A NOZZLE PULSE PRESSURISATION TECHNIQUE FOR MEASUREMENT OF BUILDING LEAKAGE AT LOW PRESSURE

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ABSTRACT

Air tightness is essential to building energy performance, which has been acknowledged for a long time. It plays a significant role in improving building energy efficiency by minimising the heating/cooling loss incurred during unwanted air movement through the building envelope, consequently reducing the building's energy demand and cutting down carbon emission in the building sector. A novel nozzle pulse pressurisation technique for determining the adventitious leakage of buildings at low pressure around 4 Pa, which is regarded as a more accurate indicator than conventional steady state measurement at 50 Pa, is investigated theoretically, numerically and experimentally. The investigation is based on the 'quasi-steady pulse' concept which produces a pressure pulse inside the building by introducing a certain amount of air in a very short time using an air compressor, solenoid valve, nozzle and control unit. The mass flow rate from the nozzle is obtained by measuring the transient pressure in the air receiver of the compressor during a test run. Simultaneously, the pressure difference across the building envelope is measured by differential pressure transducers. The quadratic equation, which can more closely represent the flow characteristics of adventitious openings, is used to determine the characteristic of building air leakage. Due to short time operation, the technique minimizes the effects of wind and buoyancy force and has proven to be highly repeatable. The pulse pressurisation using nozzle technique is compared with that using the piston technique. The comparison indicates that the present technique is reliable for determining building leakage at low pressure. It also gives great convenience in practical applications due to being more compact and portable. Moreover, it needs only a few seconds for a test run, barely needs to penetrate the building envelope and therefore can establish the leakage of a building very quickly and efficiently.

KEYWORDS

Air tightness, quasi steady, nozzle pulse pressurisation, low pressure;

1 INTRODUCTION

In European Directive 2010/31/EU (Directive, 2010) [1] on the energy performance of buildings, it is stated that the energy efficiency of buildings has to be calculated in the member states. Air leakage of a building envelope has a significant effect on the building's energy efficiency and making a building substantially air tight can make a considerable reduction in energy consumption and hence CO_2 production. In the UK, the adventitious leakage of buildings has received particular attention and a standard has been set in the form of a maximum value for the air permeability at a pressure of 50 Pa (Q_{50}) in Building Regulation (Building Regulation part L, 2010) [2]. The adoption of 50 Pa is a compromise, because leakage measurements at lower pressures are perceived to be subject to large errors arising from pressures generated by wind and buoyancy during the test. However, natural ventilation pressures are typically at an order of magnitude <50 Pa and therefore Q_{50} is not an ideal indicator of the infiltration potential of an envelope. In fact, a pressure difference of 4 Pa is commonly taken to be typical of natural ventilation and, ideally, the leakage at 4 Pa (Q_4) would be determined.

In order to test the leakage at 4 Pa directly, some investigations have been done on the basis of a pulse pressurisation technique by Roulet (Roulet, 1991) [3]. In early tests, a simple gravity-driven piston device was used to generate a pulse by Carey (Carey, 2001) [4]. Following this, a more practical version was devised by Cooper and Etheridge (Cooper, 2004) [5] in which the piston was driven by a supply of compressed air. Then, a quasi-steady piston pulse technique was developed by Cooper and Etheridge (Cooper, 2007) [6]. It has been demonstrated that direct measurement of Q_4 could give a much more accurate measure of the infiltration potential of an envelope than the current high-pressure technique in CIBSE (CIBSE 2000) [7]. The former could reduce the uncertainty by a factor of three or more, described by Cooper (Cooper, 2007) [8].

In this paper, a nozzle pulse pressurisation technique is explored, using a compressor nozzle to generate the pulse, so as to make the test rig more compact and portable. Unlike the piston pulse technique, which obtains the mass flow rate on the basis of the velocity of the piston, the present technique can obtain the mass flow rate from the compressor nozzle more directly and accurately.

2 PREVIOUS RESEARCH

Previous research carried out in measuring air tightness of buildings or ventilation systems can be classified into two categories, steady technique and unsteady technique, according to the way in which they approach the measurement. Steady technique does it by establishing a steady state pressure difference across the envelope and recording the induced leakage rate of airflow through the envelope.

