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A practical review of alternatives to the steady pressurisation method for determining building airtightness

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ABSTRACT

As an important indicator of construction quality and envelope integrity of buildings, airtightness is responsible for a considerable amount of energy losses associated with infiltration. It is crucial to understand building airtightness during construction and retrofitting to achieve a suitable envelope airtightness which is essential for obtaining a desirable building energy efficiency, durability and indoor environment. As a convenient means of measurement, the current steady pressurisation method has long been accepted as a standard testing method for measuring building airtightness. It offers an intuitive and robust approach for measuring building airtightness and performing building diagnostics. However, it also has some shortcomings that are mainly related to its high pressure measurement, requirement for skilful operation, long test duration and change to the building envelope. Efforts have been made by manufacturers and researchers to further improve its accuracy and practicality with much progress achieved. Work has also been done to develop alternative methods that can overcome some of the issues. This paper provides a practical review on the incumbent methodology and efforts that have been made over the past decades in research and development of other methods to achieve a similar purpose. It compares them in relation to aspects that are considered important in achieving an accurate, quick and practical measurement of building airtightness and the finding shows other methods such as acoustic and unsteady technique have their own advantages over the steady pressurisation method but also add some of their own restrictions, which therefore makes them suited for different applications.

1. Introduction

As the impact of climate change evolves to be increasingly disruptive, carbon reduction in the building sector has become necessary to curb global warming as this sector alone contributes up to 50% of energy consumption in developed countries and up to 40% globally [1–4]. Hence, it is essential to minimise the building energy demand to decarbonise the building sector. It is required by the Climate Change Act that the UK reaches 80% emission reduction by 2050 relative to 1990, which recently has been replaced by the Net Zero Target requiring at least 100% reduction of UK greenhouse gas emissions. By 2015, 38% reduction has been achieved but primarily in the power sector due to reduced use of fossil fuel and increased production of renewable energy, with little progress in other sectors [5]. For instance, the improved fuel efficiency in the transport sector has been cancelled out by the increased travel demand as meanwhile the economy has improved and fuel prices have dropped. Moving forward, to maintain the same progress rate in the emission reduction, efforts need to be made in multiple sectors. Analysts have suggested a complete decarbonisation of the building stock by 2050 seems to be a more realistic approach given the difficulty of reducing emissions in other sectors. Hence, a number of carbon reduction targets have been set in the building sector to meet the demand for the global carbon reduction. For example, to limit temperature rise under 2 °C, the UK government recently set the 'emission reduction plan' [5], which highlights the significance of prioritising on cutting carbon emission in multiple sectors particularly the building sector and reflects the UK's coherent efforts to echo the global ambition: 'Paris Agreement', reached in December 2015 [6].

Infiltration, fundamentally determined by building airtightness, contributes to 13%–50% of heating demand, 4–20% of cooling demand [7–12]. It is therefore essential to understand the building airtightness as the first step to minimise the energy consumption associated with infiltration. As an important indicator of building quality and energy

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Nomenclature

Symbol

a, b	Coefficients of eq. (2)
C	Flow coefficient ($m^3 \cdot s^{-1} \cdot Pa^{-n}$)
n	Pressure exponent in eq. (1)
Q	Air leakage rate, (m^3/s)
ΔP	Building pressure difference (Pa)
Q_4	Building air permeability at 4 Pa ($m^3\ h^{-1} \cdot m^{-2}$)
Q_{50}	Building air permeability at 50 Pa ($m^3\ h^{-1} \cdot m^{-2}$)

performance, airtightness has been seen as a concern since 1979 because of its fundamental impact on the infiltration-caused building energy losses [13]. It is crucial to account for airtightness in the evaluation of building energy performance due to its great contribution to building energy demand.

The infiltration rate is required as an input in the calculation of infiltration-caused building fabric energy losses [14,15]. Tests to directly measure infiltration rates are complex and time-consuming to perform [16, 17], and are therefore usually substituted with the measurement of building airtightness, which theoretically can be done by measuring the rate of airflow across building thermal envelope under certain pressure difference. Practically, this is done in a range of pressure differences, which can be established by blowing air in or taking air out of a building using a device like a fan blower. The correlation between the achieved pressure difference and the exerted air flow rate is then used to establish the leakage-pressure relationship of the building [18].

One key challenge in the measurement of air leakage is to accurately measure the building pressure. Under ambient conditions, the pressure difference experienced by a building is mainly caused by wind and buoyancy effects and typically lies in 1–4 Pa [13,19–22]. This needs to be removed from the actual measurement of pressure difference to accurately obtain the induced building pressure by the supplied airflow through the fan blower. Due to the dynamic and unpredictable nature of wind, that purpose can be difficult to achieve especially when adverse wind condition is present. Taking measurements at elevated pressures is adopted in the steady pressurisation method, alias 'blower door', to minimise such impact.

It has been widely accepted that the blower door method has provided a convenient approach for measuring building airtightness for many years. Theoretically and practically, it provides an intuitive approach to understanding and measuring this building physical property. Hence, it has also been used to provide benchmark measurements to assess the accuracy of other techniques [23, 24, 25, 26, 27, 28, 29] developed to serve the same purpose. Due to its capability of sustaining a steady pressurisation, it is able to establish a suitable indoor pressure environment where building diagnostics can be performed with the assistance of another tool, such as smoke pen or infrared camera.

However, it has some shortcomings, which have been discussed in various scenarios [28, 30, 31, 32, 33], mainly including three aspects (Table 1):

All these factors somehow contribute to the fact that current standard technique has a margin for errors in practice, which might be caused by factors like unit setup, indirect measurement of building air leakage under natural conditions, lack of building integrity, and discrepancy in operations among different operatives, leading to inaccurate evaluation of building energy performance. Individually, the lack or the inaccurate measurement of airtightness value could produce a gap in energy performance and indoor environment quality of the building between the design and as-built stages, which has been extensively discussed by Zero Carbon Hub [30] and Sherman [34–36].

The aforementioned aspects motivate the authors to carry out investigations on other testing solutions that have been explored and developed in the past and subsequent findings are summarised herein from the practical standpoint.

From the authors' perspective, the method that can be considered viable needs to meet the requirements listed in Table 2, which sets out the essential criteria in practicality and reliability. This review is not to identify a perfect match but explores advantages that other methods are able to offer and identifies hurdles that they need to overcome in order to become a suitable candidate. Considering the authors have been involved with developing some of the reviewed methods, it may be challenging to achieve a totally unbiased introduction of each method due to different technical involvement or perhaps unconscious bias. However, it is the authors' intention to be as objective as possible.

Table 1
Shortcomings of current steady pressurisation method.

	LISTA
Testing practicality	Multiple installation and disassembly procedures to follow Requirement of skilful training, leading to the scope for human errors.
Testing accuracy	Coarse interpretation of background pressure during testing. Unreliable external pressure reference (especially under windy condition). Uncertainty in extrapolating results down to low pressure. Not testing the whole envelope. Unrealistic high measuring pressure. Likelihood of opening additional leakage pathways. Non-uniform pressure in large buildings.
Legislation	Existing standards in many countries (such as France, Switzerland) already quote airtightness at low pressures

2. Fundamentals and its impact on buildings

2.1. Airtightness and its theoretical models

As a metric that describes the integrity of the building envelope, airtightness is a building property that fundamentally impacts building infiltration and is usually quantified by 'air leakage', which refers to the air movement through building leakage pathways. They are typically located at joints where walls meet the floor, ceiling, window/door frame and other walls, and at positions where mechanical, electrical and plumbing services penetrate through walls, such as air ducts, pipework and electric cables, etc. A research study conducted by BRE on 35 houses [37] indicated in the whole house air leakage, 16% was contributed by unintended gaps in windows and doors, 13% was located at the perimeter of loft hatch, window/door frames and permanent vents and 71% was from cracks, gaps and adventitious openings in the building envelope. However, the window leakage has been the most studied

Table 2
Requirements of the alternative methods.

