these tests only plate No.4 was used for the opening in the chamber. The purpose of this investigation was to observe any impact on the measurements obtained by the PULSE-80 when the position of the unit and internal barrier were changed.

PULSE-80 was tested in a five different scenarios, which can be identified by the combination of the location IDs of the sensor and barrier, as illustrated in Figure 15 and Table 9. Scenario 1 is where the PULSE-80 was placed for the previous testing of multiple plate types and hence used as the baseline scenario for the purpose of comparison i.e. no barrier used. Scenario 2 can be identified as the combination of sensor location 1 and barrier location 1.

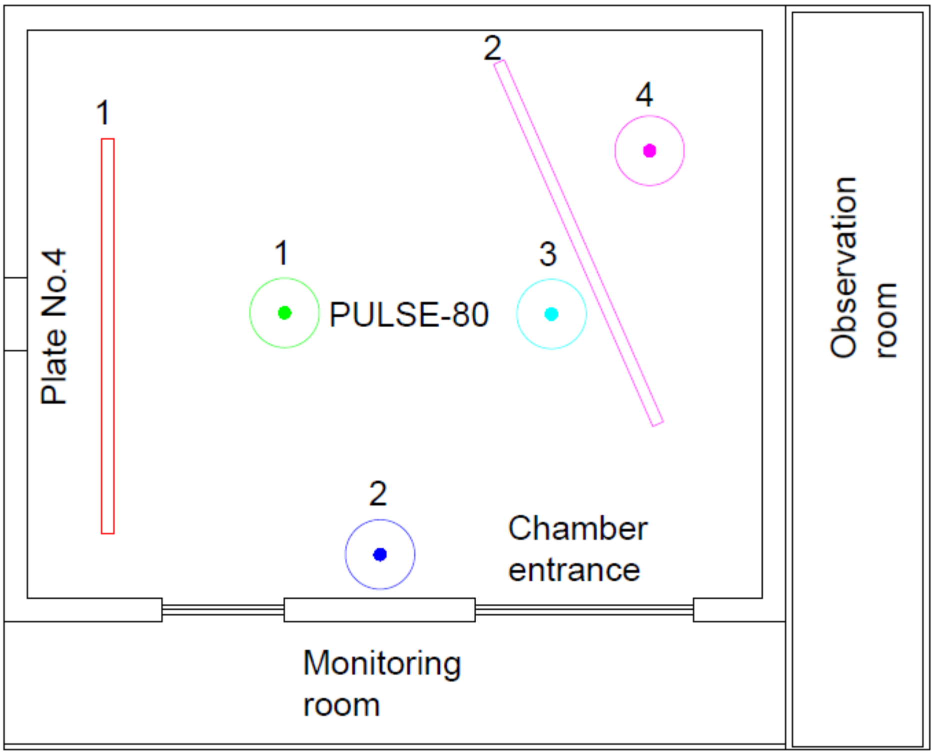


Figure 15 Testing scenarios of PULSE-80 (various locations and presence of barrier)

As shown in Table 9, it was found that the test results of different testing scenarios vary from the baseline by 1.62% to 4.65%. This difference from baseline is considered within the operational accuracy of the pulse method based on earlier studies [4, 5]. Hence, it can be considered that the variation in PULSE-80 and barrier location do not have significant impact on the test result. However, this test chamber, with an open internal space, does not replicate the space typology shown in typical buildings where the internal space is usually divided into multiple zones by partitions. Zoned spaces might change the way the pressure propagates across different zones during the pulse test. This is not reported herein because it is beyond the scope of this paper. However, this point of interest is the subject of a further investigation which includes both an experimental and numerical study. The outcome of that study will be reported in later publications.

Table 9 Q_4 ($m^3/h \cdot m^2$) at various locations using PULSE-80

Scenario	1	2	3	4	5
Q_4 (PULSE-80)	1.22	1.28	1.28	1.20	1.25
RPD (%)	Reference	4.58%	4.65%	-1.62%	2.55%
Barrier location	N/A	1	1	2	2
Sensor location	1	1	3	4	2

A particular observation of interest occurred where PULSE-80 was placed in a fenced corner, i.e. scenario 4. It was seen that rapid fluctuations were found in the building pressure readings due to the released high-speed airflow being reflected in the constrained space and impacting upon the exposed reference pressure tube. This did not produce a significant error to the results but provides knowledge that the reference pressure tube must be protected from external interference in any future development.

