Numerical and experimental validations of the theoretical basis for a nozzle based Pulse technique for determining building airtightness

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Abstract

Motivated by intentions of avoiding large net fluid flow and enabling a more practical airtightness test for large buildings, a low-pressure Pulse pressurisation technique was developed for measuring building airtightness at pressures that are considered more representative of that experienced by buildings under natural conditions. Due to the short and dynamic operation, this technique is able to minimize wind and buoyancy effects during the measurement of building pressure. The investigation, based on the "quasi-steady" temporal inertia model, explores a technique that generates a pressure pulse inside a building by releasing a known amount of air pulse over 1.5 second using a compressed air tank. The volumetric flow rate of the air pulse released from the tank is obtained by measuring the transient pressure in the air tank during a test run. The air leakage through the building envelope is then obtained by accounting for the compressibility of indoor air. Simultaneously, the pressure variation within the envelope of test building is monitored. Therefore, the leakage-pressure relationship of the building envelope can be obtained. The validity of the theoretical model and the assumptions on which the model is based are validated using experimental and numerical investigations.

Keywords

Building airtightness; The Pulse technique; Unsteady approach; Steady pressurisation method; Experimental and numerical validations;

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^{-1}·Pa^{-n})

d	Diameter of opening (m)
L	Depth of opening (m)
p_i	Building indoor pressure, Pa;
$P(t)$	Transient pressure of air in the air 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 ($m^3/h/m^2$)
Q_{50}	Air permeability at 50 Pa ($m^3/h/m^2$)
ΔQ	Measurement uncertainty of air leakage rate (m^3/h);
$Q_p\{t\}$	Transient volumetric flow rate of tank air, (m^3/s)
$q\{t\}$	Transient building air leakage rate, (m^3/s)
R	Gas constant, equal to $287.058\, J/kg \cdot K$;
T_0	Initial air temperature in the air tank
V	Building volume (m^3)
V'	Volume of air tank (m^3)

Greek letter

μ_i	Viscosity (Pa·s)
ρ_i	Indoor air density, (kg/m^3)
γ	Specific heat of air, 1.4
δQ	Overall error in obtaining the leakage rate, (%)
δQ_B	Bias error, (%)
δQ_P	Error caused by building pressure sensor accuracy, (%)
δQ_M	Model error, (%)

1. Introduction

1. 1. Background

Defined as the unintentional movement of air through building envelope driven by the pressure difference induced under natural conditions, building infiltration is uncontrolled and impacts upon building energy use and ventilation. Therefore, good understanding of building infiltration is of high importance and typically requires the measurement of building airtightness as a practical and quick alternative to a direct measurement of building infiltration [1], which is disruptive, complex and time consuming.

Airtightness is a physical property of a building fabric indicating the envelope integrity and fundamentally determines the level of infiltration. A good level of airtightness in buildings is desirable in most regions where either indoor heating or cooling is required because studies have shown building energy consumption caused by unintended building air leakage can account for 13%-50% and 4%-20% of the overall heating and cooling demand, respectively [2, 3, 4, 5, 6, 7]. This represents a significant proportion of global energy usage considering buildings are responsible for up to 40% of that and this figure goes up to 50% in developed countries [8, 9, 10]. However, designers need to be aware that the indoor air quality can be compromised if the building envelope is overly airtight, because indoor contaminants will not be diluted effectively via the infiltration. A purpose-designed ventilation strategy will therefore be required to provide sufficient fresh air for the indoor environment. Another important factor, implicated by airtightness, is the long-term impact made by moisture transportation through the building fabric. The air exchange between indoor and outdoor environments is enhanced by poor building airtightness which then leads to the formation of condensation within the building fabric, consequently deteriorates the fabric and encourages the growth of air pollutants.

It has been recognised for decades that airtightness is an important indicator of building integrity and construction quality, which is essential for buildings with good energy efficiency and indoor environment [11, 12]. Over the last few decades, global targets on the achievement of improved indoor environment at low energy cost in the building sector have witnessed the formalisation of minimum requirements on building airtightness in many countries either in building regulations or voluntary standards.

1. 2. Conventional Airtightness Measurement

In the conventional steady pressurisation test, known as the ‘blower door’, the airtightness measurement is typically done by installing a fan into an existing doorway within the envelope and taking several steady state measurements at multiple elevated pressures (typically 10 to 60Pa). Two typical setups (door fan and duct fan) are illustrated by the schematic diagrams in Figure 1. One of the main challenges in such a test is to measure building pressure accurately under natural conditions due to the uncertain and dynamic nature of environmental conditions (particular wind) experienced by buildings. These environmentally induced pressure differentials normally lie in the vicinity of 1-4 Pa [13, 14, 15, 16, 17], which presents a challenge to the accurate measurement of low building pressure as these natural effects can present significant noise. In order to obtain a reliable leakage-pressure correlation, this ‘noise’ needs to become a negligible component in the calculation. The random nature of these natural effects mean that such goal is difficult to achieve, so instead steady state measurements are taken at elevated pressure differentials thereby reducing the impact of the low-pressure noise.

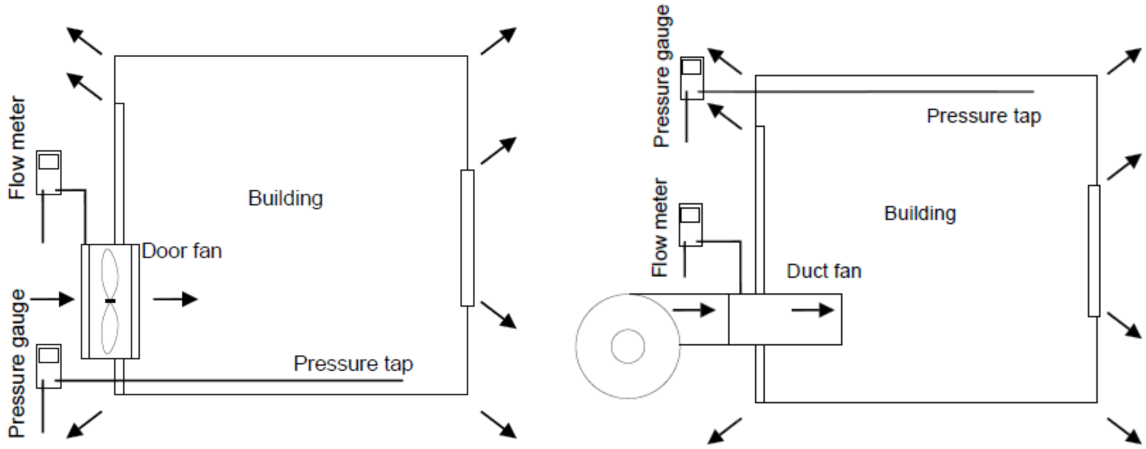


Figure 1 The conventional way of measuring building airtightness -steady pressurisation method (door fan and duct fan: in pressurisation)

While the ‘blower door’ method has been broadly accepted as the standard means of measuring building leakage, there have been longstanding uncertainties about its accuracy [18, 19, 20, 21, 22, 23]. Sherman [24] investigated the uncertainties in typical field situations derived from precision error, bias error and modelling error. Suggestions were made therein to reduce these uncertainties by taking various measures.

The authors believe that large uncertainties are sometimes inevitable [25] in the conventional steady approach especially when it is used to determine low-pressure leakage, where “direct measurement of air permeability at infiltration pressures could reduce the uncertainty by a factor of three or more” [26].

Further shortcomings have been discussed in scientific and practical studies [27, 28, 29], and mainly fall under three aspects: testing practicality, legislation and testing accuracy. The latter can be expanded on as follows:

- Coarse interpretation of background pressure during testing [30].
- Unreliable external pressure reference (especially under windy condition) [31].
- Uncertainty in extrapolating results down to low pressure.
- Not testing the whole envelope.
- Likelihood of opening of additional leakage pathways.
- Unrealistic high measuring pressure considering hydraulically dissimilar flow at high and low pressure [13, 14, 32] .