	LISTA
Practicality in operation, maintenance	Easy and reliable to operate by a non-expert. Easily portable to different test sites. Able to test any size building. Able to identify leakage paths. At least as affordable as the current standard blower door, if not more. It needs no more than annual calibrating at a reasonable cost.
Reliability in measurement	At least as accurate and repeatable as the blower door test for demonstrating compliance with regulations and comparing the building stock. At least as accurate and repeatable as the blower door test for predicting infiltration and related energy usage/waste. At least as accurate and repeatable as the blower door test for testing in adverse environmental conditions (i.e. wind and temperature).

among them all [38–43]. Sherman [19] summarised the key leakage pathways in buildings of different types. The leakage location is affected by building geometry and construction method [44], it can also change from building to building. For instance, in multi-floor apartments, it was found there was a lot of background leakage other than the usual leakage pathways [45], balcony door was found to be the main source of leakage in multi-family dwellings [46] and using plasterboard and wet plastering in masonry builds leads to very different leakage levels.

Fig. 1 illustrates the air movement through leakage pathways in a typical UK house in heating season. Due to stack effects, the warm indoor air tends to move out through leakage pathways at upper levels of the house, usually referred to as ‘exfiltration’ and cold outdoor air penetrates in through leakage pathways located at lower levels of the house, which is usually referred to as ‘infiltration’. In cooling season, the flow direction is reversed due to reversed temperature difference but it can be varied by outdoor wind condition.

The measurement of building airtightness can be done by recording the rate of airflow that is needed to pressurise the building to a certain pressure. To obtain the leakage-pressure relationship, such measurement needs to be done over a range of pressures and then represented by a mathematical equation. The power law equation is the most widely accepted and used form in the field, as given by Eq. (1).

$$Q = C\Delta P^n \tag{1}$$

where, Q, n and C are the required airflow rate (m^3/s) to produce the pressure difference ΔP, the pressure exponent and flow coefficient ($m^3/s/Pa^n$), respectively. The value of n lies in 0.5–1, governed by the regime of airflow going through building leaks. To approximately relate it to the flow regime in fluid dynamics, the flow is equivalent to being turbulent when n equals 0.5 and laminar when n equals 1. But in reality, the flow tends to be a mix of different flow regimes because of the presence of many different types of leaks in the envelope and the average value of n is normally in vicinity of 0.66 [47].

It has been found that the power law equation gives an accurate empirical representation of building leakage characteristic [19]. However, the quadratic form was preferred by Etheridge [48,49] because he thought the power law equation does not model the behaviour of adventitious openings. The quadratic form is described by eq. (2).

$$\Delta P = aQ^2 + bQ \tag{2}$$

This equation provides analytic description of the flow through leakage pathways. The first term (aQ^2) represents momentum change, such as flow in openings with variable geometry. The second term (bQ) corresponds to surface friction, such as flow in long gaps with fixed geometry. In reality, these two types of openings co-exist in buildings and therefore the quadratic form is able to provide an intuitive view on components of the flow through the envelope. Nevertheless, the power law equation is regarded as an easier and accurate form for describing the complex phenomena present in the system of interest [50], as the dimensionless number and associated exponent extract the core characteristics of envelope flow and provide good flexibility in mathematically representing the envelope flow.

2.2. Impact on buildings

Airtightness is responsible for unnecessary ventilation and subsequently affects the building energy losses through the exchange of conditioned indoor air with unconditioned outdoor air. It was found [51,52] that over 60% of the energy wastage was contributed by unnecessary ventilation, through the loss of conditioned air. The importance of airtightness test in buildings has long been recognised in developed countries due to the potential large energy savings associated with good envelope airtightness.

The indoor environment can also be influenced by it due to the transport of contaminants through the leakage pathways. Good envelope airtightness makes it easy to achieve effective ventilation and control indoor environment because a purpose-designed ventilation system can be installed to provide sufficient fresh air to occupants with the minimum energy requirement. Another important factor, which is largely influenced by the airtightness, is the long term impact of the moisture transportation on the building durability. A poor airtightness affects the building lifespan by allowing the unconditioned outdoor air to exchange with conditioned indoor air through building fabric, leading

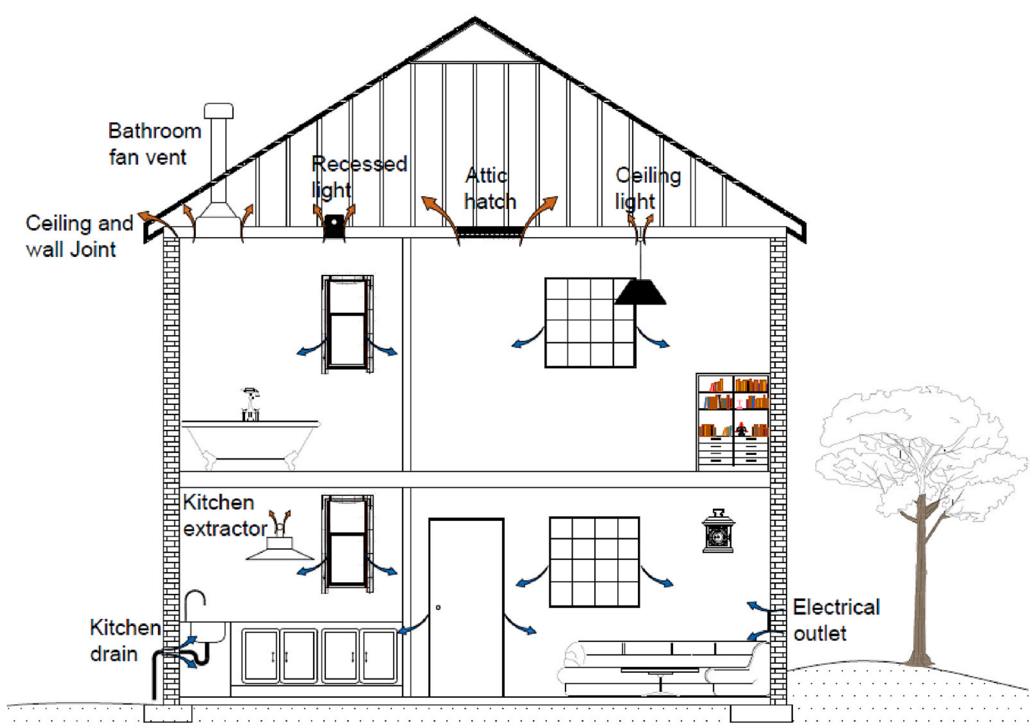


Fig. 1. Locations of typical leakage pathways in a residential building.

to condensation and consequent deterioration of the building fabric. It was reported [53,54] that about 90% of damages to building envelope is caused by temperature and moisture effects on construction materials particularly with wooden wall systems. It also creates a good environment for the growth of mould that not only damages surfaces of construction materials, but also becomes a potential source of pollutant to indoor environment.

3. Steady pressurisation method and alternatives

3.1. Steady pressurisation method

The steady pressurisation method takes the measurement of the building air leakage in a range of elevated pressures (typically in 10–60 Pa). It is done by taking air in or drawing air out of the building to establish a pressure difference using a device and recording the corresponding airflow rate required to sustain the pressure difference. A fan blower is a typical device that can be utilised to achieve that and it is usually mounted in a fenestration, as illustrated in Fig. 2.

A pressure gauge and a flow meter (Fig. 2) are employed to measure the indoor-outdoor pressure difference and the corresponding fan flow rate, respectively. This is usually implemented over a range of elevated pressures. The leakage-pressure relationship is then obtained to provide the leakage characteristic. Fig. 3 shows the leakage-pressure correlation curve obtained in a typical blower door test. The building air leakage in many countries is quoted at an elevated pressure such as 50 Pa, so that the pressure noise (wind or buoyancy effects) can be minimised to provide improved accuracy.

