Experimental studies of a pulse pressurisation technique for measuring building airtightness

Authors

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Abstract:

A pulse pressurisation technique is developed and utilised for determining building leakage at low pressure, based on a "quasi-steady pulse" concept. The underlying principle of the technique is to subject the building envelope to a known volume change in a short period of time (typically 1.5 s). The resulting pressure pulse is recorded, from which the leakage characteristic at low pressure is determined. The technique minimizes the effects of wind and buoyancy forces and has proven to be repeatable. It can use a compact and portable test rig and does not need to penetrate the building envelope. Therefore, it can obtain the leakage of a building very quickly and efficiently.

Throughout the various stages of research and development of the pulse technique, experimental investigations have been carried out under different configurations and scenarios in order to validate the changes that have been made for the purpose of system development and optimisation. This paper provides an overview of experimental investigations in the validation process by covering comparison between blower door and pulse unit, comparison between piston-based pulse unit and nozzle-based pulse unit, testing with multiple pulse units in a large building, testing with a known opening, and testing in different building types with a range of volumes and airtightness levels. It enables us to understand the strengths and the limits of the pulse technique, from the experimental and practical perspective.

Keywords

Building airtightness, Blower door, Pulse technique, Experimental validation

1. INTRODUCTION

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 used to describe how well the building envelope is sealed. 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 and it is important to measure it in the process of new construction and retrofitting in order to achieve a good building energy efficiency, durability and indoor environment.

A good building airtightness is desirable considering the fact that building energy consumption caused by building infiltration takes 13%-30% of the overall heating energy, 4-14% of cooling load (Emmerich, Emmerich 1998, Jokisalo 2009, Raman 2014, Keast 1979). The energy consumption in the building sector represents 33%-40% of global overall energy consumption (UNEP 2013, Lombard 2008, IEA 2013). However, the indoor air quality would compromise if the indoor contaminant is not diluted quickly enough by the infiltration. A purpose-designed ventilation strategy is required in this case in order to provide sufficient fresh air to occupants. The last but not the least, which is usually less concerned of than energy consumption and indoor air quality, is a long term effect caused by the moisture transportation that is largely influenced by the air tightness. A poor airtightness 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.

One of the main challenges in measuring building air leakage rate goes to the measurement of the building pressure. Under natural condition, a building would experience a pressure caused by wind and buoyancy effects, namely outdoor air movement and temperature difference between indoor and outdoor environment. This pressure is typically in the region of 1-4 Pa. It needs to be taken out from the measured pressure difference across the building envelope in order to obtain the actual building pressure. In reality, it can be difficult to achieve due to the random nature of wind. This issue becomes more outstanding when the wind condition is adverse. One of the approaches to overcome this issue is to measure the building leakage rate at high pressures in order to negate the impact of wind/buoyancy effects; this is adopted in the steady pressurisation method. One of them, blower door technique, has been well established and widely accepted as a means for measuring building airtightness. However, it comes with its own shortcomings, which have been discussed in scientific studies and practical uses (Cooper 2014, Cooper 2016, ZCH 2014, Okuyama 2012), mainly including: change of building envelope, demand of skilful training to the operative, unrealistic high measuring pressure and coarse interpretation of background pressure during testing especially under windy condition.

The historical development of the pulse technique for measuring air–tightness consists of three versions, namely a gravity driven piston unit, a compressed air driven piston unit and most recently a nozzle unit. Overall, it has gone through several developmental stages related to algorithm optimisation, system simplification and reconfiguration changing from a cumbersome and heavy unit into a more portable and quick-to-use version. Experimental validations have also been carried out through those stages, in order to prove the concept initially, and validate changes made to the pulse unit, including hardware and firmware. Comparisons have been made experimentally between the piston unit and nozzle unit in order to verify the validity of the replacement of piston with nozzle. The pulse unit has also been used to measure the size of known openings in a real house, and the air leakage characteristic of a number of UK residential buildings in different types alongside the steady test method to compare in measuring known openings and how these two methods correlate with each other in a range of UK domestic buildings. Tests in large buildings using multiple piston and nozzle units are also introduced to show the technical feasibility of testing large buildings. This series of experimental studies allow us to understand the pulse technique comprehensively.

2. PRINCPLE AND HISTORICAL DEVELOPMENT

The pulse technique measures the building airtightness at low pressures by releasing a 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. 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 a previous paper (Cooper, 2007: page 3-5). A typical pulse test measurement is shown in Figure 1. The readings of building pressure consist of three key stages, pressure variation during quasi-steady period and background pressures before and after the pulse.