3.5. Uncertainty analysis

Because the tests were carried out in a sheltered environment and the impact of external weather condition is insignificant, the uncertainty analysis herein focuses on the measurement uncertainty caused by the instrumentation precision, i.e. bias error. The overall uncertainty caused by the factors including the environment impact and instrumentation precision was previously discussed by Cooper [48]. A comprehensive uncertainty analysis associated with the blower door test has been reported by Sherman [20]. Therefore, the instrument-caused uncertainty analysis for the blower door tests is not presented herein.

Mathematically, the building leakage under a quasi-steady pulse pressurisation can be described by a quasi-steady/temporal inertia model (QT model). The QT model solves a set of simultaneous first order differential equations, namely the continuity equation for the enclosed space and an integral momentum equation for each opening. The continuity equation includes the effect of compressibility of the air in the space and takes the form:

$$\frac{V}{\rho}\frac{d\rho_i}{dt} = Q_p\{t\} - \mathrm{q}\{t\} \tag{4}$$

Isentropic expansion of the air is assumed to provide the relation between density ρ_i and internal pressure p_i as $\frac{p_i}{\rho_i^\gamma} = C$, where C is a constant; $\gamma = 1.4$ is the specific heat ratio. Therefore,

$$\mathrm{q}\{t\} = Q_p\{t\} - \frac{V}{\gamma p_i}\frac{dp_i}{dt} \tag{5}$$

In order to determine the leakage rate of the building $\mathrm{q}\{t\}$, the volume flow rate of the released air from the compressor $Q_p\{t\}$ and the corresponding pressure difference $\Delta p(t)$ between the internal and reference must be obtained. $\Delta p(t)$ can be measured directly in the test. For the $Q_p\{t\}$, a theoretical model can be used to determine the value:

$$Q_p\{t\} = -\frac{V'}{\gamma R T_0}\left[\frac{P(t)}{P_0}\right]^{\frac{1-\gamma}{\gamma}}\frac{\dot{P}(t)}{\rho_i} \tag{6}$$

Where, $P(t)$ is the transient pressure of air in the compressor tank; P_0 and T_0 are the initial pressure and temperature of air in the compressor.
γ is the ratio of specific heat, equal to 1.4;
R is the gas constant, equal to 287.058 J/kg·K;
V' is the volume of air receiver;

To analyse the overall uncertainty (denoted as Δq) of measured building leakage rate $\mathrm{q}\{t\}$, the analysis is divided into two parts, the uncertainty (ΔQ) produced in the measurement of tank airflow rate and the uncertainty (ΔE) occurred in the measurement of isentropic expansion. Hence, Δq can be obtained by

$$\Delta q = \sqrt{\Delta Q^2 + \Delta E^2} \tag{7}$$

Where ΔE and ΔQ can be determined by the second term on the right of Eq.(5) and Eq.(5), respectively. In them, the variables include the measurement of initial tank pressure P_0, transient tank pressure $P(t)$, tank volume V', building pressure p_i, building volume V and building air temperature T_0. The precision of these measurements are listed in Table 10.

Table 10 Precision of the sensors and instrumentation

Sensor/measurement	Precision	Unit
Tank pressure transducer	±0.2%	Pa
Building differential pressure transducer	±0.25%	Pa
Indoor air temperature sensor	±0.08	℃
Tank volume measurement	±0.4	litre
Building volume measurement	±10% [57]	m^3
Note: For the measurement uncertainty of building volume, it ranges from 3% to 10%, the worst-case scenario is taken, i.e. 10%.		

Figure 16 shows the uncertainty caused by the instrumentation precision ranges from 0.51% to 1.11%. Hence, the instrumentation precision has much smaller impact on the measurement uncertainty compared to the environmental condition [48].