First started by researchers [19, 55], the initial utilisation of the steady pressurisation method was aimed to understand the building infiltration and it was found that hidden leak represented a large amount of air leakage. That finding was regarded as a breakthrough in understanding how buildings work. It has since attracted wide interest in building industry. In 1980s, Home Energy in United States identified 13 blower door manufacturers, with three major manufacturers left in the business today. Nevertheless, this technology over the decades of development has evolved from early clunky version made of materials like plywood and Formica to the recent portable version made of adjustable and lightweight components. With the test duration reduced significantly, the operations have also become more user friendly.

Currently, the blower door method is the widely-used means for understanding building leakage characteristics and performing quality check and diagnostics. Also it has been adopted as a standard testing method by ASTM, CAN/CGSB, and ISO for demonstrating compliance and used in many voluntary standards across the globe, such as Passivhaus standard. Meanwhile, numerous scientific studies have been undertaken over the last few decades to investigate a wide range of building research associated with airtightness, covering unregulated or temperate/hot climate countries [56–58], its relationship with the infiltration, ventilation and indoor air quality [59–62], building characterization [56,58,63,70], retrofitting [63–65], measurement uncertainty [66–69], indoor air quality [70] and other relevant aspects [71–73].

An early summary of blower door test database was made by Orme et al., in 1994 [47] and Chan et al., in 2003 [74]. Orme et al. summarised test results of joint participation of various countries to provide key database material which may be used for design purposes. Chan et al. analysed a database of blower door tests done in a range of U.S. residential buildings to identify the relationship between house characteristic and air leakage. The finding showed that the leakage characteristic of a community of houses depended on the year of construction and floor area.

Sherman and Chan [19] reviewed the state-of-the-art research on building airtightness and introduced its fundamentals and testing techniques including steady pressurisation and AC pressurisation. The historical research has also been reviewed, including airtightness test study to various building types, the correlation between leakage characteristics and building types and the impact of airtightness to indoor air quality.

Nevertheless, this method has shortcomings which were discussed previously. Early motivations for finding other methods [28] came from its disadvantages:

- The need of using large net fluid flow;
- The results might be degraded by noise significantly [75];
- Inconsideration of fluid compressibility might lead to systematic error;
- Not easy to use, it takes long to set up [76];
- 50 Pa is much higher than the infiltration pressure [[13,19,77]];
- Impact from varying wind pressure [78];

However, the steady pressurisation method has gone through extensive developments and achieved significant improvements which make the technique more portable and easier to use compared to the early development. Optimal strategy on the selection of instrumentation and pressure stations has been made by Sherman [79]. However, from a commercial perspective, some of them are probably not practical to accommodate and the aforementioned shortcomings are still yet to be resolved. Efforts have been made to improve existing method and explore others to overcome those issues. Those reviewed herein mainly cover the acoustic method and the unsteady approach: decay method, AC method, and Pulse method.

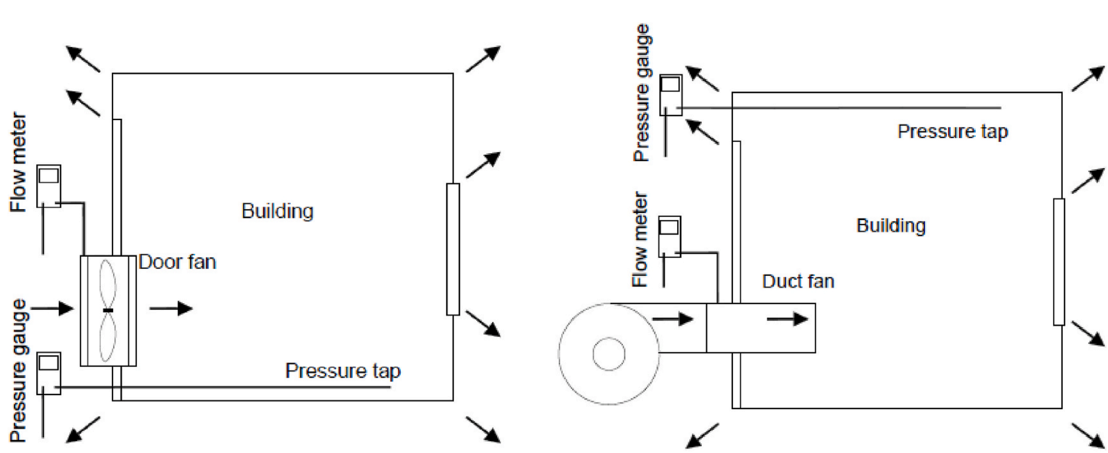


Fig. 2. Steady pressurisation method (door fan and duct fan: in pressurisation) [24].

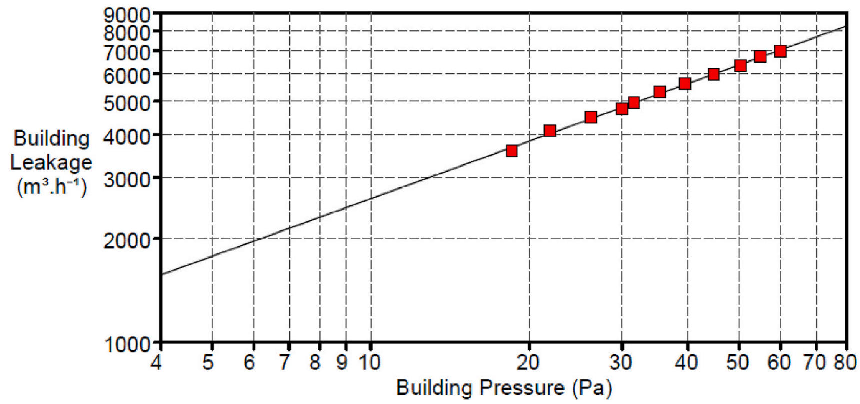


Fig. 3. A typical blower door test (Log-log plot) [24].

3.2. Unsteady approaches

Different from the steady method, the unsteady approach establishes the leakage-pressure relationship in a dynamic manner by taking continuous measurement that is lacking in the steady method. The building integrity could be maintained by adopting a self-contained installation. However, the key challenge of unsteady approach is to minimise the inertia effect occurred in the air that flows through openings under unsteady condition because it adds uncertainty to the measurement and leads to compromised accuracy [51,94].

3.2.1. Decay method

During the implementation of the decay method, the pressure inside an enclosure is increased by supplying air into it until it achieves the desired level. Then the air supply is stopped and the established pressure decays due to leakage through the building fabric. The pressure variation is recorded and used together with air leakage rate to describe airtightness characteristics of the test space. Fig. 4 illustrates how the pressure varies in an ideal testing process.

The whole process consists of three phases: rising pressure, stable pressure and decaying pressure. The rising pressure could be achieved in two ways. One is to release air from a compressed air tank that is positioned inside the building. The other one is similar to the steady method, i.e. using a duct blower. It is relatively easier to achieve the pressure variation profile shown in Fig. 4 in laboratory environment than onsite due to controllable environment and air leakage rate [80].

This method has been used to measure the airtightness of a class CL4 bio-containment laboratory [81]. It has a specific requirement for airtightness that once the supply of air is stopped, an elevated pressure of 500 Pa should not drop to 250 Pa in less than 25 min. Similar requirement has been adopted by Department of Agriculture in the US and the Canada Public Health Agency in the description of an airtightness testing procedure of CL4 bio-containment laboratory.

This method has been employed more scientifically by Mattsson [82–84] in an experimental study to a chamber, which was pressurised to the desired level through an air duct where the air was supplied by a fan, as shown in Fig. 5. The fan was installed outside the chamber and connected to the chamber via an air duct. The duct was sealed after the desired pressure level was reached. The pressure decay was measured and recorded over time. Then the leakage rate is calculated as a function of enclosure pressure across the envelope using recorded pressure profile.