“Blower door” is the most commonly used steady technique for measuring the building air tightness in construction industry. It typically uses a door fan to take the air in or out of the building to create a range of pressure difference (usually between 10Pa-60Pa) across the building envelope and the corresponding airflow rate of the fan is recorded. This technique was firstly used in Sweden around 1977 (Sherman 2004) [9]. The uncertainties existed in fan pressurization has been analyzed by Sherman [10], who introduced the uncertainties in measurements of airflow and pressure, and pointed out model specification errors may also contribute to the overall uncertainty in the estimation of 4Pa leakage. Cooper (Cooper, 2007) analysed and compared the uncertainties in Q_{50} measurement and Q_4 measurement and came to the conclusion that direct measurement of Q_4 can reduce the uncertainty by a factor of four.

According to the recent UK standard, the pressurisation at 50Pa has been widely recognised as the method for measuring the air permeability. It is selected at such a level because it is much higher than the level of pressure change caused by the wind and buoyancy effect so as to be able to neglect the errors caused by wind and buoyancy effects in the test. However, this method is a compromise due to the following deficiencies:

- The pressures it exerts on the building envelope are significantly higher than those experienced under natural conditions, which is typically around 4Pa. Therefore, it requires extrapolation from the measurement at high pressure level to calculate the leakage under natural condition. This adds uncertainty into the accuracy. The hydraulic characteristic of the opening is also changed by testing the pressure level which is much higher than the level given under natural conditions.

- It cannot make real-time leakage area measurements as the pressure and temperature vary with the weather condition, making the reading unstable and determination of the value unsure.
- The large volumes of air displaced by the fan can cause inconveniences such as large indoor temperature changes, which deviates from the thermal conditions in reality.
- The installation of blower door requires the removal or reposition of the window or door in the external opening where the blower door devices are installed and this changes the air leakage characteristic of the opening where the blower door is installed.
- One set of test can only obtain a single point result which is used to predict the leakage under natural condition using empirical value of C and n in the power law equation. This could cause non-negligible error to the prediction due to inaccuracy at low pressure. Multiple points test would give better accuracy than the single point test as it acquires the characteristic curve of the building air tightness (usually at an increment or decrement of 10 Pascal in the range of 10-60Pa). But it takes longer time to conduct and still needs to use the power law equation to extrapolate the leakage to that under natural condition.
- Such high level of pressure difference presents a risk of damaging the building structure or the fabric of the dwelling.
- The non-uniform pressure distribution cannot be avoided when large fan is used to pressurise buildings with large volume.

These deficiencies stand out more obviously when the measured buildings are in large scale because the required fan flow rate increases more or less in direct proportion to the volume of the building. The problem can be reduced by relaxing the requirement for 50 Pa down to 25 Pa or even lower, but another issue arises. The lower the pressure becomes, the less accurate the measurement is, due to being close to the pressure generated by buoyancy and wind. In order to control the error caused by this procedure within an acceptable range, the standard E779-03 (ASTM 2003) [11] recommends to only conduct the test when the product of the absolute value of indoor/outdoor air temperature difference multiplied by the building height, gives a result less than 200mºC. Hence, a preferable outside temperature, which is from 5ºC to 35ºC, is recommended in the standard to avoid any significant error caused by fan pressurisation. This also applies to the wind speed, which is under 2m/s preferably.

The unsteady technique, known as dynamic air tightness measurement technique, analyses the pressure-flow correlation when the building envelope is exposed to varying pressure. With unsteady techniques, the required information is determined indirectly by measuring the pressure response to a known disturbance (Carey 2001). It is able to accurately generate a known volume change to the building enclosure which makes the sources of error introduced by this technique less than the steady technique.

The key part of unsteady techniques is to pressurise the building enclosure or cavity to the desired pressure level by supplying air or extracting air in some occasion using pre-compressed air or outdoor air. Then the pressure is varied by devices like piston or left to decay naturally. During the pressure decay over a certain period of time, the relation between the air leakage rate and pressure difference across the building envelope is recorded. According to the pressurisation style, the unsteady technique includes three types, which are AC pressurisation, gradual pressurisation and pulse pressurisation, respectively. This paper introduces the pulse pressurisation method.