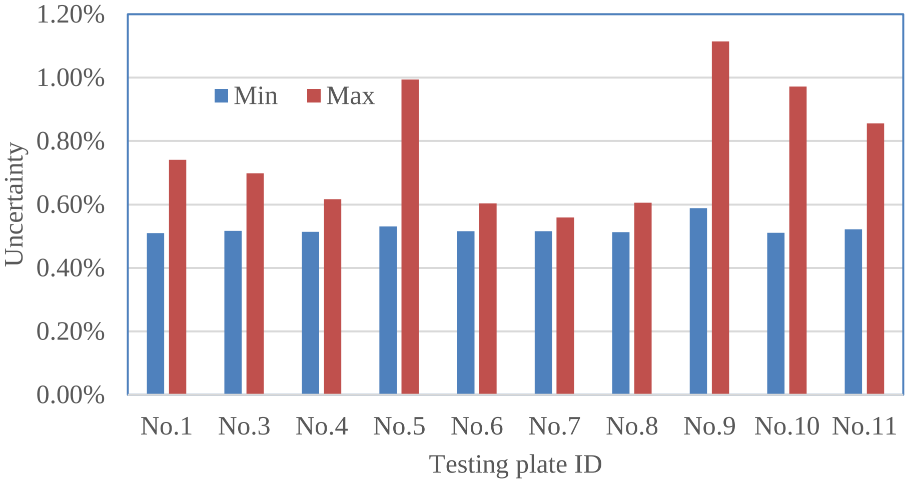


Figure 16 Instrumentation-caused uncertainties of the pulse tests with the testing plates

4. CONCLUSION

The experimental study, using PULSE-80 and DBB to measure the airtightness of a house-sized chamber in a sheltered condition, has allowed for the comparison of the two methods in an environment where the outdoor weather condition has a reduced impact on the measurement. For 9 out of 11 air tightness tests, the pulse tests using PULSE-80 and the non-standard DBB tests have given Q_4 that are in close agreement, with a percentage difference ranging from 0%-5.3%, whereas the Standard DBB tests have given a percentage difference up to 10.9%. This suggests that extrapolation error in the Standard DBB test may be contributing to the greater deviation. The tests, which used smaller effective openings in the chamber envelope, did not provide as good agreement as others due to insufficient quasi-steady period in the pulse test caused by the delayed pressure peak in a highly airtight enclosure. This has subsequently directed further research and development to extending valve opening time for the measurement of buildings with highly airtight envelopes and incorporating the feature of dynamic analysis to accommodate tests done in highly airtight buildings, such as Passivhaus standard buildings.

The results also showed that the chamber with various testing plates has leakage characteristics that are not representative of typical buildings i.e. the flows through the test chamber envelope in all the scenarios are more developed due to the presence of well-defined openings. The main objective of this study is to provide insight on the direct comparison of the measurement of air leakage at low pressures between the two testing methods in a sheltered environment. The findings suggested direct measurement of building air leakage at low pressures provides better accuracy.

One of the current disadvantages with the pulse technique lies in its inability to detect the location of the leakage pathways. Initial results showed that there is correlation between the shape of pressure pulses and the building leakage characteristics. That suggests it is possible to identify the type of leaks and predicting the rough location of distinctive openings. The tests reported herein do not provide a solution to that disadvantage but only serve as a starting point of investigating that correlation. Undoubtedly, further studies are recommended to establish the correlation.

The rapid release of compressed air into the building during a pulse test leads to the concern that it might be difficult to achieve an even pressure distribution within the building over a short period of time. The tests with the pulse unit placed at various locations in the chamber in combination with the presence of an internal barrier were conducted. The results showed that neither the unit location nor the presence of an internal barrier have significant impact on the test result, with a maximum deviation of Q_4 from the baseline result of no more than 4.65%. These tests provide some insight in relation to the pressure distribution generated by PULSE-80 in an open space. However, it is also understood that the geometrical complexities of larger buildings could result in variations in the pressure field in the property. This is therefore the focus of a future investigation.

This study has also led to a question on how they compare in a real life scenario, i.e. unsheltered environment. It was previously reported by Cooper [48] that it is unreliable for both methods to make extrapolations between low pressure and high pressure, which was based on the tests done in a number of dwellings using Minneapolis blower door model 4. Following this comparison study in a sheltered environment [34], continued comparison study, in an external chamber using the same units, has been carried out and reported by Zheng [66] with a slightly larger discrepancy, which suggests the weather condition is likely a contributor to that. More experimental studies based on the pulse technique, addressing the issues related with repeatability, comparison with steady pressurisation method and testing large buildings during the research and development, are summarised by Zheng [67].

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5. REFERENCES

[1] L. Lombard, J. Ortiz, C. Pout
A review on buildings energy consumption information
Energy and Buildings (2008), 40, pp.394-398.

