

Field trialling of a new airtightness tester in a range of UK homes

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ABSTRACT

A low pressure ‘quasi-steady’ pulse technique for determining the airtightness of buildings has been developed and compared with the standard blower-door technique for field-testing a range of UK homes. The reported low pressure air pulse unit (APU) for determining the airtightness of buildings, through several development stages related to optimizing the algorithm, pressure reference and system construction, has been trialled under various testing and environmental conditions to assess its repeatability and accuracy. The houses, representative of the UK housing stock, mostly have high levels of air leakage; resulting in poor energy performance and imbalanced indoor environments. The results of the pulse techniques are also compared with the standard blower door technique. A comparison between the results obtained using the two techniques is presented, which indicates that the pulse technique is reliable for determining building leakage at low pressure. Repeatability of consecutive tests in identical conditions is found to be within $\pm 5\%$ of the mean, and within $\pm 8\%$ when tested under different environment conditions. It has also been shown that the correct tank/valve combination is necessary to achieve the required quasi-steady flow. Tests for accuracy using the addition of known openings have been conducted and shown that uncertainties are hard to eliminate for a clean comparison when testing conditions are not controlled.

KEYWORDS

Airtightness, Building leakage, Blower door, Pulse test, Steady pressurisation, Transient;

1. INTRODUCTION

The impact of infiltration as a consequence of poor airtightness can be considerable; research by Jones (Jones, 2015) predicts that unintended infiltration across the UK housing stock may be responsible for as much as 5% of total UK energy demand. However, the standard blower-door method used to measure airtightness, in some cases to predict infiltration, could arguably be considered a compromise and concerns about this technique have led to numerous attempts to find alternative ways of determining building airtightness; a partial selection of these attempts include AC techniques (repeated sinusoidal building volume change) by Sharples (Sharples, 1996), Siren (Siren, 1997), Sherman (Sherman, 1986), Watanabe (Watanabe, 1999), Nishioka (Nishioka, 2003) and Modera (Modera, 1989), gradual decay techniques by Granne (Granne, 2001) and Mattsson (Mattsson, 2007), acoustic techniques by Varshney (Varshney, 2013) and Card (Card, 1978), and pulse techniques by Carey (Carey, 2001), and Cooper (Cooper, 2004, 2007, 2007). However, to date, none of these attempts have led successfully to widespread use by the airtightness testing industry.

The paper introduces an alternative airtightness test approach, which is the further development of a low pressure pulse technique, described in a previous paper by Cooper (Cooper, 2007). Its historical development comprises of three versions, namely a gravity driven piston unit, a compressed air driven piston unit and most recently a nozzle unit. The last one, referred to herein as air pulse unit (APU), has been through several developmental stages related to optimizing the algorithm, pressure reference and system construction and has been simplified from a cumbersome and heavy unit into a more portable and quick-to-use

version. Across the stages of development, this technology has been used for airtightness testing in a range of UK homes. The tests that are reported herein include consecutive tests in identical conditions, tests with tanks of different sizes, tests done under different environmental conditions, comparison tests with the standard blower door unit and tests for accuracy. The aim is to assess the repeatability and accuracy of APU in the UK homes under normal testing conditions and through experience of use to assess the adaptability and practicality of APU.

2. DESCRIPTION OF THE PULSE TECHNIQUE

The pulse technique measures the building airtightness at low pressures by releasing a known volume of air into the test building over 1.5 seconds from an air tank to create an instant pressure rise within the test building and reach a “quasi-steady” flow, where the pressure variations in the building and tank are monitored and used for establishing a correlation between leakage and pressure. The method used for the adjustment, which accounts for changes in background pressure, is achieved by deducting background pressure from the raw data. This is described in a previous paper (Cooper, 2007). A typical pulse test measurement is shown in Figure 1. The readings of building pressure consist of three key stages, pressure variation during quasi-steady period and background pressures before and after the pulse.

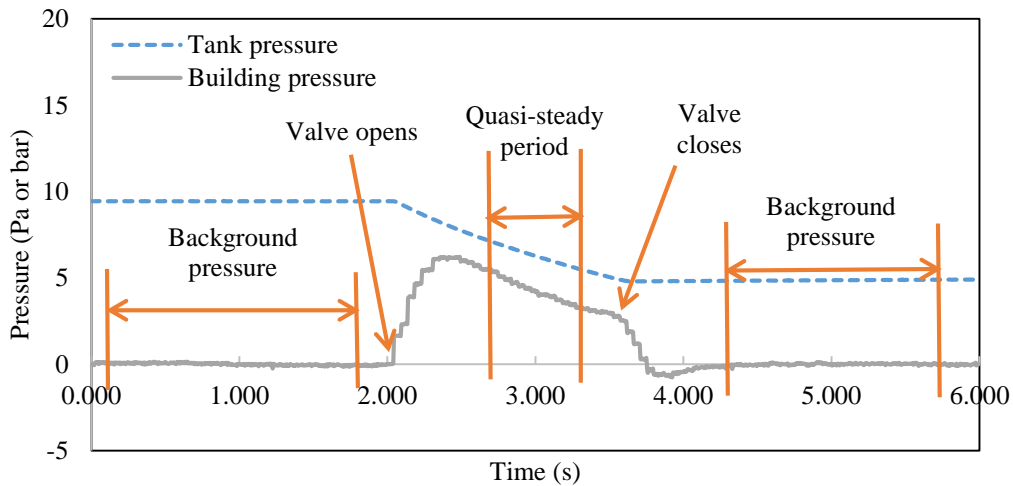


Figure 1: A typical pulse test by APU with 60 l tank (tank pressure measured in bar, building pressure in Pa)

The pulse technique measures the building leakage at various pressure levels similar to leakage measurements using as a blower door test process. However, it measures in a dynamic manner instead of taking each individual reading at a steady pressure level. The advantage of this technique is that the test can be done in 11-15 seconds. The challenge lies in the occurrence of the inertia effect of air that flows through openings, which then adds uncertainty to the measurement (Sharples et al 2005). This type of flow is addressed herein as unsteady flow. The percentage of unsteady flow in the quasi-steady period, isolated and evaluated using a momentum equation, is used to account for that inertia effect. The momentum equation is described by eq.(1).

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

The first two terms of the right hand side of eq.(1) correspond to the momentum change and surface friction. The third term accounts for the inertia effect of the air that flows through the opening.

The percentage of unsteady flow is defined as $\left| \rho_i \frac{l_e}{A} \frac{dq}{dt} \right| / (|aq\{t\}^2 + bq\{t\}| + \left| \rho_i \frac{l_e}{A} \frac{dq}{dt} \right|) \times 100\%$.

The quasi-steady period, which has been identified in previous research (Cooper 2007), lies in the latter part of the pulse. In order to allow “quasi-steady” flow to occur, the percentage of unsteady flow needs to be small enough compared to the other terms, usually less than a few percent. The full details of its mathematical representation and numerical validation are beyond the scope of this paper and will be reported elsewhere.