3 METHOD

3.1 Equipment and tests

The low pressure nozzle pulse technique generates an instant pressure pulse in the building enclosure by releasing compressed air into it via nozzle and the pressure pulse is left to decay naturally. Pressure decay is monitored and used to determine the building air tightness. This technique is worth attention due to the fact that relatively simple devices can be used to generate a pressure increase by adding a known volume of air to the enclosure. It only requires a volume change at the order of 0.004% to generate a pulse pressure in the order of 4 Pa. This technique can be implemented by releasing compressed air in a building enclosure to obtain the required pressure increase approximately.

A diagrammatic representation of the nozzle pulse generation unit is shown in Figure 1. It consists of a compressor with a 50 Litre tank and a maximum working pressure of 10 bar, a solenoid valve and a nozzle, shown in Figure 2.

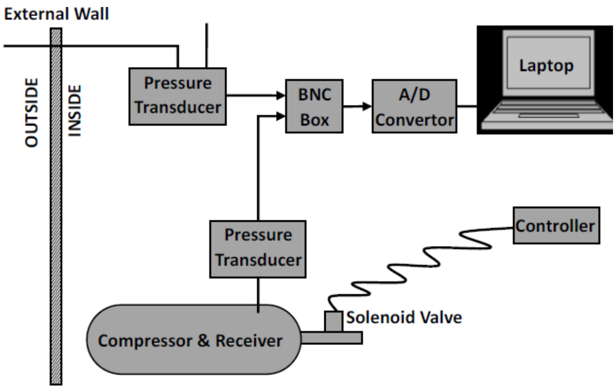

Figure 1 Schematic diagram of a single nozzle unit

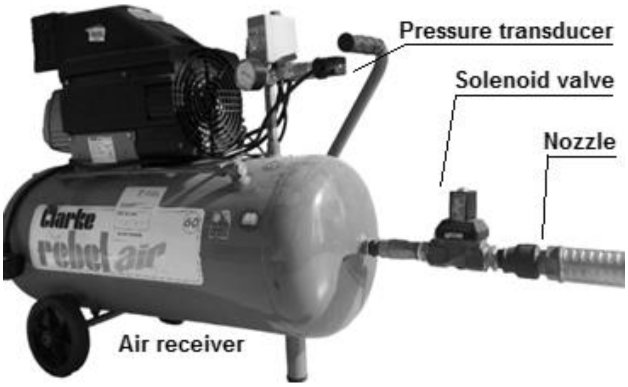

Figure 2 Set-up for one nozzle unit

The pulse generation is achieved by opening the solenoid valve for a short period. The pressure difference across building envelope and the pressure inside compressor tank are measured by differential pressure transducer and pressure transducer, respectively. At a sampling rate of 200Hz, the data is recorded by a laptop using a BNC box and A/D converter.

In the piston pulse technique, the pulse is generated by a certain volume of air which is rapidly released from a compressor tank via a solenoid valve. The solenoid valve is operated by an electronic controller which enables the air to be released in seconds. The released air is injected to the cylinder which is connected to the outlet of solenoid valve through a pipe, as shown in Figure 4. On receiving the released air from the compressor tank, the piston is moved in the cylinder due to the instant pressure increase. The piston is displaced by injecting air from the tank. A cable extension transducer (CET) is used to measure the instantaneous position of the piston. The displacement of the piston is recorded and used to calculate the volume of released air over the operating time.

The schematic diagram of piston pulse unit is presented in Figure 3. The electronic controller operates the solenoid valve by allowing it to be open for 1.5 seconds. The released air is injected to the cylinder and pushes the piston to the other side with a certain displacement. In this process, the instantaneous position of the piston, the internal pressure and external pressure are recorded by CET and differential pressure transducer respectively, and sent to the BNC terminal box via A/D converter card at a sampling rate of 200Hz.