Alternatively, compressed air was used by Moller [27] to increase the indoor pressure to the required level (around 50 Pa) and the air supply was stopped to create pressure decay. The rate of pressure drop was then used to describe the leakage characteristic of the enclosure. The results were compared with those given by a blower door and some discrepancy was observed. It was concluded that the method can estimate the leakage level approximately but the accuracy is yet to be improved.

3.2.2. AC method (repeated sinusoidal volume change)

AC pressurisation method, herein addressed as ‘AC method’ for brevity, was inspired by physical principles of fluctuating pressures, a common phenomenon that occurs when the flow reverses [28, 85, 86].

One of the setups is shown in Fig. 6. Based on steady pressure, the technique creates a repeated sinusoidal volume change to the building by a reciprocating piston [87] and measures the unsteadiness similar to the phenomenon encountered under natural ventilation caused by wind and buoyancy effects.

After recording the average values of the generated flow rate and achieved pressure difference, the collected data is then analysed in the same way as the steady pressurisation method. The effects of unsteadiness are reflected in differences between the measured average values and those given by a steady pressurisation technique.

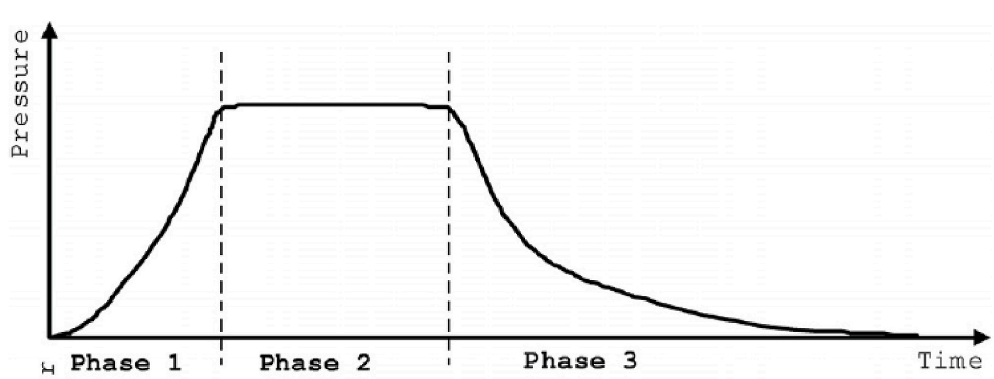


Fig. 4. Theoretical pressure variation profile at different phases of measurement [27].

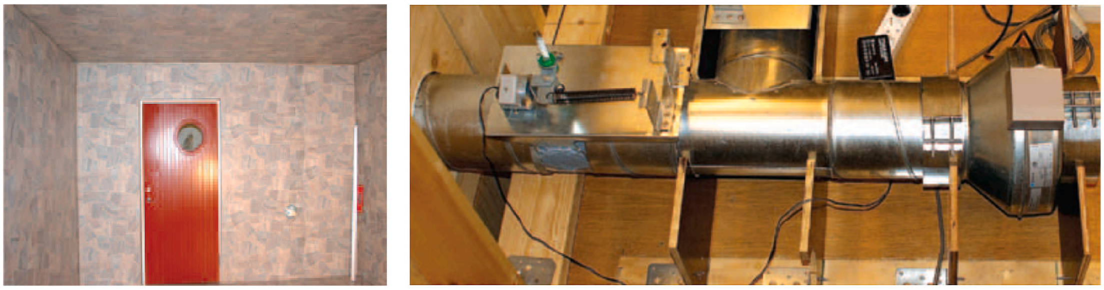


Fig. 5. Rig setup of unsteady technique using gradual pressurisation [82].

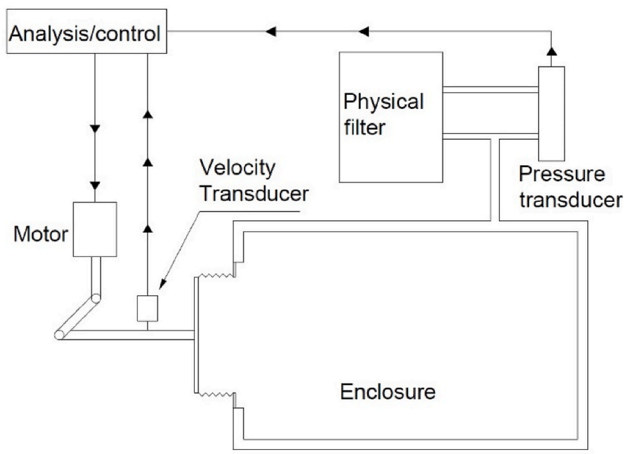


Fig. 6. AC setup on the test envelope [28].

Without having to induce large amount of flow through the envelope [86], AC method is able to take real-time leakage measurements at low pressures. More details about the apparatus, analytical technique and the laboratory measurements are described in Ref. [87]. Leakage area measurements of six single family residences were obtained using an AC method and compared with those obtained by steady pressurisation tests. It was concluded the accuracy of the AC method was rather low, agreeing with the steady method by a factor of three. At a later application, it was reported [28] that the accuracy has been improved significantly and the discrepancy between those two techniques went down to 14%. Although the AC method was quicker to set up and implement, it was more difficult to interpret the results compared to the steady method used alongside. Moreover, the measurement is limited to certain frequency due to the impact of environmental noise [88,89] and certain opening size as further increase in the opening size doesn't affect the test results. Therefore, AC method has not been widely used in the field.

3.2.3. *Pulse method*

The original drive behind the development of the Pulse pressurisation technique was the need of addressing the issues associated with measuring the leakage of large buildings by turning to the low pressure measurement so large amount of airflow could be avoided [94]. This technique is not a new idea [75,90–92], as similar concepts were proposed and investigated experimentally [75,92], but insufficient accuracy was achieved due to various reasons [77].

The Pulse technique reported herein releases a pulse of compressed air from an air tank to the building over seconds (typically 1.5 s) to create an instant pressure rise at low pressure level, which is then followed by a steady pressure drop to deliver a "quasi-steady" flow [77]. During this period, the pressure variations in the building and air tank are measured to establish the leakage-pressure correlation together with tank and building parameters. The schematic diagram is shown in Fig. 7.

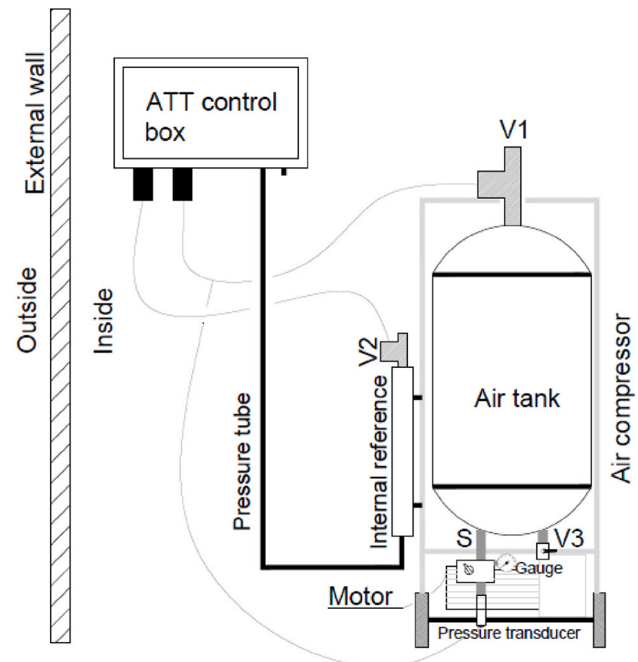


Fig. 7. Schematic diagram of the Pulse system [23].