Figure 2 shows an example of percentage of unsteady flow of a typical pulse test. Within quasi-steady period, the percentage of the unsteady flow is less than 1%. Hence, it can be concluded that a quasi-steady flow has been achieved in this test.

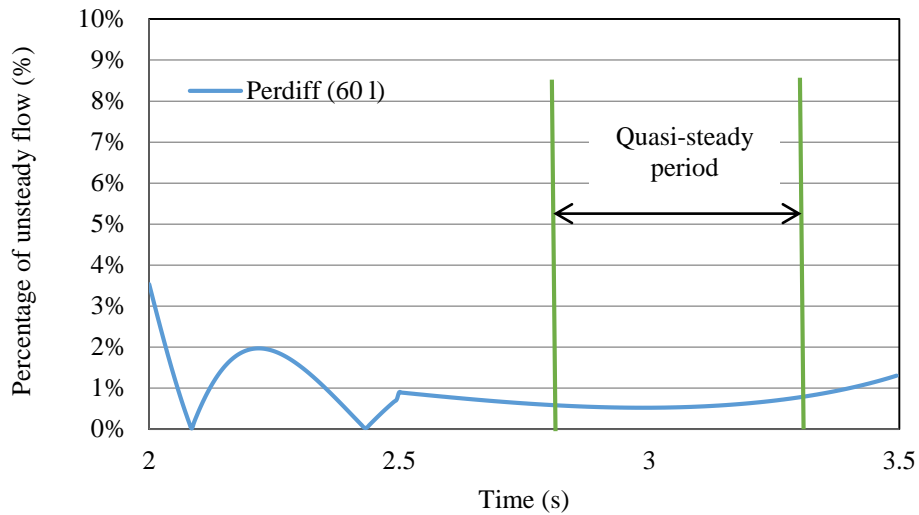


Figure 2: Percentage of unsteady flow of the pulse test in Figure 1

Figure 3 shows the results of pulse test and blower door test in the same log-log graph. They can be presented in the same format using a power law relationship.

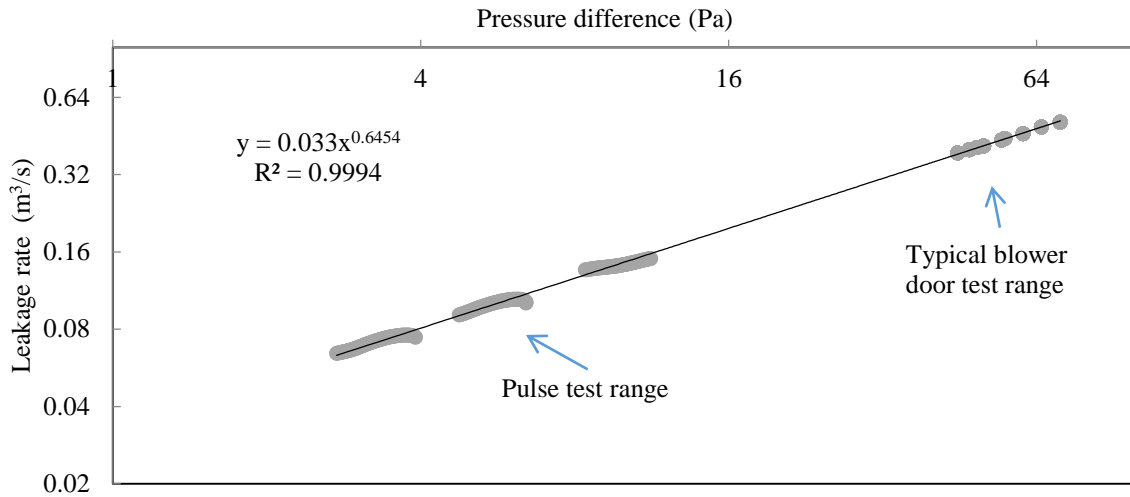


Figure 3: A log-log graph of pressure-leakage measured by APU and blower door in one building

2.1. Equipment

The full experimental setup of the APU with 50 l tank (APU-50) used for the tests is shown in Figure 4. Further details of the equipment, test procedure and proof of the pulse concept used for the APU can be found in previous papers (Cooper, 2007, 2014).

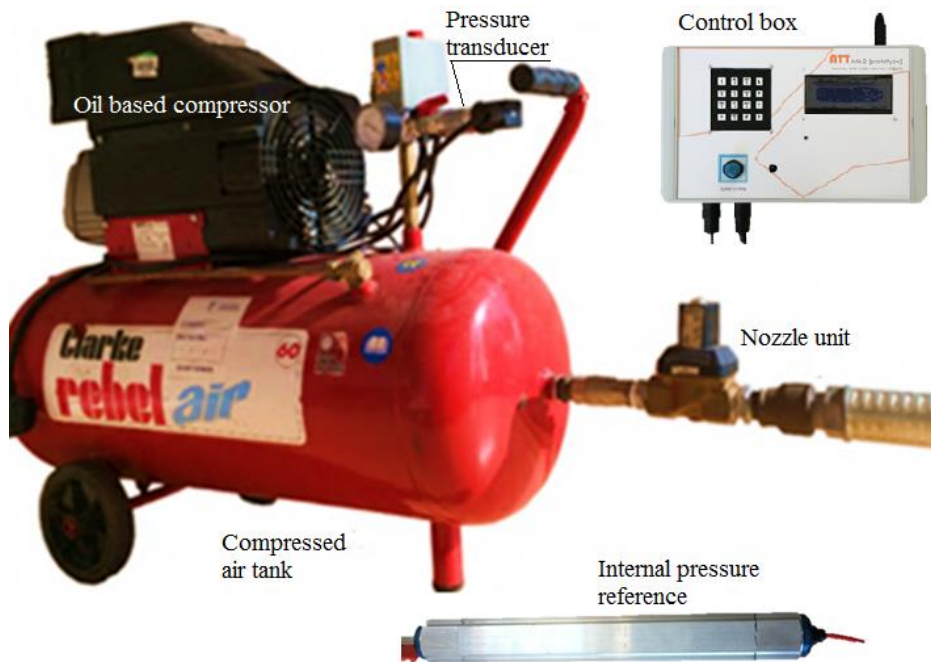


Figure 4: The Air Pulse Unit (APU-50) (not to scale)

APU-40, APU-60 and APU-80, are all later versions of the APU, which incorporate light weight composite tanks and oil free double piston compressors. These variants have also been used for comparison in the field trialling and are shown in Figure 5.



Figure 5: APU with 40 l, 60 l and 80 l tanks (not to scale)

The various tests performed throughout this investigation have used a number of different valve and tank configurations, the details of which can be seen in Table 1.