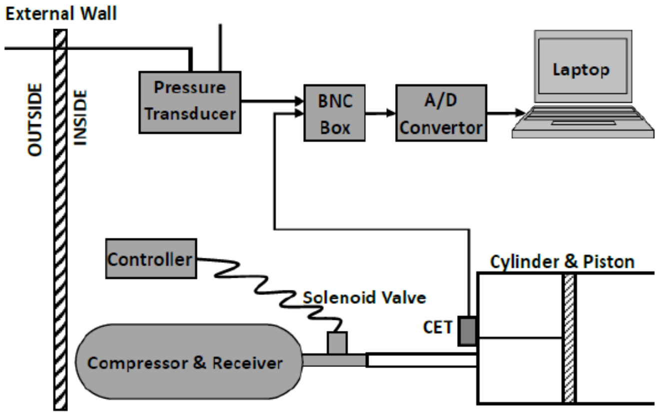

Figure 3 Schematic diagram of pulse technique using piston unit

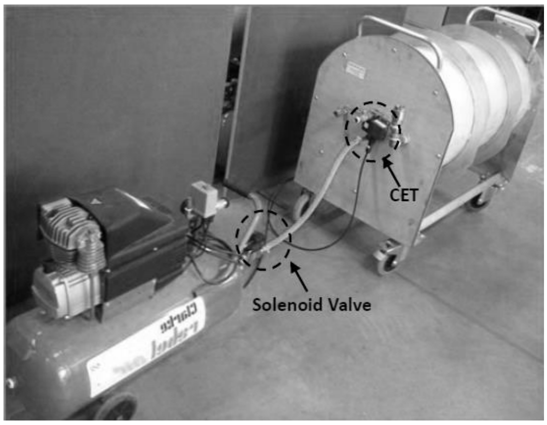

Figure 4 Installation of Pulse unit using Piston

Like the nozzle pulse unit, this technique is also designed to measure the building air leakage at low pressure. It only needs a few seconds to run the test and does not need to penetrate the building envelope. However, the airflow rate is measured indirectly through piston displacement which is driven by the injecting air from compressor tank. The recorded data of the airflow rate might be smaller than the actual value due to the unavoidable leakage at the small gap between piston and cylinder wall.

3.2 Theory

It has been shown previously that the pulse pressurisation technique creates a period of quasi-steady flow (Cooper, 2007) [6], which can be used to determine the leakage of a building. To determine it the volume flow rate of released air from compressor tank and pressure difference across the envelope must be obtained. The latter can be measured directly, but the former requires the use of a theoretical model for the nozzle technique. The air leakage rate is determined by using the gas law which correlates the time derivative of the pressure difference to a change in mass per unit time. CFD simulation (FLUENT 6.3 based on the finite volume method) has been used to numerically validate the model, specifically the following items:

1. The air pressure in the compressor tank is uniform.
2. The mass flow rate of released air via nozzle is calculated.
3. The air density in the building envelope is uniform and constant.

Due to the patent related issues, the detailed mathematical model is required to be confidential at the present stage and can’t be revealed in this paper.

3.3 Results

Two separate sets of tests have been conducted to compare the nozzle pulse with the piston pulse as well as the conventional steady state technique-blower door. The building used for the comparison between the nozzle pulse technique and the piston pulse technique has a regular cube shape with a volume of 136.1 m^3 and an envelope area of 185.8 m^2. The building used for comparing the nozzle pulse technique with the conventional blower door technique has a volume of 273.1 m^3 and an envelope area of 264.3 m^2.

Figure 5 shows the pressure pulses of five repeated tests. The curves are adjusted to take account of any variation of Δp due to wind during the pulse period, for the reason given by Cooper (Cooper, 2007) [8]. This is performed by fitting a curve to the data before and after the pulse, and then subtracting the curve from the raw data. In Figure 5 the wind effect is apparent as a variation of $\Delta p(t)$ before and after the imposed 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 6.