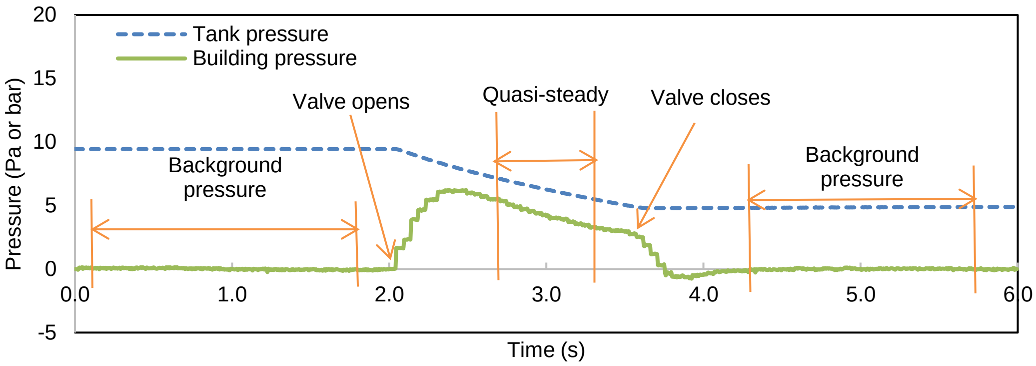


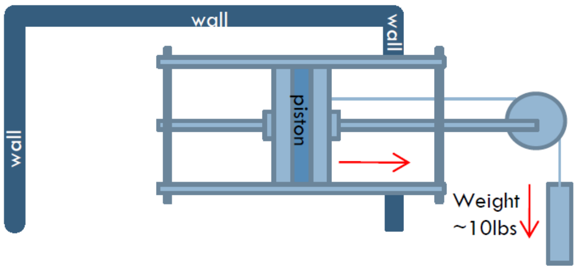
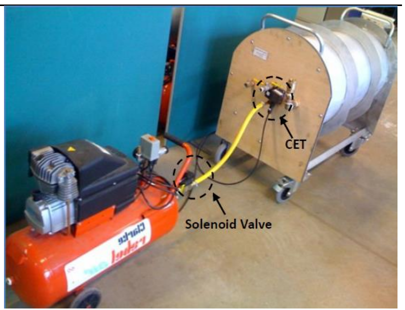
Figure 1A typical pulse test by APU with 60 l tank (tank pressure measured in bar, building pressure in Pa)

The pulse technique measures the building leakage at various pressure levels similar to leakage measurements using a blower door test process. However, it measures in a dynamic manner instead of taking each individual reading 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 (Sharples, 2005: page 168). 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, is used to account for that inertia effect. The momentum equation is described by eq.(1).

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

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.

Table 1 Developmental stages of the pulse technique

<table>
<tr><th>Developmental stage</th><th colspan="2">1 (2002)</th><th colspan="2">2 (2002-2011)</th></tr>
<tr><td>Photo or schematic diagram</td><td colspan="2">
</td><td colspan="2">
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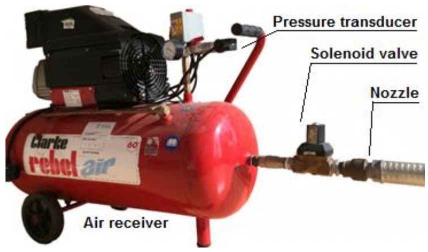
<tr><td>Developmental stage</td><td>3 (2010-2013)</td><td colspan="2">4 (2013-2015)</td><td>5 (2016-2017)</td></tr>
<tr><td>Photo or schematic diagram</td><td>
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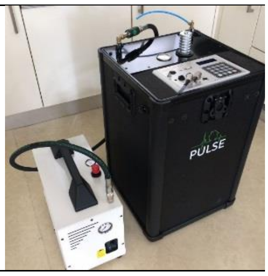
</td><td>
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Table 1 lists a summary of the pulse unit at each developmental stage with a schematic diagram or a photo of each version. As can be seen the initial process involved the delivery of a pulse of air through the use of a moving piston inside of a large cylinder. This method was superseded by the use of a nozzle attached directly to an air compressor tank. This enabled the removal of the large piston, but the nozzle method necessitates the need to measure the tank pressure throughout the test to determine a volume flow rate from the tank. The validity of this process has been shown to be accurate and repeatable as introduced in section 3.1 and further details are reported in (Cooper, 2014: 241) by Cooper. More technical details of each iteration are listed in Table 2.

The work reported in this paper focuses upon experimental investigations utilising pulse units developed at stage 2-5 i.e. no discussion in relation to gravity driven piston unit.

Table 2 System composition of the pulse unit at various developmental stages

Stage	1	2	3	4	5
Version	Gravity driven piston unit	Compressed air driven piston unit	Nozzle unit		
Tank	N/A	Steel	Steel	Composite	Aluminum
Compressor	N/A	Oil based semi-industrial. 99 dB	Oil based semi-industrial. 99 dB	Oil free double piston 65 dB	Oil free double piston 65 dB
Solenoid valve	N/A	¾” 230 VAC	¾” 230 VAC	¾” 24 VDC	¾” 24 VDC
Tank pressure transducer	N/A	PMP 1400 (GE)	PMP 1400 (GE)	PMP 5013 (GE)	PMP 5013 (GE)
Building pressure transducer	N/A	200 Hz Furness control (FCO44)	200 Hz Furness control (FCO44)	20 Hz Furness control (FCO332)	20 Hz Furness control (FCO332)
Power supply	N/A	Standalone AC/DC converters	Standalone AC/DC converters	Embedded in a control box	Embedded in a control box
Pressure reference	N/A	External	External	Internal	Internal
Data collection	N/A	A/D converter and BNC box and computer	A/D converter and BNC box and computer	Self-contained RAM	Self-contained RAM
Data analysis	N/A	Computer-based Matlab program		Self-contained firmware	Self-contained firmware

3. REPEATABILITY

During the course of research and development of the pulse technique, various changes in the system components and operations have occurred, such as the replacement of piston with nozzle, utilisations of differential pressure transducer with lower sampling rate, replacement of external pressure reference with internal pressure reference, utilisation of automated testing process, data collection and analysis. Considering repeatability is one of the key indexes of system reliability, it is important to maintain a good and consistent level of it throughout all the developments. Hence, experimental tests have been carried out at each stage to validate each change. Most of the tests were undertaken under calm or light wind conditions.