The method accounts for the pressure noise caused by wind and buoyancy effects, by taking background pressure out of the raw measurement [77]. The building and tank pressures in a standard pulse measurement are illustrated in Fig. 8. The pressure readings include pressure variations in the building and tank when the valve is open and background pressures in the building when the valve is closed.

Similar to a blower door testing process, the Pulse technique takes measurements over a pressure range, which is typically in 1–10 Pa. However, the Pulse measurement is implemented in a transient manner instead of taking individual measurement at multiple points over a range of high pressures. The low pressure approach only requires a volume change at the order of 0.004% to generate a pressure variation in the order of 4 Pa. Therefore, it has been favoured by some researchers, who have used it in different ways to measure the building airtightness.

Fig. 9 illustrates the pulse prototypes at a few developmental stages. The first pulse concept based on a gravity-driven piston (stage 1 unit) was proposed by Carey and Etheridge in 2001 [94]. At a later stage in 2004 [95], a more practical version (stage 2 unit) was designed and fabricated where the piston is moved by compressed air released from an air receiver over a short period of time via an electronically-controlled solenoid valve. The released air is then received by the cylinder that is connected to the valve outlet through a pipe. On receiving the released air, the piston is displaced in the cylinder due to the instant pressure increase and consequently introduces pressure change to the test space.

However, the use of piston was eliminated in a later version, i.e. the

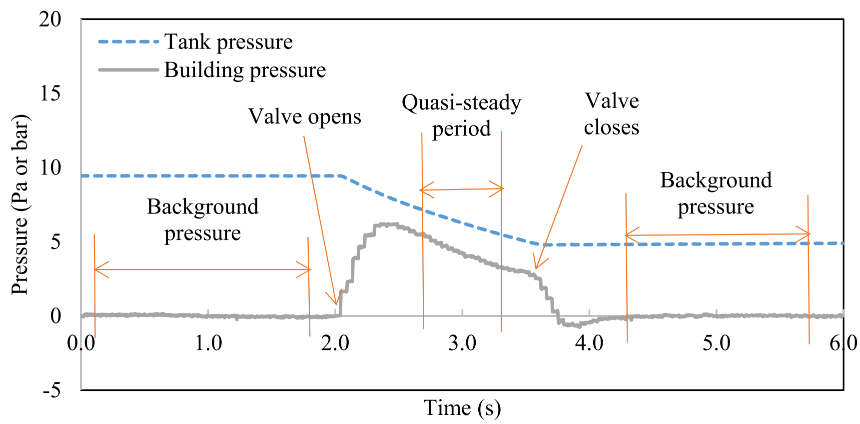


Fig. 8. A Pulse test by a unit with 60 l tank (tank pressure measured in bar, building pressure in Pa) [93].

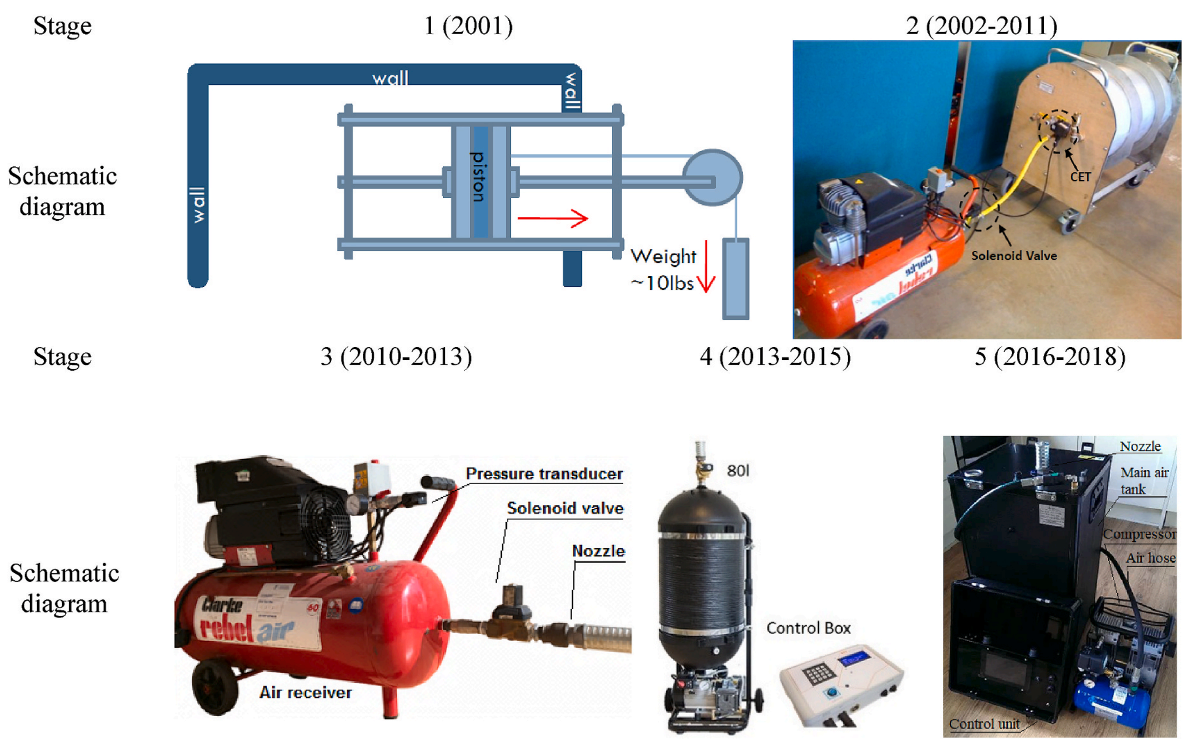


Fig. 9. Historical development of the pulse technique [96].

nozzle unit, to avoid air leak through the narrow gap between cylinder wall and the piston in order to improve the portability and accuracy. The first nozzle unit, (stage 3 unit), is comprised of a compressor air receiver, solenoid valve, and silencer. The instantaneous pressure in the air receiver is measured by a strain-based pressure transducer.

Both techniques employ portable test rigs and can be operated without penetrating the envelope. The nozzle unit is more compact and portable than the piston unit due to the absence of bulky and heavy piston. Additionally, the nozzle unit generates a pressure pulse by releasing compressed air directly from the receiver and is able to achieve higher pressure magnitude compared to the piston unit, because for the latter the air from the receiver is obstructed by the piston. Therefore, the nozzle unit is considered more accurate than the piston unit due to the elimination of uncertainties in determining the mass flow rate [97]. The fundamental and theoretical introduction of the Pulse technique is given by Cooper et al. and Zheng et al. in a number of articles [23,33,98]. An overview on the prototype development is summarised in Ref. [99]. Some initial investigations into the wind impact on the Pulse test have been performed in a number of studies and findings are reported in Ref. [93,100–102].

In addition, a recent study based on the similar concept [25,26] has been undertaken to measure the effective leakage area of a test room, but its results significantly deviate from the ones given by the steady method due to inconsideration of air compressibility and inertia effect.

3.3. Acoustic method

Previous research studies on developing acoustic method [103, 104, 105, 106] have been primarily focused on building leak detection. However, studies on using acoustic method to estimate air permeability by measuring sound transmission through openings have been undertaken since 1980s. It is done by establishing a correlation between air and noise transfer through adventitious openings [107]. A sound source is used to radiate sound waves at a known frequency on either side of a building element such as window. Sound level is sampled on both sides using sound level meters. The air leakage of the building element can be calculated once a correlation between air leakage and sound transmission loss (STL) is obtained. Early experimental attempts to find the correlation between STL and air leakage were made by a few scientists in 1980s [108, 109, 110] but without concrete findings. However, progress was reported in Refs. [108] which showed the sound source with a frequency of 2000 Hz is preferred.