Table 1: Five different tank and valve configurations

| Configuration | '40l+1/2"' | '40l' | '50l' | '60l' | '80l' |
|------------------------------------|--------------|--------------|--------------|--------------|-------|
| Tank size (litres) | 40 | 40 | 50 | 60 | 80 |
| Valve size (BSP standard) (inches) | 1/2 | 3/4 | 3/4 | 3/4 | 3/4 |
| Unit size (L×W×H: mm×mm×mm) | 850×650×1140 | 1055×310×700 | 850×650×1170 | 850×650×1350 | |
| Approximate unit weight (kg) | 37.4 | 47 | 38.7 | 40.4 | |

At this stage it's worth noting the importance of the different unit capacities. The dwellings used in the tests were of different size (volume and surface area) and leakage level. It is the combination of these two aspects, which determines the applicable unit for the test. Similar to the blower door test, the correct choice of unit capacity is needed to obtain valid test results.

In order to assess the influence of unit capacity upon the percentage of unsteady flow, tests were performed in house No. 8 using all units as detailed in Table 1. Figure 6 shows the percentage of unsteady flow produced by the five different configurations in 2.5s-3.5s. All have the percentage of unsteady flow below 2.5% with '40l+1/2"', '60l' and '80l', less than 1%. Hence, all of the configurations have given negligible amount of unsteady flow, implying building leakage with reasonable accuracy can be measured by them all, but better accuracy is given by '40l+1/2"', '60l' and '80l'. Further analysis of this testing is given in section 4.2.

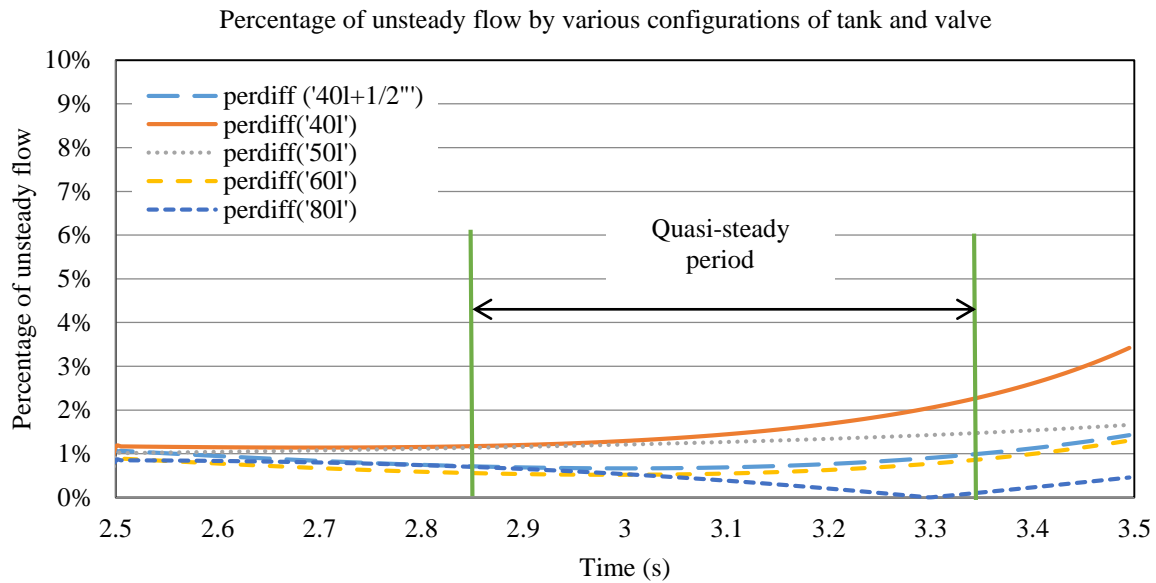


Figure 6: Percentage of unsteady flow of APU tests with different tank and valve configurations

3. CASE STUDY BUILDINGS

For validation and comparison purposes, the APU, alongside the standard blower-door unit, has been used to measure the airtightness of a range of UK homes, as shown in Figure 7. They are listed in the format of House Number-House type. The key parameters of the test houses are listed in Table 2.

Prior to testing, all the houses were prepared according to the UK's Air Tightness Testing and Measurement Association's Technical Standard L1 (ATTMA TSL1) for measuring air permeability of building envelopes in dwellings (ATTMA, 2010). The blower-door tests followed the guidelines set out in ATTMA TSL1 and the BS EN:13829 (BSI, 2001), which has been superseded by BS EN ISO 9972. As such, the results should be comparable with those carried out for demonstrating compliance with the UK Building Regulations. The tests were conducted with the fan mounted in a suitable doorway, as shown in Figure 8, and under both pressurisation and depressurisation. The mean air change per hour at 50 Pa (ACH_{50}) of each house is listed in Table 2 to indicate the leakage level of tested houses.





No.6-D



No.7-D



No.8-D



No.9-SD



No.10-SD



No.11-SD

Figure 7: Test houses (D: detached; SD: semi-detached; ET: end-terraced; MT: mid-terraced)

Table 2: Key parameters of the test houses

| House Number | Volume (m ³) | Age (years) | Position | Construction type | ACH ₅₀ (h ⁻¹) | Tank (l) |
|--------------|--------------------------|-------------|---------------|-------------------|--------------------------------------|----------|
| 1 | 157 | >100 | End-terrace | Solid wall | 12.1 | 40 |
| 2 | 196 | >100 | Mid-terrace | Solid wall | 10.5 | 50 |
| 3 | 196 | 10-100 | Semi-detached | Cavity wall | 9.0 | 50 |
| 4 | 213 | 10-100 | Semi-detached | Cavity wall | 6.6 | 50 |
| 5 | 203 | 10-100 | Semi-detached | Cavity wall | 6.8 | 50 |
| 6 | 230 | 10-100 | Detached | Cavity wall | 8.5 | 50 |
| 7 | 447 | 10-100 | Detached | Cavity wall | 8.2 | 50 |
| 8 | 343 | <10 | Detached | Modern SIP | 4.9 | 50 |
| 9 | 157 | 10-100 | Semi-detached | Solid wall | 9.0 | 50 |
| 10 | 371 | >100 | Semi-detached | Solid wall | 7.6 | 50 |
| 11 | 194 | 10-100 | Semi-detached | Cavity wall | 8.3 | 50 |

The homes are representative of those commonly found in the UK housing stock (Communities and Local Government). Six of them (No 1-5, 11) have been identified for retrofitting as part of the EU FP7 Holistic Energy Retrofit of Buildings (HERB) project and are tested both pre and post-retrofit, with only the pre-retrofit tests reported here.