3. 1. Comparisons with the piston technique

From the piston unit (stage 2) to the nozzle unit (stage 3), there is a significant change in the way of introducing the pressure pulse into the test space, i.e. replacing the compressed air driven piston displacement with direct ejection of compressed air via a nozzle. In the piston unit, the flow rate of released air is quantified by the real time movement of piston, while in the nozzle unit, it is done by monitoring the real time pressure change in the air tank. The consequent change in the mathematical model for determining the air flow rate from the tank, compared to the hardware or software modification based on the same principle, is more significant and hence more likely affects the system performance. Therefore, this section is allocated particularly to the investigation of the validity of this change by subjecting these two iterations to the same testing condition.

Tests were done in the same test room and a comparison of leak-pressure curves is shown in Figure 3. Good agreement appears and indicates that the nozzle unit is reliable for determining building leakage at low pressures. However, from Figure 3, it can be seen that the piston tests always give slightly lower values of leakage under the same pressure differences. During the piston test, there is an unavoidable leak of air from the narrow gap between the piston and cylinder wall. Therefore, the piston test may underestimate the air leakage rate slightly because it is obtained indirectly from the velocity of the piston.

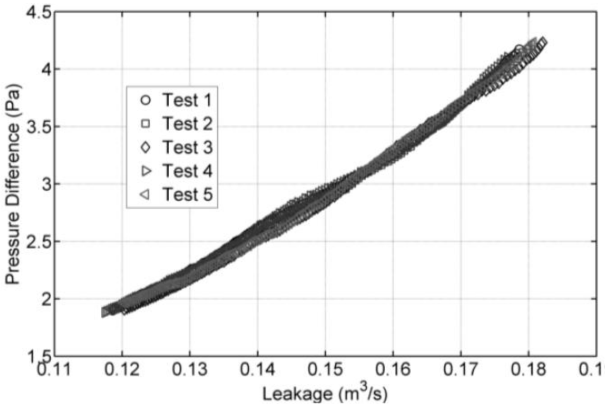


Figure 2 Nozzle test results

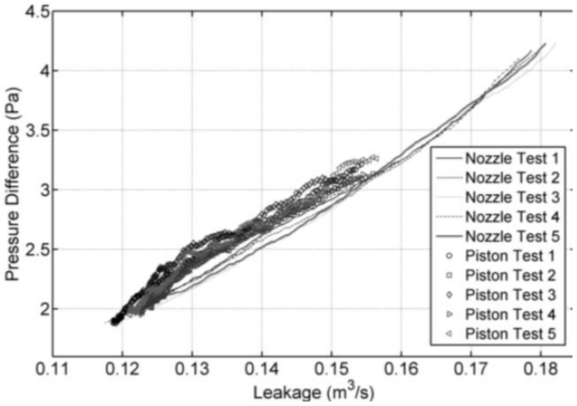


Figure 3 Comparison of nozzle and piston results

In addition to the single nozzle and single piston tests, further experimentation was also performed using simultaneous firing of two-nozzles or two-pistons, i.e. two nozzle devices or two piston devices operated at the same time to generate a combined pressure pulse, were used for the measurement. Figure 4 shows the leakage characteristics of the same building obtained by the single nozzle, single-piston, two-nozzles and two-pistons with repeated test runs. A good agreement was achieved as indicated by the same trend.

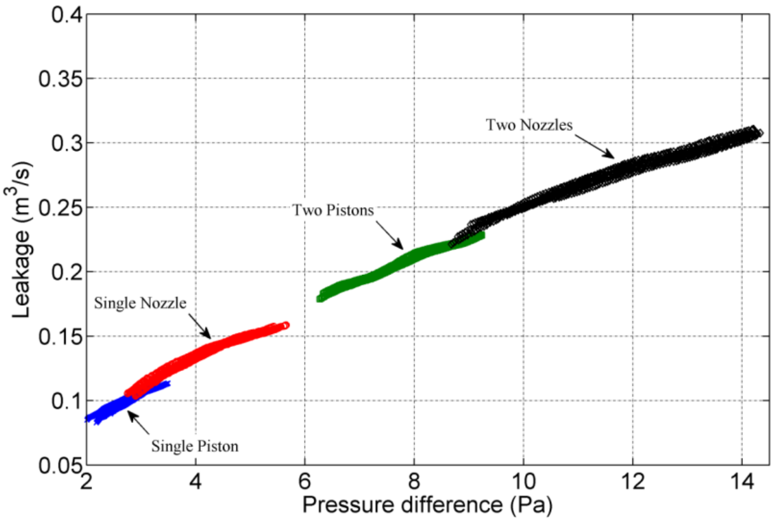


Figure 4 Comparison of the leakage of Building 2 obtained by nozzle and piston units

It was therefore concluded that the use of the nozzle technique was repeatable and provided comparable results to that of the piston technique. In terms of function and portability this provided a significant advance of the pulse technique.