Some of these factors contribute to the conventional test method having a margin of error. This impact on the performance gap has been discussed extensively by the Zero Carbon Hub [29] and Sherman [33, 34, 35]. Enabling building construction professionals to obtain airtightness test results more conveniently and efficiently could assist in the pursuit of higher quality construction. It is also desirable to test the airtightness of a building at lower pressure differentials, such that the flow through the envelope will mimic that of a building under ambient pressures. Such factors have provided the research motivation to seek for alternative methods to overcome some of the issues shown in the steady pressurisation method [36]. Among which, the Pulse technique was originally developed to overcome the large net fluid flow and uneven pressure distribution associated with testing large buildings [37, 38, 39] by proposing a unsteady method that can be implemented flexibly to determine building airtightness at low pressures. However, the study presented herein is based on tests performed with a single Pulse unit, which is designed to test residential units and small commercial buildings. For large buildings, the underlying principle is the same but multiple units are required to release air pulse simultaneously to provide sufficient flow during testing.

1. 3. The Innovative Pulse pressurisation technique

The Pulse technique achieves the measurement by releasing a short air pulse (typically 1.5 seconds) into the building from a compressed air system. A subsequent pressure increase in the building is instantly created, which is then followed by a steady pressure drop to deliver a 'quasi-steady' flow through the building envelope. During that process, pressure and temperature variations in the building and tank are measured with a sampling rate of 50 Hz to quantify in real time the delivered airflow rate from the tank and stored air in the building due to compressibility to establish the building's leakage-pressure correlation. The background pressure induced by environmental conditions is accounted for in the data treatment and the method used for the adjustment is implemented by removing background pressure trend from direct pressure measurement. More technical details on how that is implemented are described by Cooper et al [32]. Figure 2 shows a typical Pulse measurement, where readings of both tank and building pressures are illustrated comprising pressure variations during the quasi-steady period and background pressure trends before the valve opens and after the valve closes. For the tank pressure readings, only the readings during the quasi-steady period are processed to determine the mass flow rate of released air in real time, whereas for the building pressure, the readings during quasi-steady period are used to account for the compressibility of air and the background pressure readings are used for pressure adjustment to account for the wind and buoyancy effects, i.e. the aforementioned background pressure.

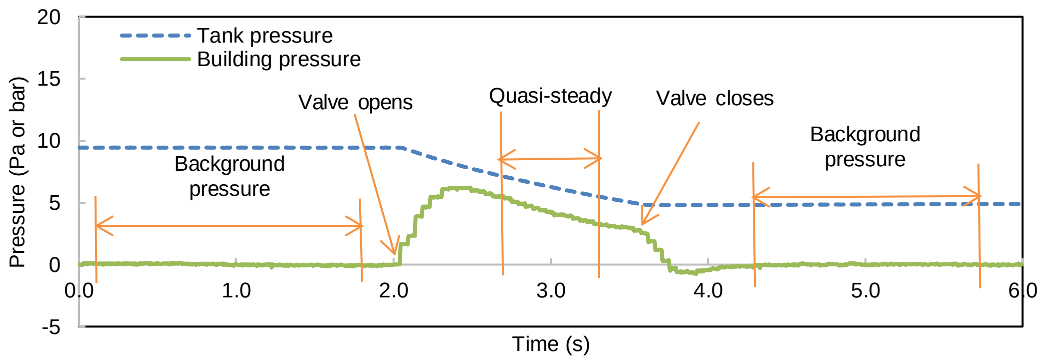


Figure 2 Pressure measurements of a typical Pulse test (tank pressure measured in bar, building pressure in Pa) [25]

To demonstrate the system structure of a typical Pulse unit and how the system works, a schematic diagram is created and shown in Figure 3. It is a standard single-tank unit comprising an air compressor (oil-free), an air tank for the storage of compressed air and a control panel used to control the actions of automated valves and acquire readings from pressure and temperature sensors. This unit is configured to measure the airtightness of small buildings, i.e. residential unit and small commercial building. Multiple tanks can be linked together to increase the test capacity to measure large buildings. The maximum working pressure of the main air tank is set to 10 bar for considerations of system cost, portability and desired unit capacity. During the Pulse test, ambient air is charged into the air tank by the compressor through a quick release air hose to a desired pressure level, usually depending on the size and leakage of the test building. Then the compressed air is discharged into the building over a short period of time (typically 1.5 seconds) through an electronically controlled solenoid valve (V1). The pressures and temperatures of the air in the tank and building are respectively measured by pressure transducers and temperature sensors, mounted within the air tank and control box. The building integrity is maintained by adopting an internal pressure reference tank in the measurement of building pressure. This reference tank is an airtight vessel, which provides a useable pressure reference prior to the measurement by closing the valve (V2) during the measurement and opening when the test is completed to allow the pressure inside to equalise with the ambient environment. Therefore, the Pulse measurement is independent of external pressure condition as it provides a useable pressure reference based on the indoor pressure so the building pressure response to the added air pulse can be measured. Such feature allows the Pulse technique to differ itself from the conventional method, which has to rely on the presence of stable and representative outdoor pressure to achieve an accurate measurement of pressure changes when the building is subjected to addition or removal of air at a certain rate.

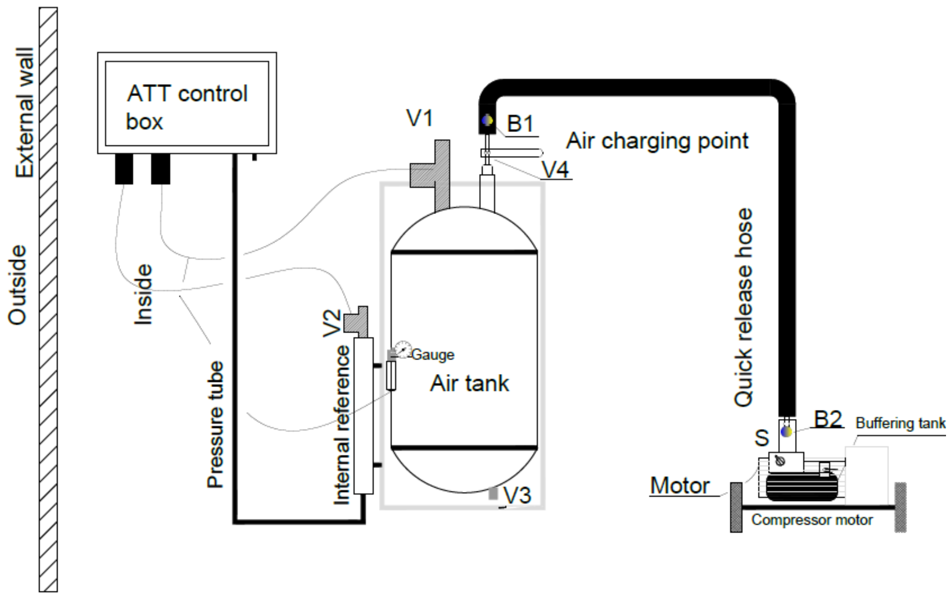


Figure 3 System diagram of single-tank Pulse unit [42]

1. 4. Aims and objectives

The Pulse technique entails a dynamic approach for measuring building airtightness at low pressures. Due to the transient nature of this testing procedure, the principle and accuracy of the Pulse test is frequently questioned by peer scientists and practitioners in the field.

This paper aims to present a comprehensive introduction on the theoretical background of the technique where the working principle and theoretical model are detailed. The validity of the theoretical model and assumptions on which the model is based is experimentally and numerically validated.

2. Theoretical perspectives

2. 1. Theory and historical development

The initial working concept of the Pulse technique is shown in Figure 4, which illustrates a volume (V) of a single zone with an opening in the envelope. A piston device which is capable of making a volume change of ΔV is installed in the envelope to provide an induced pressure change by introducing a piston movement. The piston moves in the cylinder over time (t) and introduces a piston airflow to the indoor space at a volumetric airflow rate of Q_p, which consequently increases the indoor pressure and simultaneously generates a rate of airflow through the opening (q). Such procedure has evolved to be simpler and more practical at a later stage and can be implemented through releasing a pulse of air via a nozzle directly from a compressed air tank; more details are introduced in the latter part of this section.