Figure 8: The setup of blower-door at House No.4

Table 3: Q_{50} ($\text{m}^3/\text{h}\cdot\text{m}^2$) measured by blower door of the test houses

| House | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|-----------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| BD(+) | 9.82 | 8.1 | 8.79 | 6.68 | 6.15 | 7.97 | 8.79 | 5.68 | 8.72 | 7.83 | 7.87 |
| <i>n</i> | 0.578 | 0.629 | 0.54 | 0.558 | 0.611 | 0.638 | 0.599 | 0.654 | 0.541 | 0.623 | 0.638 |
| <i>r</i> ² | 0.997 | 0.991 | 0.989 | 0.990 | 0.952 | 0.998 | 0.996 | 0.997 | 0.990 | 0.998 | 1 |
| BD(-) | 9.3 | 9 | 8.54 | 6.21 | 6.19 | 6.89 | 8.79 | 5.61 | 8.84 | 7.5 | 8.01 |
| <i>n</i> | 0.611 | 0.755 | 0.566 | 0.63 | 0.583 | 0.496 | 0.612 | 0.623 | 0.621 | 0.622 | 0.681 |
| <i>r</i> ² | 0.997 | 0.991 | 0.992 | 0.987 | 0.981 | 0.989 | 0.998 | 0.999 | 0.996 | 1 | 0.999 |

According to ATTMA TSL1, the pressurisation test in house No.5 and depressurisation test in house No.6 should be treated as invalid tests due to a r^2 value less than 0.98 and a n value less than 0.5, respectively. This may have been caused by gusty wind conditions during the pressurisation test in house No.5 and a change in building fabric in house No.6 during the depressurisation test, such as opening of a window or loosened sealing.

4. TEST RESULTS

4.1. Repeatability of identical consecutive tests

Table 4 shows the results of 18 identical consecutive tests conducted in house No. 8 using the '401' unit (3/4" valve variant) performed over a single day. The outside condition at the time of testing was categorised as light wind. The pressure-leakage relationship is represented in the table by a standardised leakage rate at 4 Pa, or V_4 . The value is derived from a curve fit to data taken directly at the low pressures. The repeatability is good, with most of the tests falling comfortably within $\pm 5\%$ of the mean V_4 .

Table 4: V_4 of 18 repeated test runs in house No. 8

| Test ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Mean |
|----------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|-------------------------------|
| $V_4(\text{m}^3/\text{s})$ | 0.1166 | 0.1189 | 0.1219 | 0.1199 | 0.1182 | 0.1182 | 0.1241 | 0.1241 | 0.1148 | 0.1201 ($\sigma=0.0032$) |
| <i>RPD</i> (%) | -2.94 | -1.01 | 1.47 | -0.16 | -1.55 | -1.60 | 3.37 | 3.34 | -4.39 | |
| Test ID | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | |

| | | | | | | | | | |
|---------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| V_4 (m ³ /s) | 0.1232 | 0.1207 | 0.1231 | 0.1194 | 0.1160 | 0.1157 | 0.1252 | 0.1194 | 0.1227 |
| <i>RPD</i> (%) | 2.59 | 0.48 | 2.47 | -0.62 | -3.44 | -3.68 | 4.21 | -0.62 | 2.18 |

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

The graph in Figure 9 shows the internal pressure pulses generated for each of the 18 repeated tests in house No. 8, after adjustment to still-air conditions. Notably, it can be seen there is considerable variation in the valve closing time for these tests, however, this part of the pulse is not used for analysis and, importantly, has no impact on the quasi-steady period, which shows good repeatability. On investigation, the variation in these tests was identified as a faulty power supply, which was replaced and subsequent tests show good repeatability for the closing point.

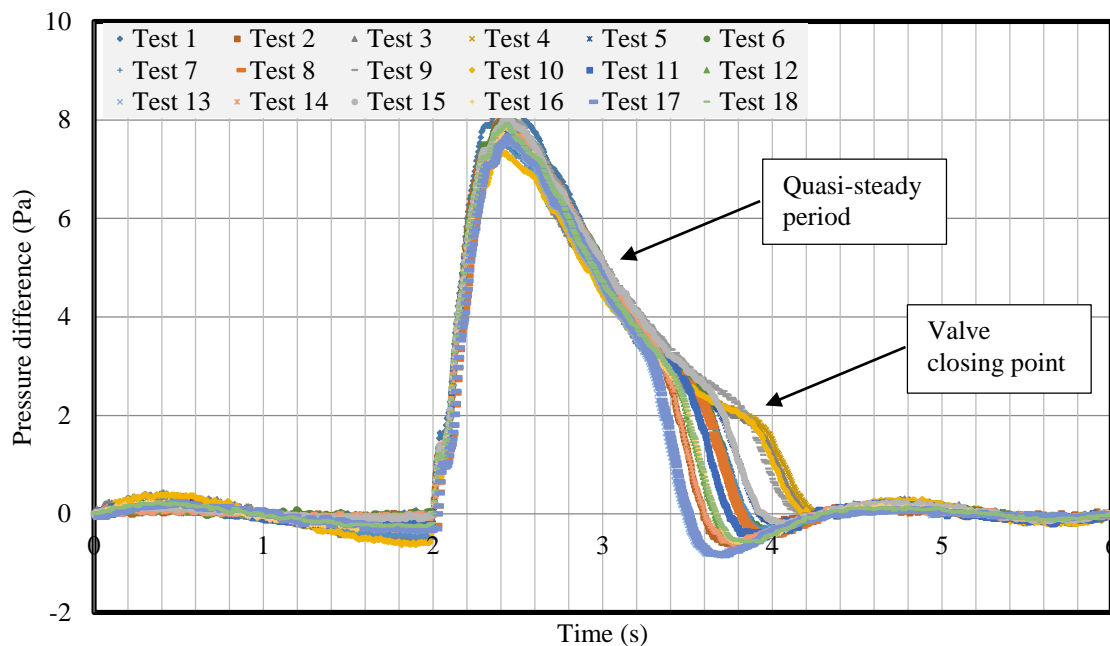


Figure 9: Adjusted internal pressure pulses from 18 repeated test runs in house No.8

4.2. Comparisons of different tank sizes in one building

Six repeated test runs, using different unit capacities were conducted under the same house and environment conditions. The pulse shapes of all the tests are shown in Figure 10 with one single test run using the ‘40l+1/2” variant plotted alongside the ‘40l’ unit. The six numbers in each group represent the test IDs generated chronologically at the time of testing. They agree well with each other in each group. Noticeably, one of the tests in the group of ‘60l’ has a short period of flat reading at the peak. This was caused by the drift of the reference pressure. However, the test results are not affected, because this part of the pulse curve is not used for analysis. Further tests didn’t experience any out-of-scale issues.