3. 2. Nozzle unit (stage 3)

The stage 2 piston unit and stage 3 nozzle unit are described in details by Cooper in (Cooper, 2007: page 3-5). They have been used to test two buildings based on the University Park campus in Nottingham. Building 1 is a single cuboid room with a length, width and height of 9.20 m, 6.04 m and 2.45 m, respectively, which gives an internal volume of 136 m^3. Building 2 is a newly built energy efficient house, with three bedrooms on the first floor and one living room on the ground floor. The total internal volume of the building is 371 m^3. The test results are listed in Table 3, where V_4 is the air leakage rate at 4 Pa.

Table 3 V_4 of 5 repeated test runs in two test buildings using nozzle unit

Building	Test ID	1	2	3	4	5	Mean
1	V_4 (m^3/s)	0.17535	0.17557	0.17704	0.17525	0.17668	

	RPD (%)	-0.36%	-0.23%	0.60%	-0.41%	0.40%	0.17598
2	V_4 (m^3/s)	0.13744	0.13762	0.13962	0.13858	0.13853	0.13836
	RPD (%)	-0.66%	-0.53%	0.91%	0.16%	0.16%	

NOTE: Mean and *RPD* stand for 'mean average' and 'relative percentage difference from mean' respectively.

The system composition of piston unit and nozzle unit is almost the same except the different way of introducing the pressure pulse into the test building. The former does it by moving a piston driven by compressed air and the latter does it by releasing compressed air directly into the test house through a nozzle. As reported in section 4, the comparison between piston unit and nozzle unit have shown similar repeatability.

3. 3. Nozzle unit (stage 4)

The Pulse technique evolved from a lab based set up to a packaged unit with integrated electronics within a control box. In comparison to stage 2 and 3, the nozzle unit at stage 4 differs itself by:

- using a differential pressure transducer with 20 Hz sampling rate instead of 200Hz;
- integrating the power supplies, BNC box, differential pressure transducer, A/D converter, data storage and analysis onto a PCB board in a single control box.

Table 1 shows how the laboratory based equipment was refined to a self-contained control box. Table 4 shows the results of 18 identical consecutive tests conducted in a test house using a 40 litre stage 4 nozzle unit performed over a single day. The outside condition at the time of testing was categorised as light wind (0.45-1.34 m/s). The pressure-leakage relationship is represented in the table by a standardised leakage rate at 4 Pa, or V_4 (m^3/s). The value is derived from a curve fit to data taken directly at the low pressures. The repeatability is good, with most of the tests falling comfortably within ± 5% of the mean V_4. More details are reported by Cooper and Zheng in (Cooper 2016).

Table 4 V_4 of 18 repeated test runs in a test house

Test ID	1	2	3	4	5	6	7	8	9	Mean
V_4 (m^3/s)	0.1166	0.1189	0.1219	0.1199	0.1182	0.1182	0.1241	0.1241	0.1148	0.1201
RPD (%)	-2.94	-1.01	1.47	-0.16	-1.55	-1.60	3.37	3.34	-4.39	
Test ID	10	11	12	13	14	15	16	17	18	
V_4 (m^3/s)	0.1232	0.1207	0.1231	0.1194	0.1160	0.1157	0.1252	0.1194	0.1227	
RPD (%)	2.59	0.48	2.47	-0.62	-3.44	-3.68	4.21	-0.62	2.18	

NOTE: Mean and *RPD* stand for 'mean average' and 'relative percentage difference from mean' respectively.

In comparison to stage 2 and 3 pulse units, the repeatability of stage 4 pulse unit has decreased, which are a consequence of the two major changes i.e. the use of a differential pressure transducer with lower sampling rate (due to the consideration of cost) and the use of low grade power supply due to the need for system integration. The new power supply on the PCB board produces more electrical noise in the readings than the previous one. However, the repeatability is still at an acceptable level lying within ±5%.

3. 4. Nozzle unit (stage 5)

During the experimental investigation using a stage 4 pulse unit, a number of practical concerns were noted. They include:

- The overall weight is around 40 kg relying on two people lifting between different levels.
- Condensation formed and accumulated at the port where the tank pressure transducer is installed.
- Some pressure tube is exposed and prone to be affected by external forces such as reflected airflow or manual operation.
- The unit does not have a casing that could protect it during transportation and onsite operation.

Accounting for the issues described above, some re-configurations were made in the stage 5 pulse unit to

- Split the pulse unit into two main parts, with the air tank being separated from the compressor module, both of which are within a single person handling limit, 25kg.
- Relocate the pressure transducer to the top of the tank.
- Replace the composite tank used in the stage 4 pulse unit with a 60 litre aluminium tank.

In the following test a 60 litre stage 5 nozzle unit alongside a 80 litre stage 4 nozzle unit was tested in a three bedroom detached house. The results are listed in Table 5 showing the 60 litre stage 5 pulse unit has maintained a similar level of repeatability with the stage 4 pulse unit. The mean value of air permeability at 4 Pa measured by both units is in close agreement, with a 3.1% percentage difference.