The use of acoustic method for measuring the leakage of building components has been recently reported by Hassan [111], but not compared with the steady method. In another study [107], an in-situ setup of acoustic test and steady test for measuring STL and permeability through windows is shown in Fig. 10. A correlation between air permeability and sound transmission loss of windows has been obtained, showing an inverse proportional relation between them.

A laboratory based experimental setup is introduced by Varshney [29]. The test chamber consists of two sub-chambers, where various test conditions can be established. Panels made of different types of materials can be mounted between two sub-chambers, with holes and slits created in the centre of test specimen.

A sound source was installed in the exterior chamber and a number of sound level meters were placed in both exterior and interior chambers at various distances from the test sample to measure the STL through the manually introduced holes/slits. Sound pressure levels were measured and recorded wirelessly by the sound level meters in a range of frequency (32–8000 Hz). The corresponding sound pressure changes in the range of 30 dB–130 dB with an accuracy of ±1.4 dB. Varshney compared this method with blower door method and found out a close correlation between the test results given by them, implying its potential for determining airtightness of building components.

Nevertheless, this method is limited by the wall structure, leakage type, leakage level and the visibility of leakage pathways due to the nature of sound propagation. It is probably more suited for testing an element rather than a whole building fabric.

4. Comparison

As listed in Table 3, the reviewed methods are compared with each other under a few key indexes that are considered important to offering a practical means for measuring building airtightness. Finally, a summary of case studies comparing the alternative methods with the steady pressurisation method is given at the end of this section.

4.1. Pressure range and results

Air infiltration is the parameter that is required to determine the building energy loss caused by infiltration. However, all reviewed methods don't measure the infiltration rate directly but measure the leakage as a quick and practical substitute. Then the infiltration rate is derived from the leakage rate. For instance, the steady pressurisation method measures the leakage typically in 10 Pa–60 Pa and quotes the leakage at various levels. Then the infiltration rate is calculated by using either a leakage-infiltration ratio, or infiltration models such as LBL infiltration model, or AIM2 model [113, 114, 115, 116]. These infiltration models rely on a power law to calculate air infiltration from data given by the steady technique and environmental/site conditions to predict air infiltration. However, it has been recognised that the building air leakage should ideally be measured at low pressures since the 1970s [13] due to the associated extrapolation error and valving effect, which occurs at high pressures sometimes and was reported recently by Cooper et al. [93].

Although some study [117] supported that the extrapolation used to calculate infiltration does not introduce a bias, findings in other studies showed that this extrapolation introduces a large error when calculating infiltration [118] due to the dissimilar hydraulic property between low and high pressures.

Investigations using AC method have taken measurements in pressure ranges of 1–10 Pa [86], 4–22 Pa [87] and quoted results at 4 Pa [86] and 25 Pa [87]. Decay method has taken measurements at various pressure levels, 0–50 Pa [27], 6–100 Pa [82] and 70–400 Pa [80]. The leakage results are quoted at 50 Pa [27,82]. The Pulse method measures the building leakage typically in 1–10 Pa and quotes results at 4 Pa.

The uncertainties existed in fan pressurisation has been analysed by Sherman [79], who introduced them in measurements of airflow and pressure, and pointed out errors caused by model specification also contribute to the overall uncertainty when the leakage at 4 Pa is estimated. Cooper et al. [77] compared uncertainties in the measurements of Q_{50} and Q_4 and concluded that direct measurement of Q_4 is able to reduce the uncertainty by a factor of 3 or 4 due to the consecutive measurement of building pressure in a short time. Nevertheless, recent studies [23,119,120] showed that when measuring building airtightness, blower door and pulse tests could reach good agreements when factors that cause difference in measurements such as equipment

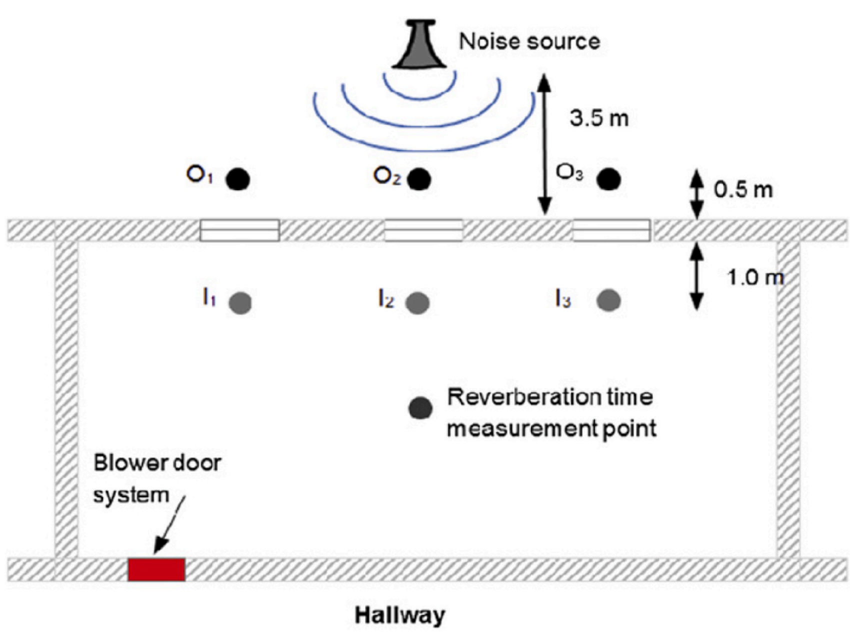
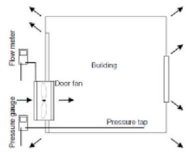
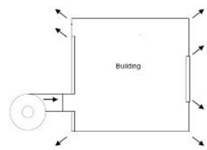
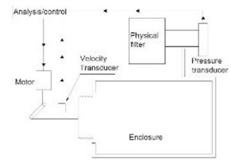
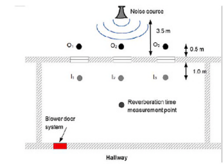
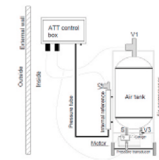


Fig. 10. Onsite comparison of acoustic measurement and pressurisation test [107].

Table 3
Criteria matrix of reviewed methods.

Methods	Steady	Decay	AC	Acoustic	Pulse
Illustration					
Building integrity	P	F/P	F/P	F	F
Time of setup/teardown (seconds)	600–1200	600–1200	Unknown	unknown	120–240
Wind pressure measurement	Coarsely measured	N/A	N/A	N/A	Continuously measured
Test duration (seconds)	600–900	13 [27]' 1.5–300 [82]	N/A	N/A	11-15 [33]
Training requirement	skilful training	skilful training	skilful training	skilful training	basic training
Extrapolation	Yes	N/A	No	N/A	No
Pressure range (Pa)	10-60+ [112]	0-50 [27], 6-100 [82]' 70–400 [80], 250–500 [81]	4–10 Pa [87]	N/A	1-10 [32,33,95,97], 50 [25]
Leak detection	Yes	No	P	P	M
Note	'P' stands for 'partially meet the requirement'; 'F/P' stands for 'the requirement can be fully or partially met'; 'F' stands for 'fully meet the requirement'; 'P' stands for possible; 'M' stands for 'possible in future';				

installation and weather condition are minimised.

4.2. Building integrity

It is imperative to maintain the building integrity during measurement to avoid adding uncertainties to the measurement. In the reviewed methods, some of them change the building envelope by mounting equipment in it. Other ones are self-contained and hence can fully maintain the building integrity.

Steady pressurisation method installs duct or blower fan in a fenestration, typically in an external doorway. The leakage characteristic of that door could be changed, either making the replacement tighter or leakier depending on the installation quality and door condition. This becomes more obvious in airtight space [120] and when the frame has an irregular shape or secure door fittings are mounted in the doorframe making it difficult to create a similar seal. Moreover, the artificially high pressure range where the measurement is taken can potentially create additional openings [93].