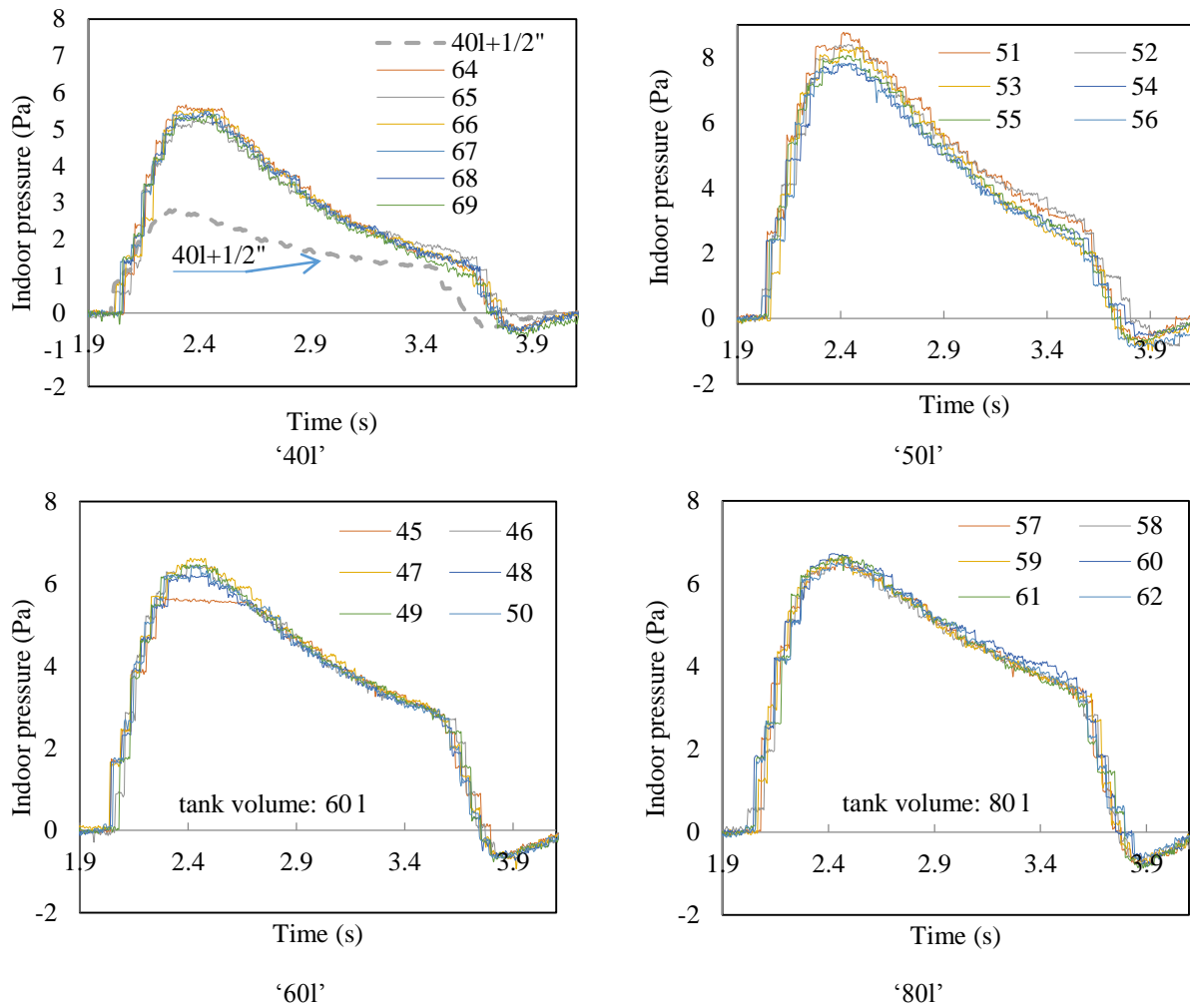


Figure 10: Repeated test runs using five configurations in house No.8

As would be expected, the pulse shape varies with tank size. A larger tank gives a steadier pressure drop than a smaller one with the same size valve. This agrees with the trend demonstrated in the theoretical analysis in Figure 6 that the larger tank gives lower percentage of unsteady flow.

Interestingly, the '50l' gives a bigger pulse magnitude than the other three; this may have been caused by the different outlet geometry of the '50l' steel tank leading to a different discharge coefficient of the outlet. Nevertheless, the quasi-steady flow is related with the pulse shape rather than with the magnitude.

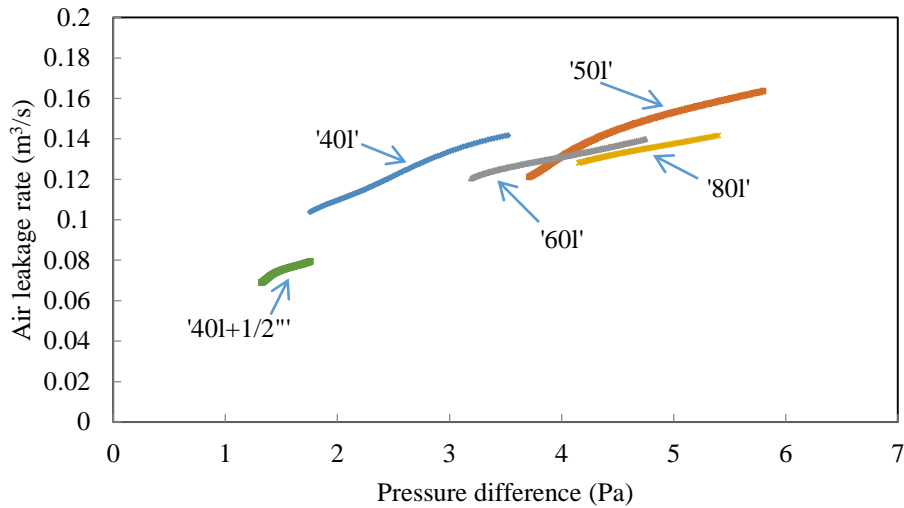


Figure 11: ΔP vs Air leakage rate of repeated tests using five configurations in house No.8

The “pressure-leakage” correlation curves measured by the tanks at low pressures are shown in Figure 11. The details, including Q_4 and its *RPD* of each test against the mean, are listed in Table 5, which indicates the repeatability is influenced by the tank size. A larger tank produces less unsteady flow and subsequently achieves better repeatability.