Table 5 5 repeated test runs in the test buildings using two different pulse units

Pulse unit	Test ID	1	2	3	4	5	Mean
Stage 4	V_4 (m^3/s)	0.1076	0.1048	0.1109	0.1077	0.1067	1.3351
	RPD (%)	0.07%	-2.57%	3.12%	0.17%	-0.79%	
Stage 5	V_4 (m^3/s)	0.1049	0.1126	0.1106	0.1153	0.1110	1.3763
	RPD (%)	-5.38%	1.56%	-0.25%	3.97%	0.10%	
NOTE: Mean and *RPD* stand for mean average and relative percentage difference from mean respectively.						*RPD (%)*	3.1%

4. COMPARISON WITH THE STEADY STATE METHOD

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 the results obtained compare with that of the steady state test at 50 Pa, blower door test herein. 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 in natural conditions, as reported by Cooper and Zheng in a field trial study (Cooper, 2016: 10-13). Hence, it is considered to be not possible to achieve a clear-cut comparison at 50 Pa between the two methods especially under natural conditions where the wind and buoyancy effects are difficult to eliminate. However, direct comparison at 4 Pa is possible to achieve under controlled environment where the wind and buoyancy effects are reduced and blower door is able to obtain accurate readings at low pressures. Initial findings showed that both methods provide measurements of Q_4 that are in close agreement under controlled conditions. This is further reported in a paper submitted to the 38th AIVC conference, September 2017. Hence, this section focuses on the experimental study in real houses.

4.1. Tests in a range of UK homes

In countries where the well-established airtightness standard sets the building air leakage at 50 Pa as a norm test, it might be difficult for the pulse technique to find its use in compliance test under current standard due to the reasons discussed above. However, it could be regarded as a useful tool for carrying out pre-compliance test, which makes indications to the contractor, or building quality control team if the dwellings are built to the level that is sufficiently airtight to pass the compliance test. Utilising pulse in this way therefore requires an interpretation of Q_4 measured by the pulse test to a value of Q_{50}, which is more familiar to many in the construction industry.

The ratio of Q_{50} measured by the blower door method to Q_4 measured by the pulse technique, Q_{50}/Q_4, has been looked into in a series of experimental studies carried out in 16 buildings, mostly residential. The blower door unit used in this study is a model 4 Minneapolis blower door (BD-M4) and the pulse unit is a combination of stage 3 PULSE-50 and stage 4 PULSE-80, both give tests in close agreement as reported by Cooper and Zheng (Cooper, 2016: page 9). The test buildings consist of 2 newly built homes and 14 existing buildings. Both testing methods were used to test each building under the same conditions on the same day.

Due to the uncertainty in extrapolation between low pressure and high pressure, both methods are not expected to agree perfectly. However, the results showed both followed the same trend (Cooper, 2016: page 11). In Figure 5, the Q_{50}/Q_4 ratio of most test houses lies in 4-6. Although the sample size of the test buildings in this study is very small, the average value of Q_{50}/Q_4 (5.26), represented by the red line in the figure, interestingly is in close agreement with the ratio (5.30). It is calculated using the average pressure exponent (0.66) in the power law equation obtained by steady state tests to a large sample size of dwellings in a number of countries reported by Orme (Orme, 1998: page 51). This might be because the type of the test building is similar to the ones reported by Orme. Nevertheless, the sample size of the test building needs to be increased in order to gain better understanding. In the figure, the annotation stands for house type, volume (m^3), age (years) and wall type. The abbreviations used in the annotation are explained in Table 6.

Table 6 Abbreviation table

House or building type	Wall type
D: detached	CW: cavity wall
SD: semi-detached	SW: solid wall
MT: middle terrace	SIP: structural insulated panels
ET: end terrace	
'ET, 157, >100, SW' means it is an over 100 years old end terrace house with solid wall structure and internal volume of 157 m^3.	

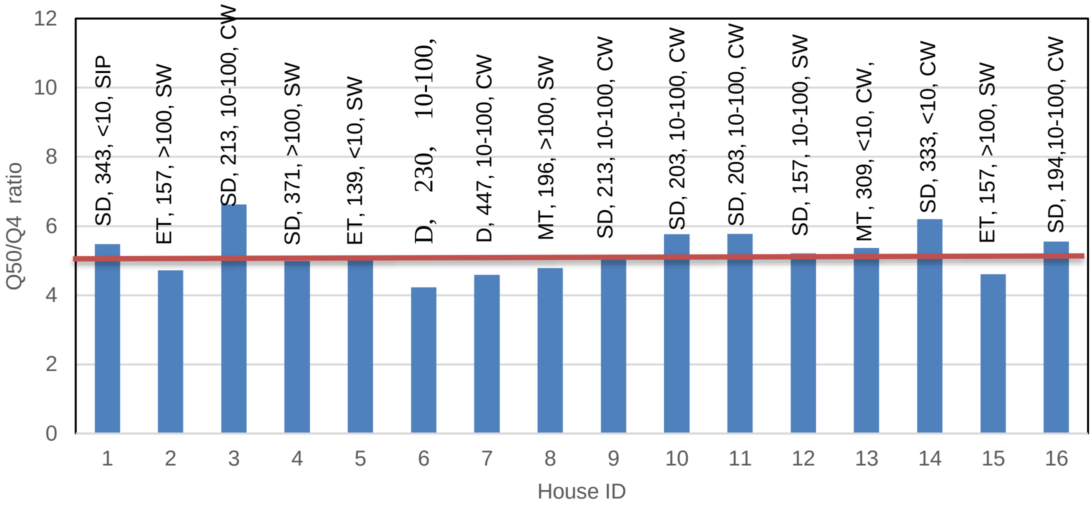


Figure 5 Q_{50}/Q_4 ratio of 16 test houses

If 5.3 is used as the average Q_{50}/Q_4 ratio to interpret the pulse test result in pre-compliance test in countries where air leakage at 50 Pa is used in the standard, the prediction of Q_{50} to the 16 test buildings showed a deviation between 1% and 25% as shown in Figure 6. Hence, this empirical ratio based calculation offers 56% chance of prediction of Q_{50} with ±10% accuracy in this case study.