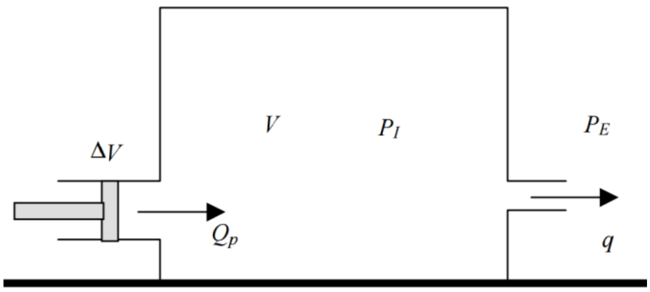


Figure 4 Envelope of a single zone volume with an opening acted on by a piston movement [40]

Following the continuity equation, the airflows through the building envelope during the piston movement can be described by eq.(1):

$$\frac{1}{\rho_i} V \frac{d\rho_i}{dt} = Q_P\{t\} - q\{t\} \tag{1}$$

Where, $Q_P\{t\}$, $q\{t\}$ and ρ_i are the real time volumetric flow rate of air introduced into the envelope by the piston movement, the rate of airflow leaving the envelope through the opening and density of indoor air, respectively. The term on the left of the equation accounts for the compressibility of the air in the space, which is one of the key factors for achieving good accuracy in this approach.

When isentropic expansion is assumed in this process, the relationship between density ρ_i and pressure P_i can be obtained as $P_i/\rho_i^{\gamma} = C$, where C and γ are a constant and specific heat ratio of air respectively, and $\gamma = 1.4$. Therefore, eq.(1) changes its form to

$$\boldsymbol{q\{t\} = Q_P\{t\} - \frac{V}{\gamma P_i}\frac{dP_i}{dt}} \tag{2}$$

Based on the same principle, when the piston movement is replaced by a pulse of compressed air released from an air tank as described in section 1. 3 (Figure 3), the volumetric flow rate of the air pulse released into the volume by the air tank can be determined by eq.(3):

$$\boldsymbol{Q_P\{t\} = -\frac{V'}{\gamma \rho_i R T_0}\left[\frac{P(t)}{P_0}\right]^{\frac{1-\gamma}{\gamma}} \dot{P(t)}} \tag{3}$$

Where, V' is the volume of air tank (m^3); $P(t)$, P_0, T_0 and ρ_i are the transient tank air pressure (Pa), tank air pressure (Pa) and temperature (K) before the release of air pulse and density of indoor air (kg/m^3), respectively; R and γ are the gas constant $(J/kg \cdot K)$ and specific heat ratio of air; $\dot{P(t)}$ is the first time derivative of tank air pressure, (Pa/s).

Similar to the leakage measurement using a blower door method, the Pulse technique takes the measurements of building leakage over a range of pressure. It differs itself from the blower door method by achieving continuous measurement at low pressures in a dynamic manner. However, due to the rapid and unsteady approach of introducing pressure change to the indoor air, this technique faces a challenge during the measurement, i.e. the occurrence of the inertia effect of unsteady airflow through openings, which adds uncertainty to the measurement and compromises the accuracy [41]. Such flow due to the inertia effect is addressed as unsteady flow, which should be minimised in order to obtain accurate measurements. More details on how the unsteady flow is quantified is given in section 1.2 in [42].

The development of the Pulse technique has gone through three stages, a unsteady technique concept of the piston unit driven by gravity [37], a practical prototype of the piston unit driven by compressed air[32, 40] and the latest more compact and portable nozzle unit [25, 27, 28, 42, 48]. The historical development of the Pulse technique and its experimental investigations has been summarised by Zheng et al [43]. Experimental validations have been conducted throughout the described stages [43]; to prove the concept of the technology, validate various changes made through the developments, including hardware simplifications and firmware modifications, and also to investigate the impact of various factors to the measurement such as environmental conditions, unit location and internal barriers. The experimental studies have been performed both in sheltered laboratory conditions [49, 42] and outdoor natural conditions

[25, 44]. Some of them are introduced herein alongside the numerical investigation to prove the validity of the theoretical model on which the Pulse technique is based.

2. 2. Impact of tank size and opening length on inertia flow

The concept of the Pulse technique or a similar approach (AC pressurisation method) has been tried in 1980s [45, 46]. Inertia effect of airflow through the opening has been the major concern for the unsteady method, as it adds uncertainty to the test results [41]. The inertia term is the third one on the right side of eq.(1) given in [42], representing the weight of unsteady flow. When the area of the opening is fixed, it is ruled by the time dependant gradient of building leakage rate $\frac{dq}{dt}$ and the length of opening l_e. The former is determined by the configuration of the unit used for testing and selection of testing period while the latter depends on the physical form of test building.

In order to evaluate how the unit configuration and capacity affects the percentage of unsteady flow, tests were carried out using units with various tank sizes, including 40 l, 50 l, 60 l and 80 l, all of which used ¾” valve. An additional configuration where the 40 l tank with a smaller valve (½”) was used for comparison with the ¾” valve to investigate the impact of valve size on the unsteady flow.

Figure 5 shows the pressure pulses produced in a three-bedroom detached house with an internal volume of 343 m^3 by the five different tank and valve combinations. For the 40 l, 60 l and 80 l with the same type of tank, the pulse magnitude extends higher when the tank size increases. But the increase in the magnitude is not significant. It is due to the same starting pressure and outlet size. However, the pressure gradient varies with the tank size, i.e. the greater the tank size, the smaller the pressure gradient is. Noticeably, the magnitude produced by the 50 l tank is larger than 60 l and 80 l tank. The tank size and magnitude rule could have been invalidated by the tank of different kind, which perhaps leads to different discharge coefficient.

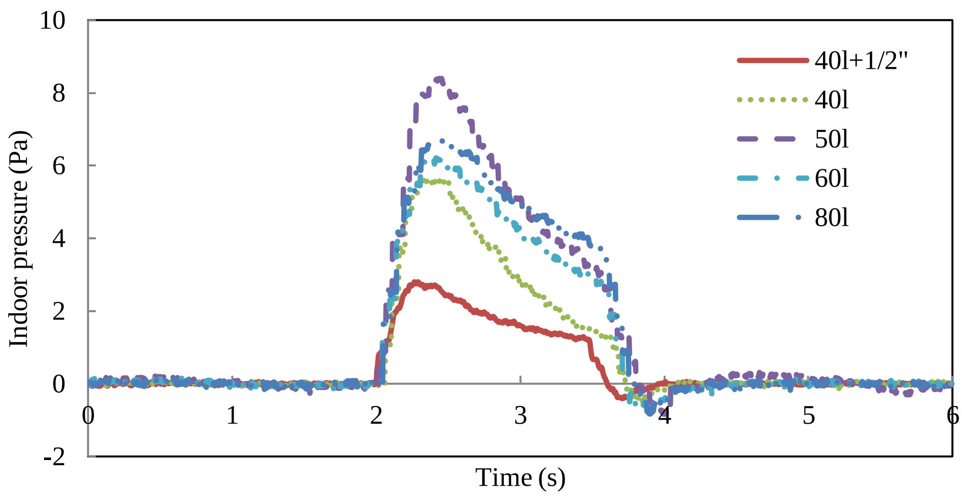


Figure 5 Pulses produced by different tank and valve combinations

Results show a negligible amount of unsteady flow was experienced by all the combinations, which suggests reasonable accuracy in the measurement of building leakage is achievable for them all, more details are described by Cooper et al in [25]. By using different tank and valve combinations, the tank pressure drop rate can be affected, which in turn affects the 'quality' of the quasi-steady period of a pulse test because it determines how quickly the building pressure drops. This explains why the pressure decay section (from the point where the valve closes) can't be used for data analysis as it is affected by the inertia effect thereby giving a poor accuracy. Such inertia effect is reflected by the pressure dip in Figure 5. Similar issue is also present when a building is too leaky or too large as in this case there is insufficient flow released from the unit to maintain a steadily decreasing flow, which is a matter of unit capacity and linking with more units can solve this problem. Nevertheless, for standard use the tank and valve combination needs to be configured correctly due to the considerations of its practicality and accuracy.