Table 5: Results of repeated tests using APU-40, APU-50, APU-60 and APU-80

| Tank | Test | 1 | 2 | 3 | 4 | 5 | 6 |
|------|--|--------|--------|--------|--------|--------|--------|
| 40 l | Q_4 ($\text{m}^3/\text{h}\cdot\text{m}^2$) | 1.6948 | 1.8774 | 1.7645 | 1.7706 | 1.7900 | 1.7183 |
| | <i>RPD</i> (%) | -4.62 | 5.66 | -0.69 | -0.35 | 0.74 | -3.29 |
| 50 l | Q_4 ($\text{m}^3/\text{h}\cdot\text{m}^2$) | 1.6296 | 1.5910 | 1.7618 | 1.7461 | 1.7318 | 1.7710 |
| | <i>RPD</i> (%) | -3.12 | -5.42 | 4.74 | 3.81 | 2.95 | 5.28 |
| 60 l | Q_4 ($\text{m}^3/\text{h}\cdot\text{m}^2$) | 1.5724 | 1.5872 | 1.5790 | 1.5984 | 1.5907 | 1.6028 |
| | <i>RPD</i> (%) | -0.75 | 0.18 | -0.33 | 0.89 | 0.41 | 1.17 |
| 80 l | Q_4 ($\text{m}^3/\text{h}\cdot\text{m}^2$) | 1.5738 | 1.5352 | 1.5543 | 1.5161 | 1.5877 | 1.5610 |
| | <i>RPD</i> (%) | 1.87 | -0.62 | 0.61 | -1.86 | 2.78 | 1.05 |

The average Q_4 of six repeated tests run by the four tanks are listed in Table 6. The 80 l tank gives lowest percentage of unsteady flow and hence should give most accurate measurement of them all. For this reason, the Q_4 measured by the 80 l tank is used as the reference for calculating the *RPD* of Q_4 measured by each tank and the results are listed in Table 6. The 60 l tank provides the closest measurement with increasing deviation as tank size reduces.

Table 6: Air permeability @4 Pa measured by tanks of 40 l, 50 l, 60 l and 80 l

| Tank | 40 l | 50 l | 60 l | 80 l |
|--|-------|-------|-------|-------|
| Q_4 ($\text{m}^3/\text{h}\cdot\text{m}^2$) | 1.770 | 1.705 | 1.589 | 1.588 |
| <i>RPD</i> | 11.5% | 7.4% | 0.1% | 0 |

Note: Q_4 represents the air permeability @4 Pa; *RPD* represents the relative percentage difference of Q_4 measured by the 80 l tank.

The pressure drops more quickly in a small tank than a large tank when the valve has the same size; hence a smaller valve ($\frac{1}{2}$ "") was trialled with the 40 l tank to compare with the $\frac{3}{4}$ ". The percentage of unsteady flow was reduced to the similar level with the '60l' as shown in Figure 6.

4.3. Repeatability of tests under different environmental conditions

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

The investigation was performed by conducting a number of tests on house No.8 over a period from September 2014 to September 2015. This period covered the summer, autumn and winter seasons, which provided test scenarios of various wind conditions and outdoor temperatures ranging from 7 °C to 21.5 °C. Due to the development of the prototype, three versions of prototypes with tanks of two different sizes have been used for these monitoring tests; the full details are listed in Table 7.

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

Table 7: Results of repeated tests under different environmental conditions using APU-50 and APU-80

| Date | Prototype | T _o / T _{in} (°C) | Wind speed (m/s) | Wind direction | Q ₄ (m ³ /h·m ²) | Sub-RPD (%) | RPD (%) |
|--|-----------------|--|------------------------|-------------------|---|----------------|------------|
| 09-Sep-14 | APU-50 (MK0) | 16/20 | 1.57 | SSE | 1.014 | 0.52 | 2.70 |
| 16-Sep-14 | APU-50 (MK0) | 17/20 | 0.9 | NE | 1.065 | 5.58 | 7.87 |
| 26-Nov-14 | APU-50 (MK0) | 7/21.8 | 0.23 | ENE | 1.002 | -0.67 | 1.49 |
| 12-Jan-15 | APU-50 (MK1) | 12/18 | 5.5 | W | 0.953 | -5.44 | -3.39 |
| Mean Q ₄ by APU-50 | | | | | 1.008 | | |
| 17-Aug-15 | APU-80 (MK2) | 21.5/23.5 | 0.45 | N | 0.985 | 1.23 | -0.24 |
| 24-Aug-15 | APU-80 (MK2) | 17/28.1 | 1.1 | NNE | 0.926 | -4.79 | -6.17 |
| 08-Sep-15 | APU-80 (MK2) | 17.8/18.1 | 0.23 | ENE | 0.997 | 2.46 | 0.98 |
| 10-Sep-15 | APU-80 (MK2) | 18/20.4 | 0.23 | E | 0.973 | 0.04 | -1.40 |
| 18-Sep-15 | APU-80 (MK2) | 19/23 | 0.6 | NNE | 0.963 | -0.99 | -2.42 |
| 21-Sep-15 | APU-80 (MK2) | 14/18.2 | 3.2 | SSE | 0.993 | 2.05 | 0.57 |
| Mean Q ₄ by APU-80 | | | | | 0.973 | | |
| Mean Q ₄ by APU-50 and APU-80 | | | | | 0.987 | | |

T_o and T_{in} are outdoor and indoor air temperature. Q₄ is the air permeability at 4 Pa, m³/h·m².

MK0, MK1 and MK2 represent different stages of prototype development.

Sub-RPD represents the RPD of Q₄ of each test in a sub-group of tests (i.e. tests done by APU-50 or APU-80) against the mean value of the sub-group. RPD represents the relative percentage difference of Q₄ of each test against the mean Q₄ of all tests given by APU-50 and APU-80 combined.

4.4. Comparison with the blower-door air leakage value at 4 Pa

The blower door measures air leakage across a high pressure range, typically 10-60 Pa, with the building air leakage typically presented at 50 Pa. The APU however measures air leakage at much lower pressure, typically a range of 1-20 Pa, with a building air leakage presented at 4 Pa. For a direct comparison of the two testing processes at the same pressure level, one of the tests has to be extrapolated and subsequently this introduces uncertainties to the results. In this report, the air permeability measured by both techniques is compared at 4 Pa and 50 Pa.

In order to predict Q_4 and Q_{50} , the power law equation $V = C\Delta P^n$ is used to make the extrapolation. In practice, the two techniques should not be expected to agree perfectly, due to the uncertainties in extrapolation, but they should be expected to follow the same trend from house to house.