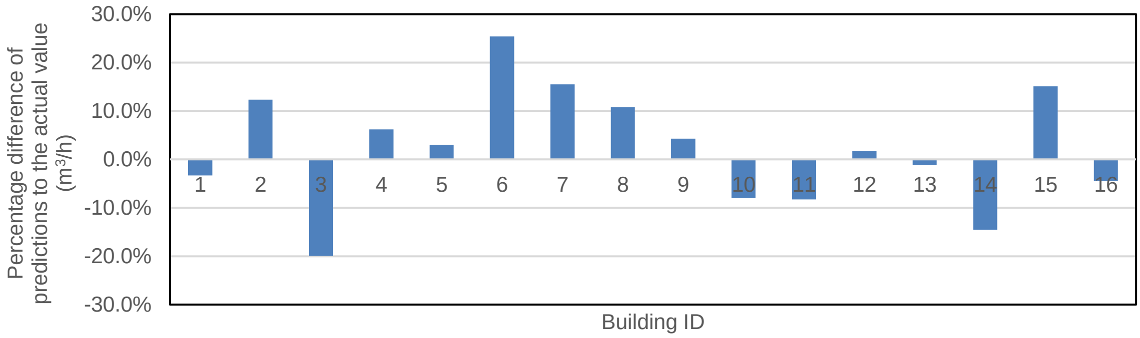


Figure 6 Percentage difference of predictions of Q_{50} to that measured by BD-M4

4.2. Testing with a known opening increase

A simple check to see which technique is more accurate at measuring an added known opening under natural conditions is also presented. A short sharp-edged circular orifice with a diameter of 100mm was added into a window of a test house, as shown in Figure 7. Assuming an appropriate discharge coefficient of 0.61 therefore gives an effective leakage area (ELA) of 4.7909×10^{-3} m^2. Tests were conducted for both techniques, BD-M4 and stage 4 PULSE-80 with and without the added opening. The increase in leakage rate measured by both techniques was then converted to an effective leakage area using eq.(2) and compared to the known opening, as shown in Table 7.

$$ELA = V\sqrt{\rho / 2P} / 0.61 \qquad (2)$$

Where, V is the air leakage rate (m^3/s), ρ is the air density (kg/m^3), and P is the building pressure (Pa). It can be seen that the measurement made by the pulse unit is relatively closer to the known effective area than the blower door measurement in most tests. However, these tests were conducted in natural conditions where environmental factors were uncontrolled; hence, there is a level of uncertainty. Therefore, the tests in this section are only for obtaining preliminary insight in comparison of testing accuracy and no solid conclusion should be drawn from them.

Figure 7: Setup of the known opening in house No. 8

Table 7 Results of other known opening tests using the blower door and APU

Test ID		Test 1	Test 2	Test 3	Test 4	Test 5
BD-M4	V_4	-2.9%	16.5%	146.7%	-71.3%	27.1%
PULSE-80	V_4	4.77%	-3.47%	32.1%	9.7%	5.1%
V4 stands for air leakage rate at 4 Pa. For BD, V4 is extrapolated from blower door test. For PULSE-80, it is measured directly						

5. REPEATABILITY OF TESTS UNDER DIFFERENT ENVIRONMENTAL CONDITIONS

This section investigates the impact of environmental conditions, including indoor/outdoor air temperature, wind speed and direction, to the building airtightness. A recent study (Remi 2016) shows an uncertainty of 6%-12% can be caused by wind speeds of 6-10 m/s combined with other sources of error in a steady state test at 50 Pa. Given the low operating pressure of the pulse unit, the wind condition can be considered the foremost environmental factor for consideration due to its direct impact on the building pressure.

The investigation was performed by conducting a number of tests on the house No.1 in Figure 5 over a period from September 2014 to September 2015. This period covered the summer, autumn and winter seasons, which provided test scenarios of various wind conditions and outdoor temperatures ranging from 7 °C to 21.5 °C. Due to the development of the prototype, three versions of prototypes with tanks of two different sizes have been used for these monitoring tests; the full details are listed in Table 7.

It can be seen from Table 7 that the greatest influence upon the variation in Q_4 values appears to be due to wind speed and direction. Across all tests, the Q_4 values are within ±8% of the mean of all test runs. It must be noted that this variation, among other factors, might also include the difference that exists in different versions of prototypes.