The type of opening (building leakage pathway) determines the flow regime. The effective length of opening is discussed in terms of its impact on the inertia effect of airflow through the openings in the building envelope. Taking a pulse test with the 60-litre tank as an example, Figure 6 shows the percentage of unsteady flow given by an opening with various effective lengths. The unsteady flow increases up to 10% from less than 1% when the effective length of opening increases up to 0.5m from 0.05m. Hence, the use of the pulse technique could be limited by the 'effective length' of openings in the test building, which is a result of combining a group of openings in the test building, in various length, size and shape. In a way, this relationship can also be interpreted by the electrical analogy, i.e. it is similar to the effective overall electrical resistance when multiple electrical components with different resistances are connected in parallel. Hence, it is worth noting that the effective length of opening discussed herein is different from the dimension of a single opening, for instance, a chimney, but rather an effective hydraulic length of all openings combined [47]. Therefore, the effective overall flow resistance of a network of building leakage pathways is dominated by the ones with small flow resistance, such as short and wide openings.

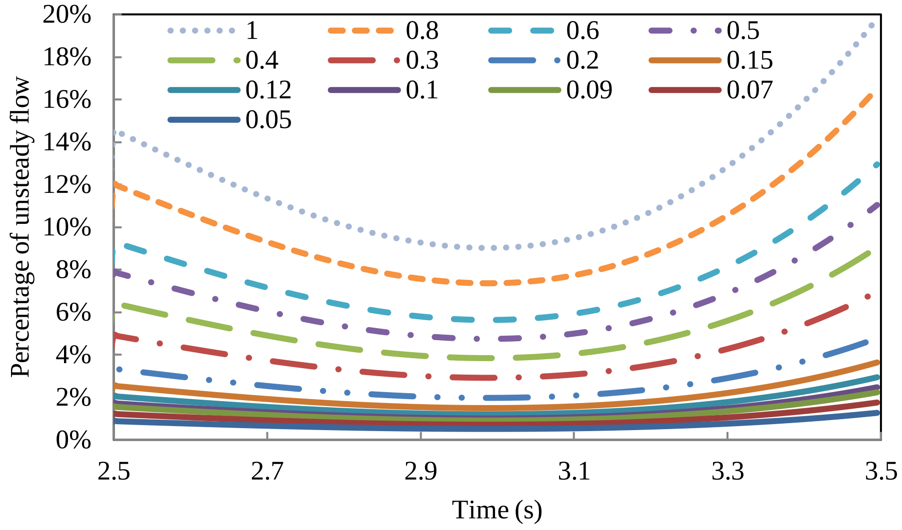


Figure 6 Length of opening (m) vs. percentage of unsteady flow

3. Numerical validation of theoretical model assumptions

The theoretical model described in the previous section determines the building air leakage rate by calculating the transient flow rate of the air pulse released from the compressed air tank and the amount of indoor air that has been stored within the building due to the compressibility of air during the pulse period. Apart from temperature measurements, these calculations largely rely on the measurements of real-time pressures in the air tank and building during testing and therefore the reliability of the calculations is determined by how accurately the pressure measurements represent the actual pressures in the air tank and building. To practically achieve a sufficient accuracy in pressure measurements in both domains using an engineering application, the pressure distributions within them need to be uniform. Therefore, prior to the experimental validation of the accuracy of the Pulse technique for determining the building air leakage rate, these two assumptions on which the theoretical model is based need to be validated first.

3. 1. Model and configurations

The assumptions were numerically validated using CFD simulation. ANSYS Fluent was used for the numerical simulation. Energy and momentum equations were discretized using the second-order upwind scheme with transport equations discretized using power law scheme. The SIMPLEC algorithm was used to solve the discretized equations.

For the purpose of validation, the numerical simulation was based on an experimental study where a detached three bedroom house was tested by a Pulse unit with a 80-litre air tank. To save on computation time, the problem was simplified to a two-dimensional axisymmetric domain as shown in Figure 1 in supplemental material 1. The compressed air tank had an orifice with a diameter of 19.1 mm and a length of 20 mm. The volume of the computational domain is 290 m^3, equal to the volume of the house. The distribution of the leakage pathways in the envelope is not considered herein but represented by a circular opening with an area of 0.0404 m^2, which was obtained in an experimental study. A mix of quad and triangular cells were used to mesh the whole domain with finer mesh applied to the areas inside and adjacent to the air tank for a more detailed computation. Coupled heat transfer condition was specified at the walls of the nozzle and air receiver. The building opening was set as pressure outlet with a constant pressure of 101325 Pa. Initially, the temperature in the whole computational domain was T_0=288.16 K; the absolute pressure in the compressor air receiver and nozzle was 879200 Pa and the pressure in the remaining area was set at 101325 Pa.

The real time building and tank pressures are of interest. Hence, the problem was defined as transient. Considering the air is compressible, the air used in the simulation was treated as ideal-gas and the density-based solver was used to provide the density-pressure relationship. Energy equation was used in conjunction with realizable K-epsilon with scalable wall functions. Building opening was set as pressure outlet and the gauge pressure is set as 0 Pa (i.e. absolute pressure 101325 Pa), which means there was insignificant pressure difference between indoor and outdoor. Patch function was used to apply initial starting pressure to the tank air. The building pressure was not patched as it was the same with the operating pressure, i.e. 101325 Pa. The size of the time step Δt is determined by eq.(4):

$$\Delta t \leq \Delta x / u \tag{4}$$

Where, Δx is the smallest cell in the domain, and u is the corresponding velocity in that cell.

The smallest cell is located at the orifice, which has a radius of 9.55mm with 9 cells, making Δx = 1.06 mm. The velocity at the orifice can be calculated using the flow rate as $u = \frac{Q}{A} = 540 m/s$, where Q is the volumetric flow rate and A is the geometric area of the orifice. Hence, $\Delta t \leq 1.06/540 = 1.96*10^{-6}$ s. In order to numerically calculate 1.5 second pulse flow, the number of time steps is determined as 1.5 s/$1.96*10^{-6}$=764150, but for the ease of post CFD analysis, the number of time steps was set as 750000.

The silencer, which is attached to the nozzle, helps diffuse the compressed air into the test building, consists of meshed steel housing and sintered PE. In the numerical simulation, the configuration of the silencer has been simplified into a porous jump media according to the flow resistance. Its parameters are listed in Table 1.

Table 1 Settings of porous jump media

Parameters	Face permeability (m^2)	Porous medium thickness (m)	Pressure-Jump Coefficient (1/m)
Value	1e+11	0.012	1900000

3. 2. Results and discussions

3.2.1. Uniformity of air pressure in the compressed air tank

The derivation of Eq.(3) is based on the assumption that the pressure in the tank is uniform during the pulse period. Therefore, the uniformity of air pressure over the time of testing needs to be verified.

To provide an example, Figure 2 in supplementary material 1 shows the contour of pressure distribution in and around the bottom half of the tank at 0.0s and 0.5s. It can be noted that the pressure contour in the nozzle is different from that in the tank. That is caused by the airflow occurred during air releasing process but does not affect the pressure distribution in the tank. The pressure contour in the tank indicates the pressure variation across the air tank is minimal. To further check the uniformity of the tank air pressure, the real time variation of area-averaged pressure at top and bottom cross-sections were tracked as illustrated in Figure 2 (a) in supplementary material 1. Figure 7 shows the pressure difference between the two cross-sections is unremarkable. Therefore, the pressure distribution in the tank can be considered highly uniform and only one pressure transducer should suffice for the measurement. However, the location of the sensor needs to avoid the impact of air movement for optimal accuracy. Hence, the mounting position should be distanced from the tank orifice/nozzle.