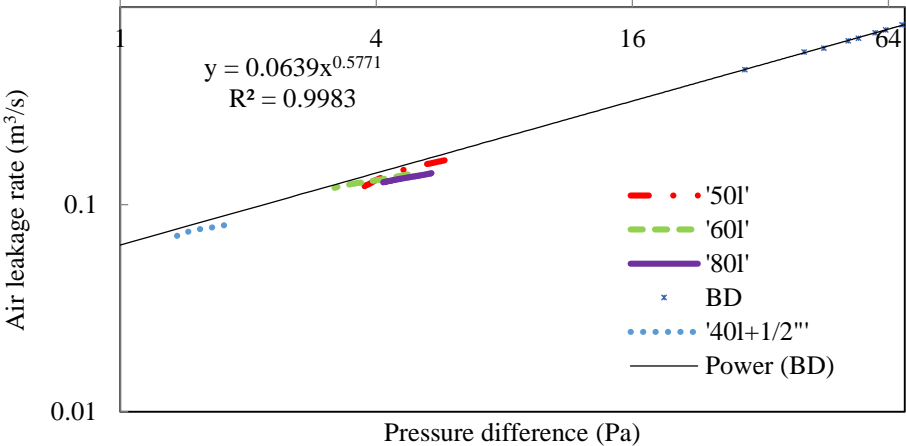


Figure 12: ΔP vs Air leakage rate of repeated tests using the pulse configuration 40l+1/2', 50l, 60l, 80l and blower door in house No.8 (BD in pressurisation mode)

Figure 12 shows the air leakage rate of house No.8 in a range of pressures measured by four different pulse configurations listed in Table 1 and a standard Minneapolis blower door Model-4 unit. For the blower door test, only the pressurisation mode is plotted to keep the consistence between the two techniques. A power law curve has been fitted to the blower door test result and extended down to the low pressures. The air leakage rate by the APU devices visually lies within a reasonable proximity of the prediction by the blower door but with slightly smaller values. More details are presented in Figure 13, which shows Q_4 predicted by the blower-door, $Q_4(BD)$ in both modes, and by the APU, $Q_4(APU)$. $Q_4(APU)$ is used as the reference for calculating the RPD considering it is measured directly at low pressure. The RPD between $Q_4(BD)$ and $Q_4(APU)$ lies within -17.1%-33% for the pressurisation and depressurisation combined, -17.6%-50.2% for the pressurisation only and -26.5%-28.3% for the depressurisation only.

Despite the wide range of difference between Q_4 given by both techniques, it shows most of them follow a similar pattern and interestingly the APU gives lower Q_4 values than the blower-door in 8 out of 11 houses (average of both modes and pressurisation mode), 9 out of 11 houses (depressurisation mode).

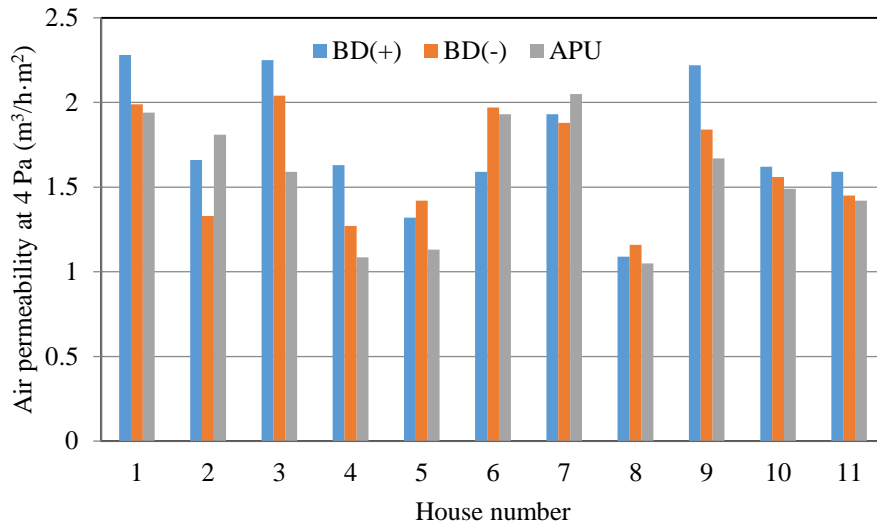


Figure 13: The permeability @4Pa, $Q_4(m^3/h \cdot m^2)$, predicted by the blower-door (BD) and measured by the APU (Pulse)

The exceptions are houses No.2, 6 and 7, where the APU gives a higher Q_4 than the blower-door. However, in house No.2, during the blower-door tests, it was noticed that the upper part of a loosely installed plasterboard panel, shown in Figure 14, opened when the blower-door depressurised the building, but not when it was pressurised. The thermographic image on the right side of Figure 14 shows the gap during depressurisation; the cool air being drawn into the building through the gap can be seen clearly by the plume surrounding the opening. The higher the pressure difference, the bigger the opening becomes and consequently the higher the leakage rate. Perhaps counterintuitively, this actually leads to a lower $Q_4(BD)$ for the depressurisation than pressurisation, due to the lower gradient of the relationship between leakage and pressure, as illustrated in Figure 15. In this graph, the annotated line represents the power law curve fit between the building leakage rate and pressure difference across the envelope if the position of the plasterboard were not affected by the induced depressurisation. It can be seen to make a significant difference at low pressure.

In practice, the effect is reduced by averaging the pressurisation and depressurisation results, but the impact would still be enough to explain the difference in the trend between house No.2 and the other houses. For house No.6, the ‘ n ’ value less than 0.5 indicates some change in building fabric in depressurisation test, which, although arguably could be avoided in some cases, reflects the potential issues the blower door technique faces in reality.



Figure 14: Photograph and thermographic image of a loosely installed plasterboard panel in house No. 2.

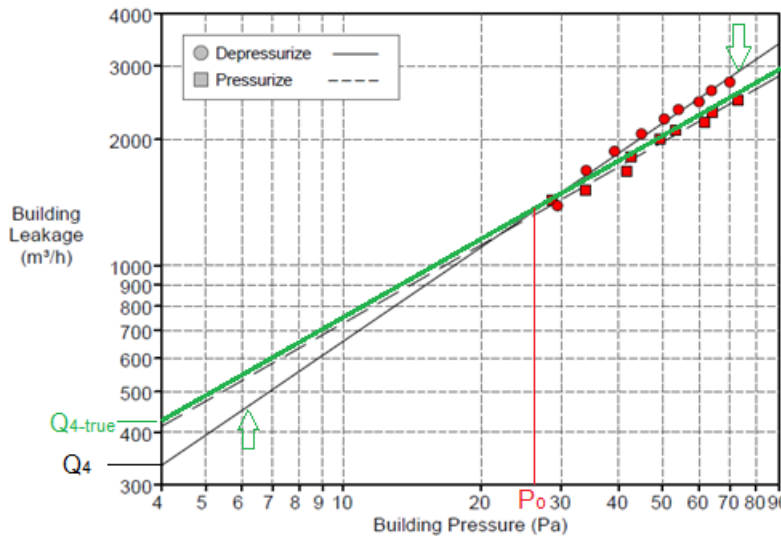


Figure 15: Logarithmic plot of blower-door test result for house No.2

4.5. Comparison with the blower-door measurement at 50 Pa

Figure 16 shows Q_{50} , predicted by the APU (Pulse) and measured by the blower-door (BD). The prediction is made based on three pressure exponent ' n ' values, including $n = 0.66$ (which has been regarded by previous research (Sherman 1986) to be representative of most typical residential dwellings), the value measured by blower door in pressurisation and depressurisation mode.