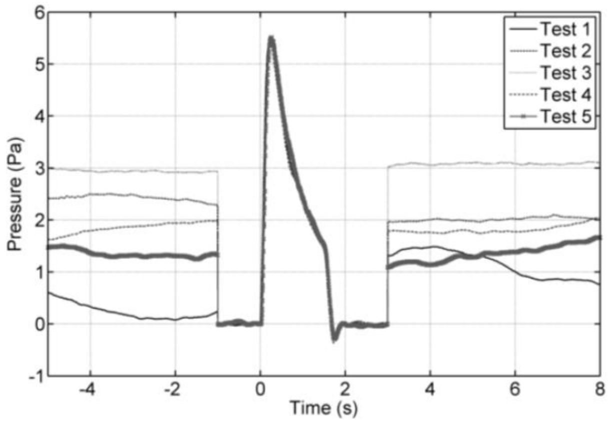

Figure 5 Five repeated pulse tests

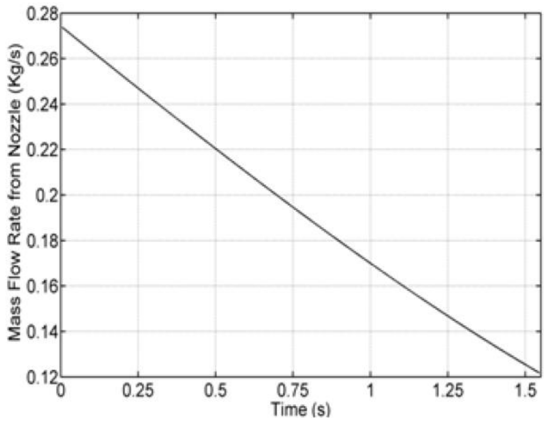

Figure 6 Transient mass flow rate of the air released from nozzle

The good repeatability of the technique can be seen in the plotted $\Delta p(t)\text{-}q(t)$ correlation curve, as shown in Figure 7, where the average Q_4 = 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 previously mentioned piston technique [6] was tested in the same test room under the same conditions and a comparison is shown in Figure 8. Good agreement appears and indicates that the nozzle technique is reliable for determining building leakage at low pressures. However, from Figure 8, it can be seen that the piston tests always give slightly lower values of leakage under the same pressure differences. During the piston test, there is an unavoidable leak of air from the narrow gap between the piston and cylinder wall. Therefore, the piston test may underestimate the $Q_p(t)$ slightly because it obtains $Q_p(t)$ indirectly from the velocity of the piston.