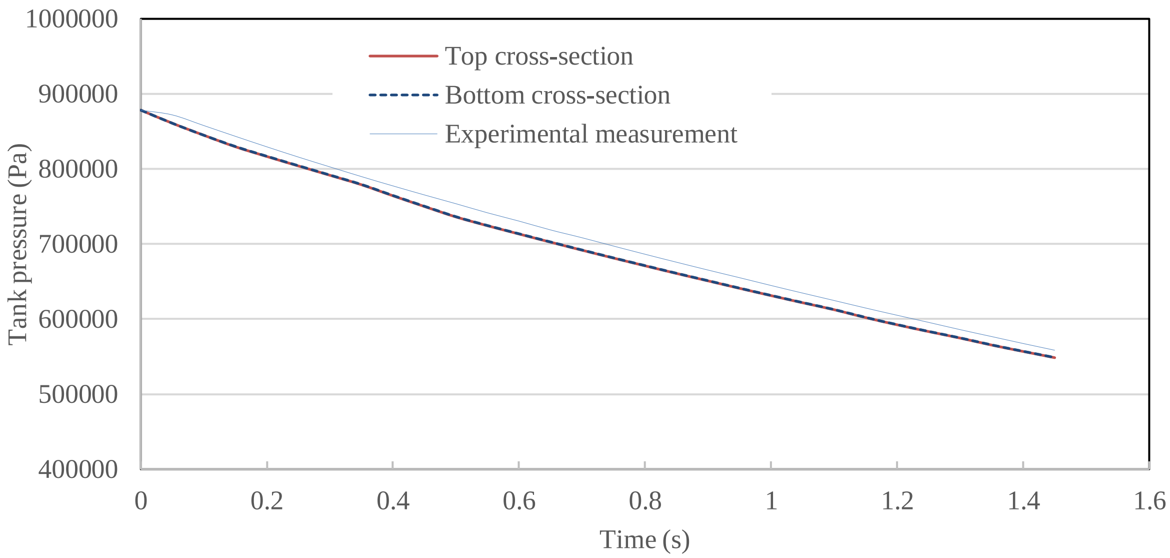


Figure 7 Comparison of tank pressure variations during the pulse period in experimental measurement and numerical simulation with the area-averaged pressures at top and bottom cross-sections

Figure 7 shows the transient tank pressures during the 1.5-second pulse period obtained in the experimental measurement and numerical simulation. The pressures given by the numerical simulation are smaller than those given by the experimental measurements, but within 2.4%. This might be caused by the difference in temperature condition between numerical simulation and experimental setup during the pulse period due to different heat transfer occurred through the tank and nozzle walls. Nevertheless, a good agreement between them was demonstrated.

3.2.2. Uniformity and invariability of air density in the building envelope

To confirm eq.(3) is valid for calculating $Q_P\{t\}$, the density of air within the building envelope must be uniform and invariable during the whole pulse period. Figure 8 shows the density distribution of air around the nozzle when t=0.5s. It can be noted that there is a relatively obvious gradient of air density in the region near the outlet of the compressor nozzle. However, the area represents a very small part of the whole domain and the effect on the air density in the test space is highly likely to be insignificant.

To check the uniformity of density during the pulse period, the volume-averaged density $\bar{\rho}\{t\}$ in the simulated building envelope is used. To confirm the invariability of the air density during the pulse period, the variation of volume-averaged density with time within the simulated building envelope is illustrated by a graph embedded at bottom left corner of Figure 8. It can be noted that, during the pulse period, the change of $\bar{\rho}$ is very small, with a change of 0.06% during the period of $0 \leq t \leq 1.5$. Therefore, the impact to overall density distribution caused by the uneven density distribution near the nozzle outlet can be considered negligible, and good uniformity is present in the test space during a pulse test. This result was agreed by an initial experimental study on the pressure distribution of a five-bedroom house [48].

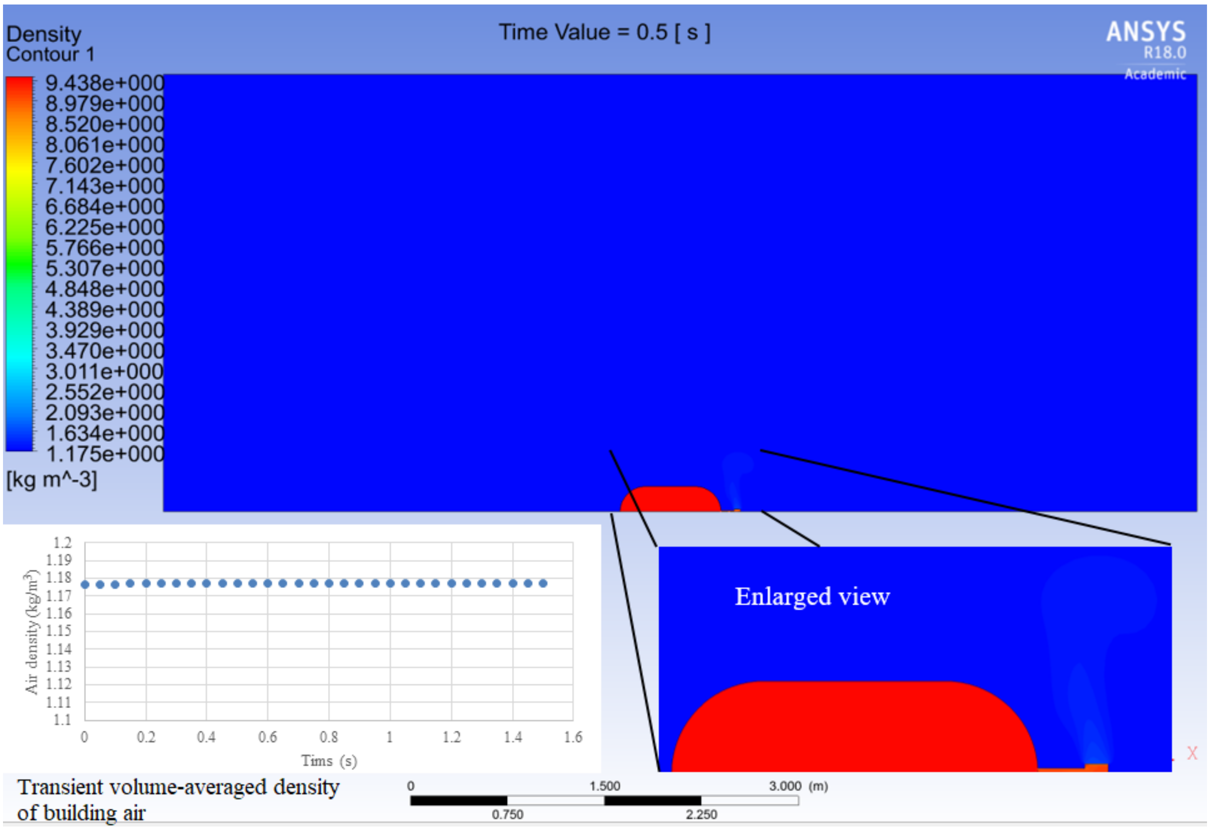


Figure 8 Density distribution (kg/m^3) around the nozzle when t=0.5s

4. Experimental validations of the Pulse test

Through development, the Pulse technique has utilised two different methods to deliver a known volume of air into the test building. The initial version (piston unit) relied upon a compressed air mechanism to drive a large piston to move over a set distance in a known length of time to introduce pressure change to the building. The nozzle unit achieves such pressure change by discharging a pulse of compressed air into the building directly from a compressed air tank via a nozzle. Both methods rely upon the same fundamental principle defined above. But the piston unit relies on the velocity of the piston's movement, whereas the nozzle unit determines the mass flow rate more directly from the pressure variation in the compressor tank. This necessitates the measurement of tank pressure and temperature in order to calculate the flow rate of the air pulse released from the tank. Therefore, the experimental validations of current nozzle-based Pulse technique consist of the one against the original piston unit and the other against the conventional steady pressurisation method.