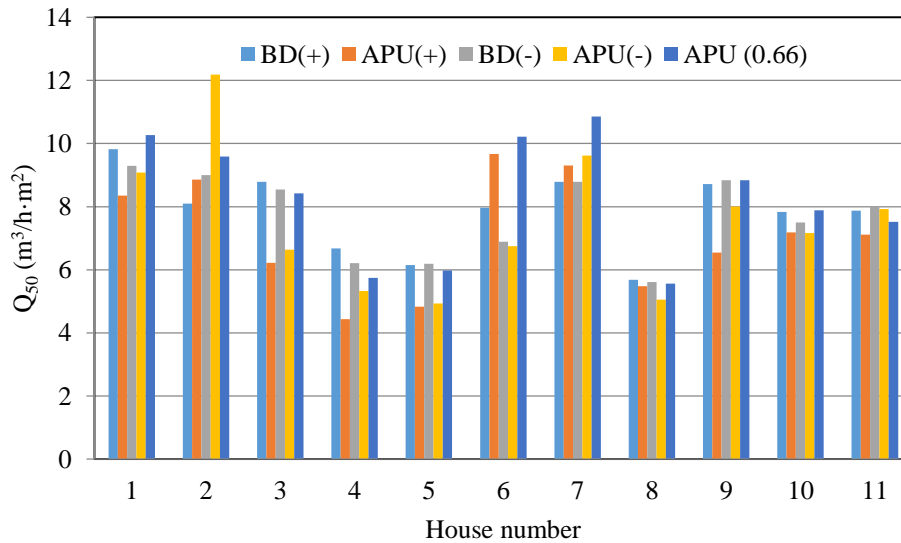


Figure 16: Q_{50} ($m^3/h \cdot m^2$), predicted by the APU (Pulse) and measured by the blower-door (BD)

Comparing with the Q_{50} (BD) measured in the same mode, the *RPD* of Q_{50} (APU) predicted by using the n value measured by blower door in pressurisation mode lies in -33.5%-21.3% and -22.2%-35.4% in the depressurisation mode. When $n = 0.66$, the predicted Q_{50} (APU) is -10.9%-37.6% out from the mean of Q_{50} (BD) measured by the blower door in both modes. The Q_{50} predicted in these ways doesn't provide sufficient accuracy for practical use. This is similar with the comparison at 4 Pa when the blower door test result is extrapolated down. Hence, significant error can occur in the extrapolation made between low pressure and high pressure. For the pulse technique, one of the major sources of error in extrapolation comes

from the lack of measurement over a wide pressure range, which for the future can be resolved by conducting stepped tests at various pressure levels.

4.6. Accuracy of measuring a known opening

A full explanation for why the APU mostly gives a lower permeability than the blower-door is beyond the scope of this paper, however a simple check to see which technique is more accurate at measuring an added known opening under natural conditions is presented.

A short sharp-edged circular orifice with a diameter of 100mm was added into a window in house No.8, as shown in Figure 17. Assuming an appropriate discharge coefficient of 0.61 therefore gives an effective leakage area of $4.7909 \times 10^{-3} \text{ m}^2$. Tests were conducted for both techniques with and without the added opening. The increase in leakage rate measured for both techniques was then converted to an effective leakage area and compared to the known opening, as shown in Table 8. It can be seen that the measurement made by the APU is relatively closer to the known effective area than the blower door measurement in most tests. However, these tests were conducted in natural conditions where environmental factors were uncontrolled; hence there is a level of uncertainty. Therefore, the tests in this section are only for obtaining preliminary insight in comparison of testing accuracy and no solid conclusion should be drawn from them. Laboratory tests, conducted under controlled conditions in a similar setup, have given a relative difference of around 2% between two techniques. The full details will be reported elsewhere.



Figure 17: Setup of the known opening in house No. 8

Table 8: Results of other known opening tests using the blower door and APU

| Test ID | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 | |
|------------|-----------|--------|--------|--------|--------|-------|
| BD | V4 | -2.9% | 16.5% | 146.7% | -71.3% | 27.1% |
| APU | V4 | 4.77% | -3.47% | 32.1% | 9.7% | 5.1% |

BD stands for blower door; V4 stands for air leakage rate @4 Pa pressure difference. For BD, V4 is extrapolated from blower door test. For APU, it is measured directly.

5. DISCUSSION OF PRACTICALITY AND ADAPTABILITY

Mobility

The field testing also assessed the practical aspects of using the APU for site testing. The houses used for the testing were of different UK housing stock typology and provided typical accessibility scenarios. The APU was found to be highly portable and easily manoeuvred by a single person. However, it is considered that problems could arise when the test dwelling is a new construction and an accessible route has not been established. In this instance, lifting

of the unit would be inevitable. With the unit being over 25 kg it is likely that the unit would need to be disassembled; a scenario not uncommon with the handling of the blower door.

Setup and teardown

The current APU does not require any detailed assembly on site and therefore is seen to be quick and efficient in terms of test setup, implementation and teardown. When on site, the unit requires charging to reach the necessary tank pressure, which is typically performed between 3 and 9 minutes depending on the tank size. Charging of the tank is autonomous, which allows the operative to perform simultaneously any obligatory sealing of vents within the building envelope prior to the test.

Operation and analysis

The APU provides an efficient process of operation, requiring only simple input of the tank and building parameters, with data analysis performed in a few seconds. The low pressure test also avoids some of the problems associated by pressurisation and depressurisation of a building envelope e.g. movement of poorly fitted building fabric due to large pressure differences, as seen in section 4.4.

Leakage pathway identification

A noticeable disadvantage of the current APU lies with its inability to identify the location of leakage pathways on its own. Present development includes investigating the appropriateness of locating the leakage pathways by identifying the type of leaks from data.

Potential application in non-typical buildings

As the pulse technique is self-contained, able to be automated and building integrity can be maintained during testing, the APU could be tailored for the buildings or spaces where a constant monitoring of airtightness is beneficial, such as clean rooms. It can also be tethered for testing large buildings where a more practical setup and test could be achieved due to its flexibility.

6. CONCLUSIONS

The low pressure air pulse unit (APU) has been field trialled for measuring the airtightness of a range of typical UK home types under various testing and environment conditions. Repeatability of multiple tests in identical conditions was found to be within $\pm 5\%$ of the mean and within $\pm 8\%$ for repeated tests under different environmental conditions. The tests with different tank size and valve configurations have indicated that an appropriate tank/valve configuration is important for achieving quasi-steady flow. A comparison with the standard blower door technique has shown the results measured in normal testing conditions are comparable with each other but an error up to $\pm 50\%$ could occur when an extrapolation has to be made between low pressure and high pressure. For the pulse technique, one of the major sources of error in extrapolation comes from the lack of measurement in a wider pressure range and this is considered an area for future improvement. Tests under natural environment conditions where the leakage was increased by a known amount showed uncertainties can't be eliminated for a clean comparison of the two techniques. The APU has been shown to provide practical advantages in relation to reliable, quick and efficient checking of the airtightness in existing UK homes.

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