Table 7: Results of repeated tests under different environmental conditions using stage 3 PULSE-50 and stage 4 PULSE-80

Date	**Prototype**	**T_o/ T_{in} (°C)**	**Wind speed (m/s)**	**Wind direction**	**Q_4($m^3/h{\cdot}m^2$)**	***Sub-RPD (%)***	***RPD (%)***
09-Sep-14	PULSE-50	16/20	1.57	SSE	1.014	*0.52*	*2.70*
16-Sep-14	PULSE-50	17/20	0.9	NE	1.065	*5.58*	*7.87*
26-Nov-14	PULSE-50	7/21.8	0.23	ENE	1.002	*-0.67*	*1.49*

12-Jan-15	PULSE-50	12/18	5.5	W	0.953	*-5.44*	*-3.39*
Mean Q_4 by PULSE-50					1.008		
17-Aug-15	PULSE-80	21.5/23.5	0.45	N	0.985	*1.23*	*-0.24*
24-Aug-15	PULSE-80	17/28.1	1.1	NNE	0.926	*-4.79*	*-6.17*
08-Sep-15	PULSE-80	17.8/18.1	0.23	ENE	0.997	*2.46*	*0.98*
10-Sep-15	PULSE-80	18/20.4	0.23	E	0.973	*0.04*	*-1.40*
18-Sep-15	PULSE-80	19/23	0.6	NNE	0.963	*-0.99*	*-2.42*
21-Sep-15	PULSE-80	14/18.2	3.2	SSE	0.993	*2.05*	*0.57*
Mean Q_4 by PULSE-80					0.973		
Mean Q_4 by PULSE-50 and PULSE-80					0.987		

T_o and T_{in} are outdoor and indoor air temperature. Q_4 is the air permeability at 4 Pa, $m^3/h{\cdot}m^2$.
MK0, MK1 and MK2 represent different stages of prototype development.
Sub-RPD represents the *RPD* of Q_4 of each test in a sub-group of tests (i.e. tests done by PULSE-50 or PULSE-80) against the mean value of the sub-group. *RPD* represents the relative percentage difference of Q_4 of each test against the mean Q_4 of all tests given by PULSE-50 and PULSE-80combined.

6. TESTING WITH MULTIPLE UNITS IN A LARGE BUILDING

The original impetus of developing the pulse technique was to overcome the issues of testing the airtightness of large buildings using the steady state method, such as:

- Large amount of airflow is required to pressurise the building.
- Difficult to achieve even pressure distribution in the building.

The pulse technique was considered to show a significant advantage by testing at much lower pressure and therefore negates the need for large airflow delivery. The setup of multiple pulse units is also flexible and uniform pressure distribution can be obtained by setting up the units evenly in the building. Testing using multiple stage 2 units (piston) and multiple stage 3 units (nozzle) have been carried out in a number of large buildings in order to verify the technical feasibility.

The first one is a two-storey Environment and Education Centre (EEC) studio on Nottingham University Park campus, tested by four piston and four nozzle units. During the tests, four differential pressure transducers were connected to the external and internal tappings with different locations. The studio, divided into 8 zones with wood boards, has a volume of 2130 m^3. Figure 8 gives the layout of the studio and the locations of the units.

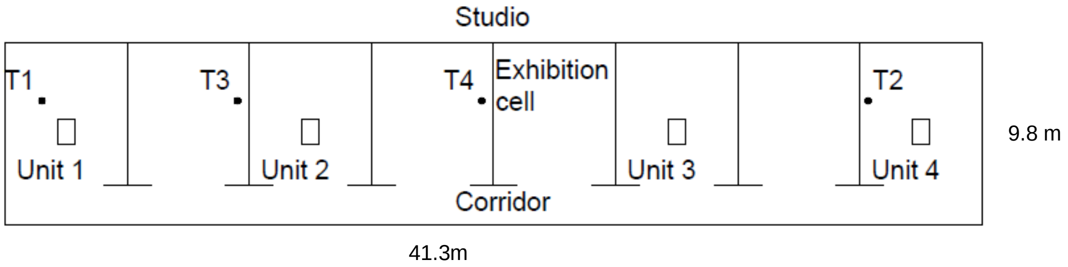
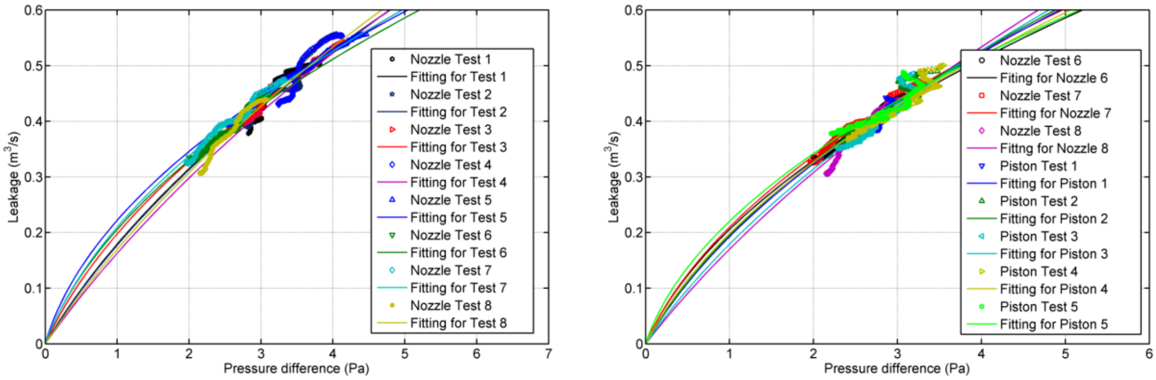


Figure 8 Basic structure of EEC Studio and locations of pistons/nozzles and internal pressure tappings (T1-T4).