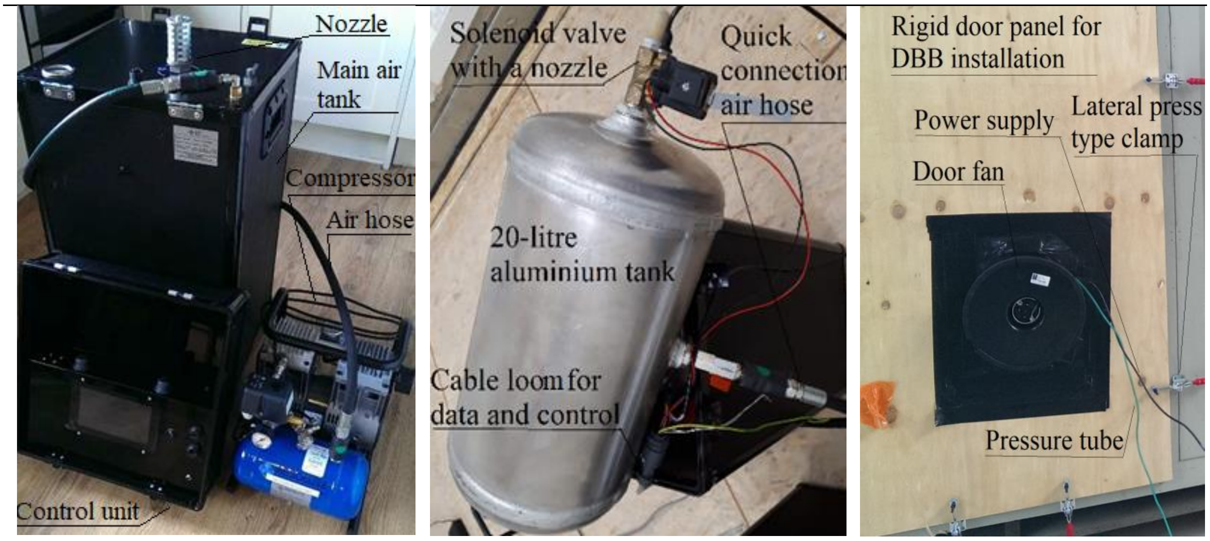
4. 1. Experimental setup and testing arrangement

The building used for the comparison between the nozzle unit and the piston unit has a volume of 136.1 m^3 and an envelope area of 185.8 m^2 with a cube shape. A sheltered chamber, which is 16 m^3 in volume and 40 m^2 in envelope area, was used for testing to compare the nozzle unit with the blower door technique.

In the first experimental validation, the nozzle unit at stage 3 was compared with the piston unit at stage 2 [43]. In the second one, Duct Blaster B (DBB), a low range Minneapolis blower door, was utilised for comparison with the stage 5 Pulse unit. The DBB comprises a small variable-speed fan, a pressure-flow gauge, an adjustable door frame and a flexible canvas panel. It is designed to take more accurate readings in the low range of fan flow than larger models. Therefore, it was utilised in the comparison tests with the PULSE-40/20 units, as listed in Table 2.

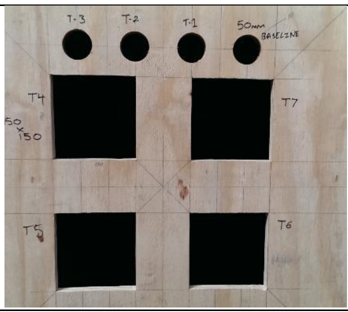
Table 2 Pulse and blower door units used for comparison

PULSE-40 (cased)	PULSE-20 (without casing)	Energy Conservatory Duct Blaster B



The Pulse units incorporated a lightweight aluminium tank (39.8 litre and 20.1 litre) and a double piston compressor. The outlet utilises a ½ inch (PULSE-40) and ¼ inch (PULSE-20) (BSP) automated fast responding valve to discharge compressed air into the chamber from the air tank over 1.5 seconds. The corresponding pressure and temperature signals are taken and processed by the control unit.

Table 3 Setup of the DBB and test plates in the chamber

	
Setup of the DBB in the chamber	
	
Testing plate A with a number of well-defined openings	Testing plate B with three circular holes (two extended by pipes)

As listed in Table 3, two test plates were used for testing, herein named as test plate A and B. The test plate A has four square (150mm×150mm) and four circular (diameter: 50mm) short and sharp-edged openings in the middle of the plate, similar to holes that might be found in construction material layers or in window frames. Test plate B has three circular openings with tubular pipes connected to the top two openings. Plate B seeks to represent those openings found in service penetrations such as ventilation ducts or cable casing running through the wall. More details about the various testing scenarios are given in [49]. During testing, these plates were installed with screws on the opposite side of the fenestration where the DBB was mounted. Wing screws were utilised to fix the plate onto the external surface of the chamber wall.

Eight different testing scenarios were achieved by sealing up various combinations of openings in the two plates. Table 1 in supplemental material 2 shows the details of how the eight testing scenarios were prepared using sealing tapes. Each testing scenario was named according to the testing order, from scenario T0 to scenario T7. For instance, the blower door tests were performed first in scenario T0. After the scenario T0 was completed, a piece of sealing tape was removed to introduce one more opening to the scenario T1, and this testing procedure was repeated until the scenario T7 was completed. The same testing process was repeated for the Pulse unit after the blower door testing was completed. One pressurisation test was run in each scenario while the Pulse test was repeated three or four times in each scenario, except scenarios T6 and T7, where the test could only be performed twice due to the time constraint at the end of testing. This testing arrangement allowed both testing methods to be subject to various leakage characteristics and levels.

4. 2. Results and discussions

4.2.1. Comparison with the piston unit

Figure 9 shows the pressure pulses of five repeated tests. The curves are adjusted to account for any variation of Δp caused by environmental conditions but particularly wind during the pulse period to obtain the building pressure change induced by the release of the air pulse [32]. Such process is done by fitting a curve to the background pressure trend given by building pressure before and after the pulse, and deducting the curve from the raw measurement. In Figure 9 (left) the wind effect is noticeable as indicated by the fluctuations before and after the pressure pulses, and the quasi-steady period occurs between 0.4 and 1.4 s. The calculated transient mass flow rate for one of the tests is shown in Figure 9 (right).

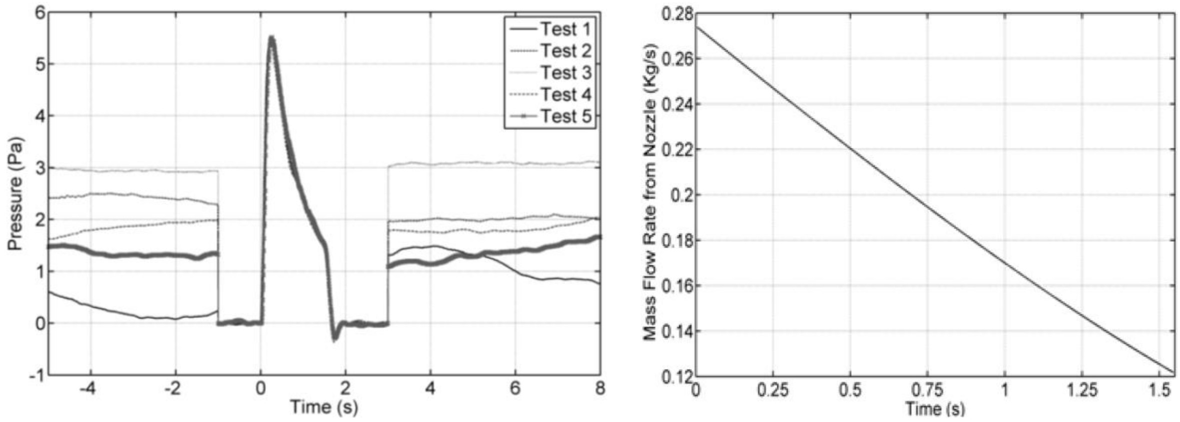


Figure 9 Pressure pulses (left) and transient mass flow rate of the air released from nozzle (right) of five repeated Pulse test

The good repeatability of the technique can be seen in the plotted $\Delta p(t)\_q(t)$ correlation curve in Figure 10, where the average air leakage rate at 4 Pa was 0.17598 m^3/s. Further tests were done to assess the sensitivity of the technique by sealing and unsealing the openings around the test room door. The technique measured an average difference of 0.01626 m^3/s, suggesting the technique is sufficiently sensitive to small changes in leakage.