[2] International Energy Agency 2013
Transition to Sustainable Buildings-Strategies and Opportunities to 2050

Available from: http://www.iea.org/Textbase/npsum/building2013SUM.pdf

[3] UNEP
Buildings and Climate Change, Summary for Decision-Makers
Sustainable Buildings & Climate Initiative, 2013. Available from:
http://www.unep.org/sbci/pdfs/SBCI-BCCSummary.pdf

[4] M. Orme
Estimates of the energy impact of ventilation and associated financial expenditures
Energy and Buildings (2001), 33, pp.199-205.

[5] S.J. Emmerich., A.K. Persily
Energy impacts of infiltration and ventilation in U.S. office buildings using multizone airflow simulation
IAQ and Energy 98, pp.191-203.

[6] J. Jokisalo, J. Krunitski, M. Korpi, T. Kalamees, J. Vinaha
Building Leakage, infiltration, and energy performance analyses for Finnish detached houses
Building and Environment (2009), 44, pp.377-387

[7] G. Raman, K. Chelliah, M. Prakash, R.T. Muehleisen
Detection and quantification of building air infiltration using remote acoustic methods
Internoise 2014 Melbourne, Australia, 16-19 November

[8] D. Etheridge
A perspective on fifty years of natural ventilation research
Building and Environment (2015), 91, pp.51-60.

[9] AIC
Air infiltration instrumentation and measuring techniques
1st AIC Conference, Windsor, Berkshire, UK, 6-8 October, 1980

[10] Committee on Climate Change
Meeting Carbon Budgets-2016 Progress Report to Parliament
Available from: https://www.theccc.org.uk/wp-content/uploads/2016/06/2016-CCC-Progress-Report.pdf

[11] United Nations
Paris Agreement 2015
Available from:
https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

[12] M.H. Sherman, R. Chan
Building Airtightness: Research and Practice
Lawrence Berkeley National Laboratory Report (2004), Report No. LBNL-53356

[13] A. Anderson
The history of the blower door

Home Energy Magazine Online November/December 1995,
http://homeenergy.org/show/article/year/1995/id/1171

[14] Y. Ji, L. Duanmu
Airtightness field tests of residential buildings in Dailan, China
Building and Environment (,, 2017), 119, pp. 20-30

[15] Y. Ji, L. Duanmu, X. Li
Building Air Leakage Analysis for Individual Apartments in North China
Building and Environment (2017), 122, pp. 105-115

[16] A. Salehi, I. Torres, A. Ramos
Experimental Analysis of Building Airtightness in Traditional Residential Portuguese Buildings
Energy and Buildings (2017), 151, pp. 198-205.

[17] M. Prignon, G. Van Moeseke
Factors influencing airtightness and airtightness predictive models: a literature review
Energy and Buildings (2017), 146, pp. 87-97

[18] T. Baracu , V. Badescu, C. Teodosiu, M. Degeratu, M. Patrascu, C. Streche
Consideration of a new extended power law of air infiltration through the building's envelope providing estimations of the leakage area
Energy and Buildings (2017), 149, pp. 400-423
.

[19] Sinott, D. & Dyer, M., 2012. Ait-tightness Field Data for Dwellings in Ireland. Building and Environment, Volume 51, pp. 269-275

[20] M. Sherman, L. Palmiter
Uncertainty in fan pressurisation measurements
Airflow Performance Conference, ASTM International, West Conshohocken, PA, 1995, pp. 266-283, https://doi.org/10.1520/STP14701S

[21] S. Howieson, T. Sharpe, P. Farren
Building tight - ventilating right? How are new air tightness standards affecting indoor air quality in dwellings?
Building Services Engineering Research & Technology, 35(5), pp. 475-487.

[22] G. Guyot, J. Ferlay, E. Gonze, M. Woloszyn, P. Planet, T. Bello
Multizone air leakage measurements and interactions with ventilation flows in low-energy homes
Building and Environment (2016), 107, pp. 52-63

[23] J. Furbringer, C. Roecker, C.-A.Roulet
The use of a guarded zone pressurization technique to measure air flow permeabilities of a multizone building
9th AIVC Conference “ Effective ventilation”, Gent, Belgium, 12-15 September 1988

[24] E.B. Moller, T.V. Rasmussen
A simplified method using compressed air to determine air leakage
2010 ASHRAE.

[25] W.H. Card, A. Sallman, R.A. Graham, E. Drucker
Air leakage measurement of buildings by an infrasonic method. Syracuse University
Technical Report TR-78-1, 1978.