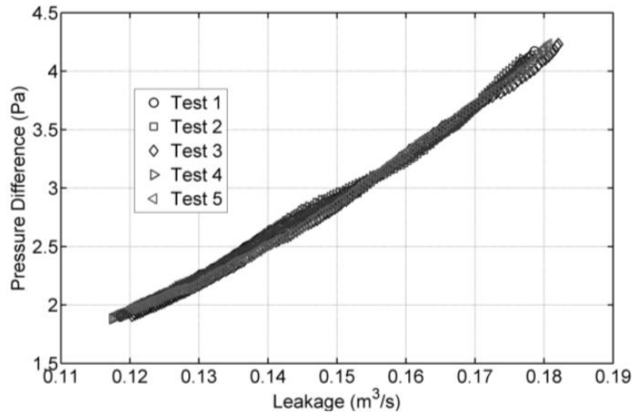

Figure 7 Nozzle test results

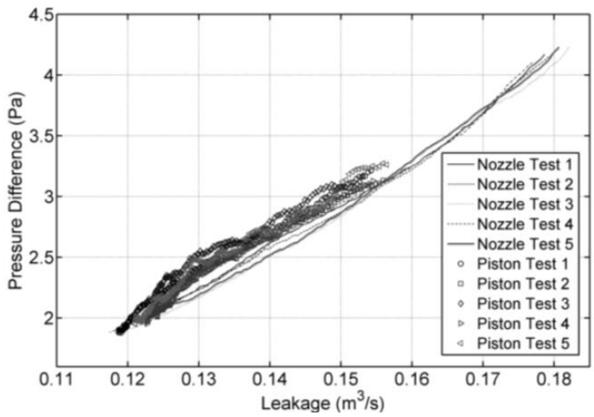

Figure 8 Comparison of nozzle and piston results

Blower door technique, which has been a globally adopted method for measuring airtightness (ISO 9972: 2006, EN 13829:2000), has been used to test the same property along with the nozzle pulse technique to see the correlation between the air leakage results given by these two techniques. There isn't a straightforward comparison between them because the air leakage rate is obtained under different pressure difference level. It is inappropriate to simply conclude the accuracy of one technique over the other. However, by plotting them together in a graph enables us to gain insight into the relation between them. As shown in Figure 9, the power law equation is used to fit the permeability-pressure obtained by both techniques. An accurate fit has been obtained because R^2 equals 0.9956, very close to 1. It gives a good indication that the low pressure pulse technique gives a good agreement with the blower door test results at high pressure (typically 50 Pa). In order to obtain the permeability at 4 Pa which is a more accurate indicator of building airtightness in reality, the airtightness characteristic obtained at high pressure by the conventional steady state technique need to be extrapolated down to 4 Pa. Extrapolating the air leakage rate at high pressure (typically 50 Pa) down to infiltration pressures (typically 4 Pa) has been shown by various authors, as summarized in the ASHRAE Fundamentals Handbook (2014) [12], to incur significant uncertainty. Murphy et al. (Murphy 1991) [13] and Cooper and Etheridge (Cooper 2007a) [8] have respectively shown experimentally and theoretically that the errors can be as high as +/- 40%.

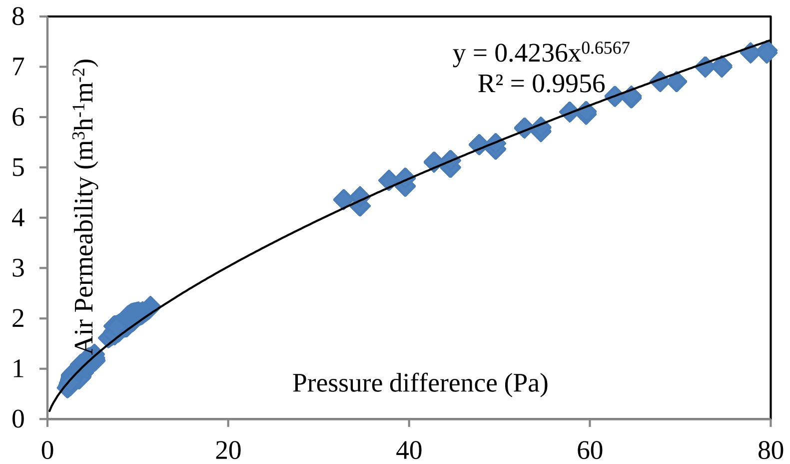

Figure 9 Power law curve fitting to the results obtained by both techniques

Moreover, at low pressure the power law equation shows a significant difference from the quadratic equation proposed by Etheridge (Etheridge 1998) [14], who believes the quadratic equation is more accurate and easier to use than the power law. The quadratic equation also gives a good representation of the flow characteristic of openings over a wide range of pressures. Etheridge pointed out that the power law can give a good fit but only over a limited range of pressures (Walker 1996) [15]. Compared to the power law, the quadratic equation should be used in preference for modelling the behaviour of adventitious openings due to the following facts:

- The quadratic equation was derived for developing flows and it does not rely on any significant length of fully developed flow within the opening. Meanwhile, it is unlikely that turbulence within the opening is a significant factor in adventitious openings (Etheridge 1996) [16].
- It is a simple matter to obtain the coefficients of the quadratic equation from existing data and the equation is easier to use compared to the power law.
- Compared to the power law, the quadratic equation relates to the unsteady behaviour of leakage openings and allows a consistent approach to be used for investigating the effects of changes to the geometry of an opening on both inertia and steady flow effects due to its reflection of the relationship between the equation and the geometry of the opening. Therefore, it can more closely represent the flow characteristics of adventitious opening.

4 CONCLUSIONS

A novel nozzle pulse pressurisation technique for determining the leakage of buildings at low pressures has been developed. The technique generates the pulse using a compressor and nozzle, so as to make the test rig compact and portable. A theoretical model for determining the pulse volume flow rate has been briefly introduced. The test results show that the present nozzle pulse technique can minimize the effects of wind and buoyancy force and has proven to be very repeatable and sensitive to small changes in leakage. In addition, a comparison between the nozzle test and piston test has been performed and indicates that the nozzle technique is more reliable, as some uncertainties in determining the volume flow rate can be avoided. In a power law fitting, a good agreement with the steady state test has been shown by the experimental results obtained in a test using the nozzle pulse technique. The mathematical representations for these two different techniques, that approach the measurement of building air tightness in different ways, are worth further experimental verifications and discussions.

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