Eight nozzle tests and five piston tests were carried out. Among them, nozzle tests 1~5 and piston tests 1~5 were operated with the maximum air tank pressure (around 10 bar); while, nozzle tests 6~8 were performed with un-fully charged air tank to give the range of pressure pulse similar to that generated by pistons for comparison. The low-pressure leakages obtained by eight nozzle tests is shown in Figure 9. The repeatability of the experimental results is shown to be good, despite the strong wind at the time of testing.



a. Nozzle b. Piston

Figure 9 Leakage characteristic measured by piston and nozzle based pulse units

The second building is a laboratory on the ground floor of Sustainable Research Building (SRB) on the University Park campus, at the University of Nottingham. It has a regular cubic shape with a volume of 631.7 m^3. Three-piston and three-nozzle tests were carried out and the leakage characteristics is shown in Figure 10. A good agreement has been achieved between tests using multiple units of both types.

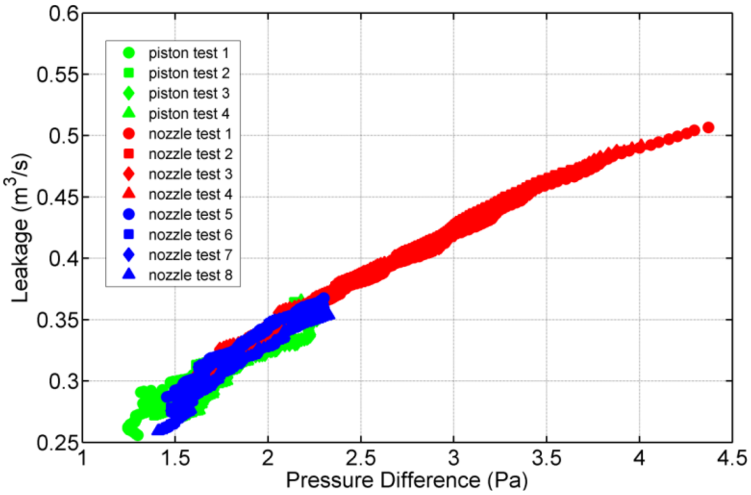


Figure 10 Comparison of results obtained by three nozzle units and three piston units

Multi-piston tests on the third building- a church with a volume of 8000 m^3 have been carried out together with research partners in Sweden. To determine the lower pressure leakage characteristic of the church, tests were carried out with 7 piston units for generating pressure pulse and 2 differential pressure transducers for measuring the pressure difference across the building envelope. A number of tests have been carried out with vents sealed and unsealed. A few of them were invalid due to the strong wind condition during testing. However, for the valid tests, a good repeatability has been obtained in two testing scenarios as shown in Figure 11 and Figure 12.

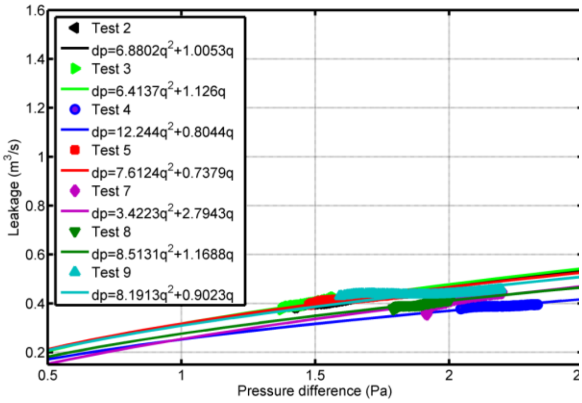


Figure 11 Leakage characteristic and power law fitting when vents were unsealed

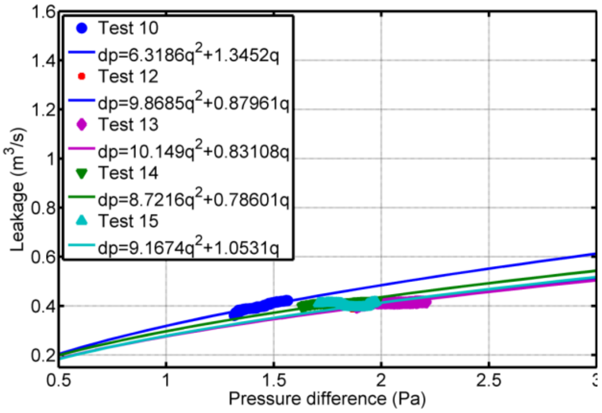


Figure 12 Leakage characteristic and power law fitting when vents were sealed

7. CONCLUSIONS

This paper provides a succinct overview of experimental validations testing throughout some of the key developmental stages of the pulse technique over the last 15 years. The pulse unit has gone through a development evolution from being a heavy and bulky unit to compact and easy to use version. Tests have shown that a good level of repeatability has been maintained. Although being unable to provide direct comparison with blower door test under naturel condition due to uncertainty in extrapolation, it was shown both methods have followed the same trend from dwelling to dwelling in side-by-side testing. Known opening tests under natural condition were carried out but no solid conclusion was drawn due to uncertain environment factors in natural condition. Testing using early multiple pulse units in large buildings have also been carried out and insight has been gained to the feasibility of testing large buildings. It was found that the pulse technique is able to test large buildings and provide results of good repeatability. However, it was also observed that the resilience of the pulse technique to wind effects was reduced in the large less airtight buildings.

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