[26] Y. Watanabe, H. Kobayashi, Y.Utsumi
Development of validation of AC-pressurization measuring of leakage area of houses
Available from: http://www.ibpsa.org/proceedings/BS1999/BS99_PA-09.pdf

[27] B. Mattsson
A transient pressurisation method for measurements of airtightness
Journal of Building Physics (2007), 31, No.1

[28] F. Granne
Air and Water Tightness in Building Envelopes – Evaluation of Methods for Quality Assurance
Report R-01/187-SE (2001), Stockholm, KTH.

[29] T Nishioka, Q. Chen, N. Arai, K. Fujiwara, N. Umemiya, R. Okura
Unsteady pressurization method to measure the airtightness of the building envelope
Available from: http://www.irbnet.de/daten/iconda/CIB2449.pdf.

[30] P.S. Carey, D.W. Etheridge
Leakage measurements using unsteady techniques with particular reference to large buildings
Building Serv. Eng. Res. Technol. (2001), 22, pp.69-82

[31] E.W. Cooper, D.W. Etheridge
Measurement of building leakage by unsteady pressurisation
25th AIVC Conference "Ventilation and retrofitting", Prague, Czech Republic, 15-17 September 2004

[32] E.W. Cooper, D.W. Etheridge
Determining the adventitious leakage of buildings at low pressure. Part 1: uncertainties
Building Serv. Eng. Res. Technol. (2007), 28, pp.71-80

[33] E.W. Cooper, X.F. Zheng, M. Gillott, S. Riffat, Y.Q. Zu
A nozzle pulse pressurisation technique for measurement of building leakage at low pressure
35th AIVC conference "Ventilation and airtightness in transforming the building stock to high performance", Poznan, Poland, 24-25 September 2014

[34] X. Zheng, E. Cooper, J. Mazzon, I. Wallis, C.J. Wood
A comparison study of the blower door and novel pulse technique on measuring enclosure airtightness in a controlled environment
38th AIVC conference, Nottingham, United Kingdom, 13-14 September 2017

[35] X.F Zheng, E. Cooper, Y.Q. Zu, M. Gillott, D. Tetlow, S. Riffat, C.J. Wood
Experimental studies of a pulse pressurisation technique for measuring building airtightness

17th International Conference on Sustainable Energy Technology, Wuhan, China, 21-23 August 2018

[36] M.J. Lee, N. Kim, H.S. Ryou
Air tightness measurement with transient methods using sudden expansion from a compressed chamber
Building and Environment (2011), 46, pp.1937-1945

[37] S. Bae, H. Moon, M. J. Lee, N. Kim, H.S. Ryou
Improvement in the applicability of the air tightness measurement using a sudden expansion of compressed air
Building and Environment (2013), Volume 61, pp. 133-139.

[38] M. Ringger, P. Hartmann
Evaluation of an acoustical method for detecting air leaks
Air Infiltration Review, Vol.11, No.1, December 1989

[39] D.N. Keast, H.S. Pei
The use of sound to locate infiltration openings in buildings
Proceedings ASHRAE/DOE Conference “Thermal performance of the exterior envelopes of buildings”, Florida, December 3-5. 1979

[40] M. Sherman, M. Modera
Signal attenuation due to cavity leakage
J. Acoust. Soc. Am. 84 (6), December 1988

[41] V. Iordache, T. Catalina
Acoustic approach for building air permeability estimation
Building and Environment (2012);57:18-27

[42] T. Sonoda, F. Peterson
A sonic method for building air-leakage measurements
Appl Energy 1986, 22, 3, pp.205-224

[43] G. Benedetto, E. Brosio
A relation between transmission loss and air infiltration characteristics in windows
Turin: lstituto Elettrotecnico Nazionale Galileo Ferraris; 1981. pp. 1-4

[44] O. Hassan
An alternative method for evaluating the air tightness of building components
Building and Environment (2013), 67, pp. 82-86.

[45] M. Sandberg, M. Mattsson, H. Wigo, A. Hayati, L. Claesson, E. Linden, M. A. Khan
Viewpoints on wind and air infiltration phenomena at buildings illustrated by field and model studies
Building and Environment (2015), 92, pp. 504-517.