The piston unit (stage 2 in [43]) was tested in the same test room under the same conditions and the results are illustrated by Figure 11. A good agreement was observed indicating that the nozzle-based Pulse unit provided consistence results with the piston unit. Interestingly, it is noticeable that under the same pressure differences slightly lower values of leakage were consistently given by the piston tests. This discrepancy is attributable to an unavoidable leak of air from the narrow gap between the piston and cylinder wall during the piston test [43]. Therefore, slightly underestimated leakage $Q_P\{t\}$ could be measured in the piston test because $Q_P\{t\}$ is obtained indirectly from measuring the displacement of the piston with regard to time using a cable extension transducer. Nevertheless, the results suggested that the nozzle approach is a valid means of introducing transient pressure change to the test building.

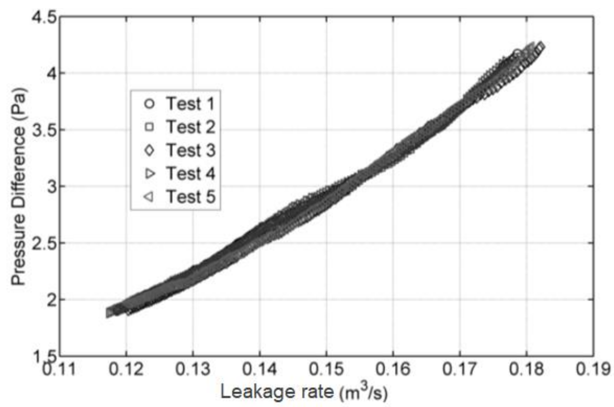


Figure 10 Nozzle test results

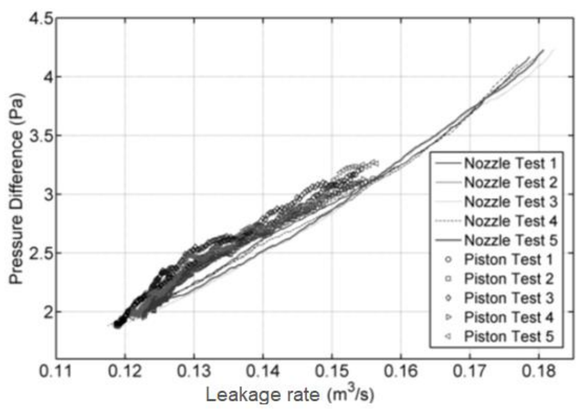


Figure 11 Comparison of nozzle and piston results

4.2.2. Comparison with a low range blower door in a sheltered environment

Table 2 in supplementary material 2 lists the leakage-pressure graphs of both tests taken in the chamber in eight scenarios. Crossover in data in most of the scenarios were achieved to provide direct comparison. For instance, in scenario T0 (Figure 12), the lowest point in the overlapped pressure range was at 10 Pa where the difference in test result between the both tests was 8.8% and the highest was at 18 Pa with 4.8% difference. The percentage difference of the test results in all testing scenarios given by both testing methods is summarised in Table 4.

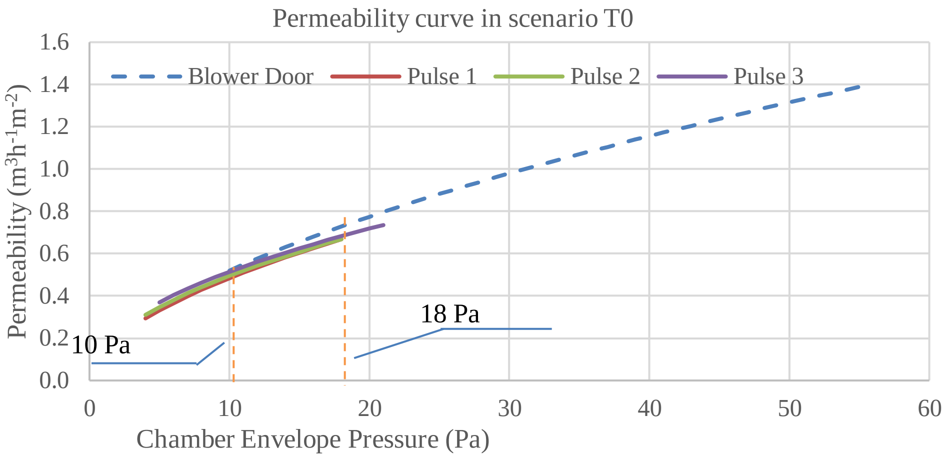


Figure 12 Testing results of scenario T0 [49]

Table 4 Summary of test results given by the blower door and Pulse tests in all scenarios

Scenario	Range of crossover (Pa)	Minimum (%)	Maximum (%)	Average (%)
T0	10-18	4.1%	7.8%	6.4%
T1	5-23	2.5%	7.8%	4.9%
T2	6-16	0.8%	4.1%	1.6%
T3	7-20	0%	2.2%	0.6%
T4	N/A	N/A	N/A	N/A
T5	9-13	6.0%	12.8%	9.6%
T6	16	7.4%	7.4%	7.4%
T7	14-20	3.8%	6.4%	5.5%

Note: N/A means no pressure overlap was achieved.

The results show the difference between both testing methods varies from scenario to scenario with the average difference ranging from 0.6% to 9.6%. Scenario T3 gave the best agreement followed by the scenario T2, both of which showed an average percentage difference less than 2%. The largest difference was seen in the scenario T5 where four circular openings and two square openings were present in the test plate. The openings were lying closely in the centre of the test plate and hence large net fluid flow was generated through the test plate likely creating a ‘pressure sink’ near openings, i.e. non-uniform pressure distribution in the vicinity of openings. This might consequently lead to errors in the pressure measurement, especially so in a small test space and therefore produce larger percentage difference between the two. The average difference in overlap between the blower door and Pulse data is 6.0%. Although this testing does not yield a consistent offset that may be accounted for as all testing comes with an inherent level of measurement uncertainty, with BS EN ISO 9972:2015 [50] citing an overall uncertainty of lower than ±10% in calm conditions for the blower door fan and the manufacturer citing ±5% uncertainty for Pulse measurements [25]. In this context, the level of agreement is generally encouraging, especially for test scenario T2, T3 and T7. A similar finding was reported by Zheng et al [42] in another comparison study where both testing methods were utilised to measure the leakage of a sheltered house-sized chamber, which was set up with various leakage scenarios and levels. Therefore, the Pulse technique is able to provide measurements that are in close agreement with the blower door method.

4. 3. Error analysis

The measurement uncertainty of the experimental validation is evaluated to assess the confidence level of the results. Considering the purpose of the comparison with the piston unit essentially serves the development of the nozzle-based Pulse unit and their working principles are similar, the error analysis herein is therefore focused on the experimental study where the latter is validated against the blower door unit.

Theoretically, the overall error in obtaining the leakage rate at a given pressure level comprises those errors caused by instrumentation accuracy (bias), background pressure induced by environmental conditions (precision) and modelling (model) [24]. In order to illustrate the sources of error in obtaining the leakage rate using the Pulse and blower door methods, an error source diagram is created, as shown in Figure 13. Due to some similarity between both testing methods, five error sources are shared by them. They are mainly related to the measurement of building parameters such as dimensions, pressure and temperature as well as model specification. Other error sources are from the measurement of the airflow delivered by each method to pressurise the building. For the Pulse method, it is the combination of measurements of volume, air pressure and temperature of the tank that is used to determine the delivered airflow from the air tank corrected by the room air temperature, while for the blower door method, the delivered airflow is determined by the fan flow but corrected by indoor and outdoor air temperature. The overall error in obtaining the leakage rate can be described by eq.(5):

$$\delta Q = \sqrt{\delta Q_B^2 + \delta Q_P^2 + \delta Q_M^2} \tag{5}$$

Where, δQ, δQ_B, δQ_P and δQ_M are the overall error in obtaining the leakage rate, bias error and error of leakage rate at the quoted pressure level caused by the building pressure sensor accuracy and model error, respectively.