For the decay method, the building integrity could be fully or partially maintained depending on the approach taken, blower fan or compressed air. For the former [82], the integrity is partially maintained. For the latter [27], the integrity is fully maintained.

AC method can also maintain the building integrity partially or fully, depending on which setup is adopted. When a mobile standalone device is used, it can be placed within the enclosure of the building without changing the building fabric. The other one requires mounting the drive component in the envelope and therefore changes it.

For the Pulse technique, the earliest concept, gravity driven piston unit, relies on a door or window installation [94] and hence changes the envelope. The later versions, which are compressed air driven piston unit and nozzle unit, are operated within the enclosure, and therefore fully maintain the building integrity.

The acoustic method reviewed in this paper is laboratory based and designed to locate leakage. The measurement is limited to the specimen and not suitable for onsite measurement due to the complexity. It is the leak detection that has been discussed more extensively. Nevertheless, the setup of acoustic method is able to fully maintain the building integrity.

4.3. Time for setup and disassembly

The setup of the steady pressurisation method (blower door) involves two major steps [121]:

Setup of door panel-This is comprised of fitting the frame and fabric into an external doorway, placing tubes through the fabric and installing the fan. Generally the front door is chosen for ease of access and installation, but other door should be used if it provides better safety to members of public or if it offers better sheltering from wind.

Connecting the gauge to the blower door-This step involves mounting the pressure/flow gauge to the blower door frame or door panel, connecting pressure tubes to the gauge, fan blower and outdoor environment, and connecting speed controller to the fan blower.

In most scenarios the door can be set up and ready to test in around 3 min. In some cases, it can take up to 10 min depending on the operative's proficiency and the site conditions.

For the decay method, two different setups have been reported in previous research. One is based on the duct blower which pressurises the enclosure in the same way as the standard pressurisation method [82]. The time for setup and disassembly lies in the similar spectrum with the standard pressurisation method. The other one is based on compressed air which, reported in Ref. [27], is a standalone device, whose installation is simpler and hence needs less time to set up. The installation is similar with the Pulse method.

For AC and acoustic methods, there has been no report on the time required for setup and disassembly. However, by the look of the setups shown in Fig. 6 and described in Ref. [86], some light can be shed onto the timescale. The acoustic method is based on an established test chamber which needs to be used in a laboratory environment. The setup involves with installing the test specimen and can be quick to do but it is not suitable for onsite measurement. The AC setup on the test envelope shown in Fig. 6 needs to be built in a bespoke manner in order to fit various testing sites as the equipment setup relies on the building envelope and onsite situation which could vary from building to building. The setup of AC method in Ref. [86] is a standalone device and doesn't involve penetrating building envelope and the pressure tubes are not required. Hence it should be relatively easy and quick to do.

For the Pulse technique, it is a standalone and portable device that needs to be plugged to the wall socket. The control box and main tank needs to be connected by a cable loom to allow the control box to control the valve action and receive data readings from sensors. The time that is required for setup and disassembly is about 1–2 min. Prior to implementing the pulse test, the air tank needs to be charged to a desired level and it takes from 4 to 10 min depending on the tank size and required pressure level. However, this time penalty can be avoided by simultaneously performing other tasks such as building preparation due to autonomous charging process.

4.4. Background pressure measurement

The background pressure is defined as the pressure experienced by buildings under natural conditions. By measuring it during a standard test, the impact of background pressure could be taken out from the raw measurement to obtain the building pressure response when subjected to a known change of indoor air and hence uncertainties could be minimised. For steady environmental conditions, theoretically a number of measurements before and after the test is sufficient to represent the trend [18,122]. When unsteady, the frequency of measuring background pressure needs to be increased to represent the trend with adequate accuracy.

In a steady pressurisation test, the measurement of background pressure is termed as the baseline (zero-flow) measurement. It is typically done by taking three 5-s averaged pressure readings before and after the test with the fan blower off and covered [122]. It was later modified to 10 consecutive readings over 30 s before and after the test [18]. These background pressure readings are used to account for background pressure. However, a test usually lasts 4–10 min, during which the background pressure can experience different fluctuations. This background pressure measurement is representative when the wind condition is stable, but less so when fluctuations are present in environmental conditions.

Decay method, the measurement of background pressure has not been discussed in previous research. This could be because studies related to the decay method have been performed mainly in a laboratory environment where the test is sheltered. The background noise measurement has not been discussed in previous studies on AC method and acoustic method. For the latter, it seems unnecessary to remove the background noise when the measured sound level is 10 dB higher than the background noise sound level [105].

For the Pulse technique, the background pressure is measured at a sampling rate of minimum 20 Hz for 2 s before and after the pulse. Moreover, the whole test is conducted over a short duration of time. Therefore, the way that the background pressure is measured is deemed to be more representative of that caused by environmental conditions.

4.5. Test duration

The test duration is defined as the time used for running a test excluding that for setup or disassembly. Running a steady pressurisation test usually takes 4–10 min according to the required procedures [18,122]. It can be varied by the fenestration condition, operative's proficiency and weather conditions.

For the decay method, when a duct fan is used, the test duration largely depends on the airtightness of test envelope as it is implemented by monitoring the pressure decay from a stabilised pressure (typically at 100 Pa) to 10 Pa or lower pressure level depending on the measuring resolution [81,82]. For a space volume of 40 m^3, the test duration ranges from 1.5 s to 300 s when the envelope's leakage rate changes from 200 m^3/h to 1 m^3/h. When compressed air is used, a test run takes about 13 s.

With regard to AC method and acoustic method, no discussion has been made to the test duration. The acoustic method has been used mostly for leak detection claimed to be less laborious to perform than the combination of fan pressurisation and smoke tracer to detect leakage location.

4.6. Leakage detection

The leakage detection is important when the presence or certain level of leaks has a big impact to the system performance or safety such as gas pipelines, clean rooms or ultra-high vacuum systems. The leakage detection becomes less important than quantification when pressure level is relatively low and when leakages are desirable or can't be avoided such as an acoustic enclosure or the shell of a house [28].

The steady pressurisation method is able to detect the leakage location with the assistance of infrared camera or smoke gun [33], sometimes acoustic device [103–105]. The detection can be done by fixing the blower door in a fenestration to establish pressure difference across the envelope and identifying the leakage location using an infrared camera or smoke pen. Acoustic method also has been used for leakage detection using the sound source and meter. It has been proved technically feasible. However, the leakage detection relies on the equipment setup near the target area and requires setup on both sides. This implies that multiple equipment setups are required to perform the leakage detection to the whole building. Hence, the detection could be restrained by the availability of external setup. There have been some unpublished discussions on the possibility of detecting the leakage location by 3D-mapping the pressure level of the sound in a room. This approach could potentially simplify the equipment setup and accelerate the leakage detection process, but it is at the early research stage.

Regarding other methods, the leakage detection has not been reported. However, for the ones that offer a viable measurement of building air leakage, a cheap and off-the-shelf fan can also be utilised to establish a sustained indoor-outdoor pressure for the purpose of leakage detection, such as some commercially available leak checker.

4.7. Skill level required

Practical training generally covers two parts, the building preparation and test implementation. Considering the building preparation procedures should not vary significantly with the used method, the skill level discussed here focuses on the test implementation only.

The steady pressurisation method has been adopted internationally as the standard method for measuring building airtightness. In order to govern the test validity and accuracy, the operative needs to be trained and qualified for the purpose of demonstrating compliance. Testers need to follow the procedures specified in different national testing standards, most of which comply with the international testing standard, ISO 9972. The training needs to cover the unit setup, test implementation and data analysis due to great involvement of manual operation. However, the test results could vary from operative to operative even when fully trained and qualified operatives measure the same properties [30]. Having said that, the operation has been made easier in the latest development by introducing easy-to-follow onscreen instructions.