[46] E.W. Cooper, D.W. Etheridge
Determining the adventitious leakage of buildings at low pressure. Part 2: pulse technique
Building Serv. Eng. Res. Technol (2007); 28: pp. 81-96

[47] E.W. Cooper, X.F. Zheng, M. Gillott, S. Riffat, Y.Q. Zu
A nozzle pulse pressurisation technique for measurement of building leakage at low pressure
35th AIVC Conference "Ventilation and airtightness in transforming the building stock to high performance", Poznan, Poland, 24-25 September (2014)

[48] E.W. Cooper, X.F. Zheng, C.J. Wood, M. Gillott, D. Tetlow, S. Riffat, L.D. Simon
Field trialling of a new airtightness tester in a range of UK homes
Int. J. Ventilation, 18(1) (2019), pp.1-18.

[49] Zero Carbon Hub
Closing the gap between design and as-built performance
End of term report, July 2014. Available from:
http://www.zerocarbonhub.org/sites/default/files/resources/reports/Design_vs_As_Built_Performance_Gap_End_of_Term_Report_0.pdf

[50] M.H. Sherman, D. Dickerhoff
Air-Tightness of U.S. Dwellings
15th AIVC Conference: The Role of Ventilation (1994), Vol. 1, pp. 225-234. (LBNL-35700)

[51] M.H. Sherman, N.E. Matson
Air Tightness of New U.S. Houses: A Preliminary Report
Lawrence Berkeley National Laboratory, LBNL 48671 (2002)

[52] M.H. Sherman
Infiltration in ASHRAE's residential ventilation standards
Lawrence Berkeley National Laboratory, LBNL-1220E (2009)

[53] C.F. Remi, V. Leprince
Uncertainties in building pressurisation tests due to steady wind
Energy Build. (2016), 116 pp. 656-665

[54] S. Sharples, S. Closs, N. Chilengwe
Airtightness testing of very large buildings: a case study
Building Serv. Eng. Res. Technol. (2005), 26(2), pp. 167-172

[55] DW Etheridge, M Sandberg
Building Ventilation -Theory and Measurement
John Wiley & Sons, Chichester, 1996

[56] ATTMA Technical standard L1
Measuring air permeability in the envelopes of dwellings
The Air Tightness Testing & Measurement Association (2016)

[57] BS EN ISO 9972
Thermal performance of buildings-Determination of air permeability of buildings-Fan pressurisation method
BSI Standards Publication (2015)

[58] M. Orme, M. Liddament, A.Wilson
An Analysis and Data Summary of the AIVC's Numerical Database

Technical Note 44 (1994), Air Infiltration and Ventilation Centre

[59] D.W Etheridge
A note on crack flow equations for ventilation modelling
Building and Environment (1998), 33 (5), pp.325-328

[60] D.W. Etheridge
Crack flow equations and scale effect
Building and Environment (1977), 12, pp.181-189

[61] Y.H. Chiu, D.W. Etheridge
Calculations and notes on the quadratic and power low equations for modelling infiltration
Int. J. Ventilation (2002), 1(1) pp.65-77

[62] I. Walker, D.J. Wilson, M.H. Sherman
A comparison of the power law to quadratic formulations for air infiltration calculations
Energy Build. (1998), 27 pp.293-299

[63] I.S Walker, D.J. Wilson, M.H. Sherman
Does the power law rule for low pressure building envelope leakage?
Proceedings of 17th AIVC Conference, Gothenburg, Sweden. 17-20 September 1996.

[64] D.W. Etheridge
Nondimensional methods for natural ventilation design
Building and Environment (2001), 37, pp.1057-1072

[65] C.J. Wood, X.F. Zheng, A.V. Pasos, Y.S. Hsu, L. Smith
An extended pressure range comparison of the blower door and novel pulse method for measuring the airtightness of two outdoor chambers with different levels of airtightness
39th AIVC conference, Juan-Les-Pins, France, 18-19 September 2018

[66] X.F. Zheng, J. Mazzon, I. Wallis, C.J. Wood
Experimental study of enclosure airtightness of an outdoor chamber using the pulse technique and blower door method under various leakage and wind conditions
39th AIVC conference, Juan-Les-Pins, France, 18-19 September 2018

[67] X.F. Zheng, E. Cooper, Y.Q. Zu, M. Gillott, D. Tetlow, S. Riffat, C.J. Wood
Experimental Studies of a Pulse Pressurisation Technique for Measuring Building Airtightness
Future Cities and Environment (2019), 5(1): 10, 1–17 DOI: https://doi.org/10.5334/fce.66