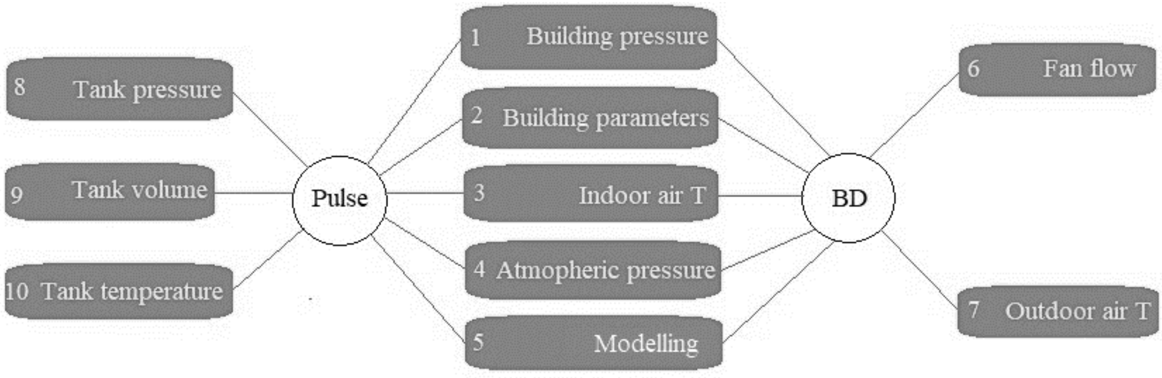


Figure 13 Source of error in the Pulse and blower door test (BD) (Note: No.1 Building pressure represents the building pressure response to the added or removed air in the airtightness test; for blower door, it is the difference between indoor and outdoor pressure; in the Pulse test, it is the difference between indoor pressure and reference tank pressure)

Table 5 summarises the measurement uncertainty of each error source and the three main error types with the responsible error sources. For the model error δQ_M, it is defined as the deviation between the mathematical model predictions and the measurements. It should be noted that the model error herein is mainly determined by model specification but also varies with the measurement of chamber pressure. Hence, the model error appraised in this study also contains the impact of environmental condition to the chamber pressure measurement and an average error across the overlapped pressure range is taken for analysis.

Table 5 Summary of error source for both testing methods

ID	Error source	Accuracy (%)	
		Blower door	Pulse
1	Building pressure (Pa)	±0.9%	±0.25%
2	Building parameter (m^3 or m^2)	±10% [50]	
3	Indoor air temperature (℃)	±0.2	±0.08
4	Atmospheric pressure (hPa)	±3	N/A
5	Modelling	0.45%-1.79%	0.60%-3.90%
6	Fan flow (m^3/h)	±3.0%	N/A
7	Outdoor air temperature (℃)	±0.2	
8	Tank air pressure (Pa)	N/A	±0.2%
9	Tank volume (litre)		±0.4
10	Tank air temperature (℃)		±0.08

Error type	**Bias (δQ_B)**	**Precision (δQ_P)**	**Model (δQ_M)**
Note	Instrumentation accuracy	Weather condition	Model specification
Error source ID	Blower door: 1, 3, 4, 6, 7 Pulse: 1, 2, 3, 4, 8, 9,10	Blower door: 1 Pulse: 1,	Blower door: 1, 5 Pulse: 1, 5

For the Pulse measurement, the analysis of instrumentation caused error (bias) has been described in details in [42]. Due to the fact the test was carried out in a sheltered environment, the impact of the environment condition on the measurement of chamber pressure is minimised but still reflected in the reading of chamber pressure and therefore it is included in the analysis. The theoretical support of the Pulse technique is fundamentally based on the quadratic equation, which is used to understand the Pulse performance and determine a reliable configuration that is able to accurately measure the building leakage over a range of pressure. However, the power law equation, as widely used and accepted mathematical representation of the leakage-pressure relationship, is used in both tests to describe the building's leakage-pressure relationship for simplicity and user friendliness. Therefore, the error of calculating the leakage rate using the power law equation at the quoted pressure level due to the measurement accuracy of chamber pressure (δQ_P) can be described by eq.(6).

$$\delta Q_P = \frac{(1 \pm \delta P)^n - 1}{1} \tag{6}$$

Where, P and δP are the chamber pressure and accuracy of chamber pressure sensor, respectively.

Using eq.(5), the overall error in obtaining the chamber leakage rate in the sheltered condition using the both methods in all the test scenarios are calculated and the results are listed in second and third row of Table 6. The results show that in the validation tests the blower door has delivered measurements with overall error below 3.5% in all eight scenarios, with most scenarios in close vicinity of 3%. For the Pulse tests, most of the scenarios have obtained an overall error below 3.5%, except for the scenario T5, which is slightly higher at 4.4%.

Table 6 Overall error of both testing methods and combined error in comparison

Scenario	T0	T1	T2	T3	T4	T5	T6	T7
Blower door	±3.14%	±3.23%	±3.10%	±3.13%	±3.05%	±3.07%	±3.19%	±3.53%
Pulse	±3.01%	±2.31%	±2.18%	±2.53%	±3.62%	±4.39%	±2.41%	±2.30%
Comparison	±6.15%	±5.54%	±5.28%	±5.65%	±6.68%	±7.47%	±5.60%	±5.83%

When both testing methods are used to measure the chamber leakage under the same scenario for comparison, the resulted maximum difference between the measurements given by both testing methods against the measured leakage rate can be calculated, as shown in the bottom row of Table 6. Compared to the average relative percentage difference between the results given by both testing methods listed in Table 4, the overall errors obtained in all the test scenarios fall outside the error range by 0.25%-2.13%. Considering the factors (such as equipment setup, chamber preparation etc.) leading to difference in the chamber leakage between both tests might not be fully eliminated during testing, such error is considered acceptable for the purpose of validation.

The error analysis presented here only assesses the confidence level of the comparison between the measurements given by both testing methods as part of the experimental validation. In practice, the measurement uncertainty at the referenced pressure especially at a low level is often of concern due to the greater wind impact and should be discussed. However, for the Pulse tests in this study, the measurement uncertainty at 4 Pa falls within the reported values and therefore is not singled out in the analysis because it doesn't add much value to the validation purpose and the wind impact was minimised in the tests due to the sheltered condition.

5. Conclusions

The Pulse technique for determining the adventitious leakage of buildings at low pressures has been developed to overcome some of the issues experienced by the conventional steady pressurisation method. As an unsteady approach, the challenge for the Pulse technique lies in minimising the inertia effect of unsteady flow through building openings, which is common in the unsteady flow conditions. The presence of unsteady flow adds uncertainty to the measurement and leads to compromised accuracy when it represents a significant proportion in the overall flow. The key reasons why the Pulse technique works are due to the consideration of compressibility of the air and the use of quasi-steady temporal inertia model, which is the underlying principle of the Pulse technique because it is able to quantify the unsteady flow by isolating the unsteady term in the momentum equation. Such that the correct unit configurations can be identified to deliver accurate and repeatable measurements. The theoretical model for determining the mass flow rate of the air pulse released from the nozzle is based on assumptions that the pressure distribution in the air tank and test building is uniform. Numerical investigations and experimental validations showed that the assumptions are true and that the results of both tests in a sheltered environment agreed with each other well. The experimental validations against the steady pressurisation method in various leakage scenarios under a sheltered environment where the impact of outdoor weather condition was reduced have achieved a good agreement between the tests by both testing methods. The error analysis to the experimental validations has proved that the results are reliable. Therefore, the Pulse technique can be considered a feasible and accurate low pressure approach for measuring building airtightness.

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