Based on the reviewed studies, decay method, AC method and acoustic method have been mainly used for research purposes as the utilisation of them is limited to scientific study at current stage. The Pulse method has gone through the crucial research stage and currently is moving towards commercial application [33]. The Pulse unit in its current form doesn't require sophisticated setup apart from simple data and power cable connections and inputs of a few parameters related to the building and operative. The test can be implemented by a series of button operations. The data is analysed by a processor embedded in the control box and the results are instantly available onsite.

4.8. Case studies of comparison

To provide a quantitative understanding of how alternative methods compare with the steady pressurisation method in measuring the enclosure airtightness of a test space, either real building or test chamber, test results from some representative experimental studies have been collated and listed in Table 4. Extensive discussions are not made

Table 4
Summary of case study comparison of alternative methods against steady method.

Comparing method	Steady pressurisation method	
Decay	Outdoor [27] and sheltered [82]	7%–55% [27]' 20% [82]
AC	Outdoor [28]' [123]	0–300% [123], 3–24% [28], 0–37% [75]
Pulse	Outdoor [24] and Sheltered [23,119]	7.9%–16.0% [24], 0–5.3% [23]' 0.6%–9.6% [119]
Acoustic	Outdoor (windows) [107]	5% [107], 0–33% [29]

here because relevant discussions have been made in other sections. Some of them were carried out in an outdoor environment and others were carried out in a sheltered environment where different setup has been adopted to minimise the impact of certain factors, such as wind or equipment installation. It seems all of the alternative methods are able to deliver a measurement that is in close agreement with the steady method in some cases. But a significant discrepancy can be observed in other cases for the decay method, AC method and acoustic method with an increased discrepancy also observed in the Pulse method in some cases. However, when the conditions that lead to leakage difference in the enclosure of the test space is minimised, better agreement can be obtained, especially with the Pulse method. Although acoustic method is able to provide measurements in a good agreement with the steady pressurisation method, its use is limited to the measurement at the building element level, more discussions have been given in section 3.3.

5. Summary

5.1. Discussions

The steady pressurisation method is able to measure the building air leakage and detect the leakage location in conjunction with infrared camera or smoke pen, and predict infiltration using infiltration models or empirical ratios. Running a test involves a number of procedures and requires the operative to be fully trained and qualified to perform certified tests. But it leaves a margin for errors due to the significant involvement of manual operation. In a standard practice, the background pressure has been taken in a manner which could lead to inaccurate representation of it when the building is subject to unsteady wind condition. The pressure range where the building leakage is taken is much higher than that experienced by buildings under natural conditions. Apart from the fact that new openings could be created under high pressure [93], modellisation error could also be introduced into the extrapolation [86] because the flow regime of the airflow through the leakage pathways under high pressure and low pressure is dissimilar.

Both decay method and AC method have two similar setups, i.e. envelope dependent setup and envelope independent setup; the latter can be considered as a more advanced option than the other when the commercial adaptability is factored in. However, no further development has been continued in the research reviewed herein. The gap of the results given by them to that given by the steady pressurisation method has been reduced, but further improvement to the accuracy and practicality is still required if it were to be utilised as a standardised method.

Pulse method shares some similarities with both decay and AC method in terms of the system setup, which fully maintains the building integrity and is able to conduct the test in a dynamic manner. The differences are that it measures the building leakage at infiltration pressures and it accounts for the air compressibility. That makes the measurement more representative of the leakage characteristic and more accurate than other unsteady methods. Its downside is being unable to detect the leakage location and there isn't any well-established model available to predict air infiltration from measurements. However, initial research [22, 124, 125, 126] has been performed to look into it and preliminary findings were reported, but further systematic research on the topic is required.

Among the reviewed methods, only the steady pressurisation ('blower door') and Pulse methods have been commercialised. According to the current market pricing in the UK, the cost of a blower door unit that is designed for testing houses of a similar size is approximately 5%–10% lower than a Pulse unit. However, it needs to be calibrated on an annual basis due to the likelihood of altered fan flow rate caused by physical change of the fan blower, the calibration cost ranges in £500-£600 depending on the calibration requirement. For the Pulse unit, a bi-annual calibration is required to the pressure and temperature sensors only with inspections to the physical intactness of the air tank. Therefore, the overall cost of utilising both equipment fall on a similar level in the short term, but the Pulse unit potentially shows a cost-saving potential in the long term; however the maturity of the market for Pulse is yet to be reached at the time of writing.

5.2. Future research direction

Required by the pressing need of achieving substantial carbon reduction in the building sector, buildings with high-spec envelopes will be necessary in future developments to provide the optimal envelope integrity and construction quality. Such trend is not only a result of industrialised construction process which is essential to achieving a maximised material efficiency and standardised construction to specifications, but also one of the important approaches to minimise the building energy demand and deliver a more controlled built environment. This becomes increasingly important as the climate changes and buildings need to achieve a more refined operations to provide a resilient, safe and healthy indoor environment for occupants to accommodate new challenges created by the constantly changing environmental conditions.

Therefore, it is important to gain more control on the building ventilation due to the need of minimising the negative impact of surrounding environment at a minimal energy cost such as contaminated air in adjacent zones or polluted outdoor air. For instance, the recent pandemic related to Covid-19 poses a huge challenge to the indoor environment where infection rate is much higher than outdoor due to the confined space. It is difficult to achieve a safe and controlled environment when the ventilation relies on natural or loosely controlled mechanical means. Building an envelope with a high level of airtightness is perhaps more beneficial and necessary in this circumstance because more control can be gained in the building ventilation to create a smart and organised ventilation.

To achieve that goal and deliver the desired ventilation requirement for each zone of a building economically, it is important to develop an airtightness testing method that provides an accurate, quick and representative measurement of the airtightness, not only at the building level, but also at the zonal level. Such that the ventilation performance gap can be minimised and the ventilation system can work reliably. Maintaining the integrity of the test space during testing is one of the key requirements to achieve that goal especially when the test envelope is highly airtight [120]. Leakage detection plays an important role in identifying fabrication and construction defects and providing useful feedback for further improvement to the construction process. However, when the construction process is standardised with sufficient quality assurance, the detection of leakage location becomes unnecessary as the envelope quality can be checked by performing a quick and accurate measurement of the airtightness.

6. Conclusions

The current steady pressurisation method has been the standard one for measuring building airtightness in many countries for decades. However, it has shortcomings due to a number of aforementioned factors. Other methods have been reviewed. Each might have its own advantages over the steady method but also adds some drawbacks. The pros/cons of each method have been discussed and compared with each other from a few key aspects. These aspects are based on considerations of technical and commercial feasibility, accuracy and practicality, reiterated as follows:

- The steady method has obvious advantages over other methods on leakage detection, maturity of development and degree of acceptance. But it is unable to fully maintain building integrity, involves extensive manual operation and gives coarse interpretation of background pressure. It also requires high testing skill.
- Other methods offer solutions to some of the issues shown in the steady method, such as fully maintaining building integrity, shorter test cycle, realistic testing pressure, and potentially deskilled operation. However, shortcomings do exist in most of them, which include the inability of detecting the leakage, poor accuracy and practicality.
- Pulse method shows advantages in maintaining building integrity, continuous measurement of background pressure, representative pressure level, short test cycle and deskilled operation. But it has disadvantages including inability of detecting the leakage locations and absence of infiltration model for predicting air infiltration.

The efforts on developing methods for measuring building airtightness have crystallised on a number of techniques although each has its own advantages and disadvantages, which have been demonstrated and identified in a great amount of industrial practices and scientific studies. It somehow reflects the need for improving current incumbent method and developing others, which could address shortcomings of the steady method. Nevertheless, continuous work has been ongoing to improve the steady method to overcome current drawbacks and developing alternatives with improved accuracy, practicality and commercial applicability to make the goals of achieving good build quality and reducing the infiltration energy loss more achievable.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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