Field trialling of a pulse 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 for determining the airtightness of buildings, through several development stages related to optimising 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 technique are also compared with the standard blower-door technique. The comparison 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 ±5% of the mean, and within ±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.

1. Introduction
The impact of infiltration as a consequence of poor airtightness can be considerable; research by Jones et al. (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 (BD) 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 and Thompson (1996), Siren (1997), Sherman and Modera (1986), Watanabe, Kobayashi, and Utsumi (1999), Nishioka et al. (2003) and Modera (1983), gradual decay techniques by Granne (2001) and Mattsson (2007), acoustic techniques by Varshney, Rosa, Shapiro, and Scott (2013) and Card, Sallman, Graham, and Drucker (1978) and pulse techniques by Carey and Etheridge (2001) and Cooper and Etheridge (2004, 2007a, 2007b). 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 and Etheridge (2007a, 2007b). 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 optimising 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 BD 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 rapidly releasing a known volume of air into the test building, thereby creating an instant pressure rise that quickly reaches ‘quasi-steady’ conditions. The pressure variations in the building and tank are monitored and used for establishing a correlation between leakage and pressure. 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. A method used for adjustment to still-air conditions, 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 & Etheridge, 2007a, 2007b).

The pulse technique measures the building leakage at various pressure levels similar to leakage measurements using a BD test process. However, it measures in a dynamic manner instead of taking each individual reading at a steady pressure level. The advantage of this approach is that the whole test can be done in 11–15 s. The challenge lies in the occurrence of the inertia effect of air that flows through openings, which adds uncertainty to the measurement (Sharples, Closs, & Chilengwe, 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

![Figure 1. A typical pulse test by APU with 60 l tank (tank pressure measured in bar, building pressure in Pa).](image-url)
inertia effect. The momentum equation is described by Equation (1).

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

The first two terms of the right hand side of Equation (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. For quasi-steady flow to occur, the inertia term in Equation (1) needs to be small compared to the other terms, typically less than a few percent. The percentage of unsteady flow is hence defined as

\[
\left| \frac{\rho_i \frac{l_e dq}{A dt}}{aq(t)^2 + bq(t) + \left| \frac{\rho_i \frac{l_e dq}{A dt}}{A dt} \right|} \right| \times 100\% \tag{2}
\]

The quasi-steady period, identified and expanded on in previous research (Cooper & Etheridge, 2007a, 2007b), lies in the latter part of the pulse. Figure 2 shows an example of percentage of unsteady flow of a typical pulse test. Within the quasi-steady period, the percentage of the unsteady flow is less than 1%; hence, it can be concluded that quasi-steady flow was achieved.

Figure 3 shows the quasi-steady results of pulse tests and a BD test in the same log–log graph. A power law curve fit shows good agreement between the two test types ($R^2 = 0.9994$).

![Figure 2](image1.png)

**Figure 2.** Percentage of unsteady flow of the pulse test in Figure 1.

![Figure 3](image2.png)

**Figure 3.** A log–log graph of pressure-leakage measured by APU and blower-door in one building.
2.1. Equipment

The early setup of the APU with a 50 l tank (APU-50) is shown in Figure 4. Further details of this equipment, the test procedure and the proof of concept used for the APU can be found in previous papers (Cooper & Etheridge, 2007a, 2007b; Cooper, Zheng, Gillot, Riffat, & Zu, 2014).

The APU-40, APU-60 and APU-80, shown in Figure 5, are all later versions of the APU used in trials. They incorporate lightweight composite tanks and oil free double piston compressors.

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.

At this stage it is 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 BD 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 from 2.5 s to 3.5 s. All have the percentage of unsteady flow below 2.5%, with ‘40 l + 1/2”’, ‘60 l’ and ‘80 l’ less than 1%. Hence, all of the configurations show negligible unsteady flow, implying building leakage with reasonable accuracy can be measured by them all, with better accuracy given by ‘40 l + 1/2”, ‘60 l’ and ‘80 l’. Further analysis of this testing is given in Section 4.2.

### Table 1. Five different tank and valve configurations.

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

![Percentage of unsteady flow by various configurations of tank and valve](image)

**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 BD unit, was 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 BD 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<sub>50</sub>) of each house is listed in Table 2 to indicate the leakage level of tested houses.

The homes are representative of those commonly found in the UK housing stock (Communities and Local Government, 2010). Six of them (No 1–5, 11) were identified for retrofitting as part of the
EU FP7 Holistic Energy Retrofit of Buildings (HERB) project and were tested both pre- and post-retrofit, with only the pre-retrofit tests reported here.

Table 3 lists the results of BD tests of the test houses under pressurisation and depressurisation mode. 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.

Table 3. $Q_{50}$ ($\text{m}^3/\text{h-m}^2$) 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 |
| $N$ | 0.578 | 0.629 | 0.54 | 0.558 | 0.611 | 0.638 | 0.599 | 0.654 | 0.541 | 0.623 | 0.638 |
| $r^2$ | 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 |
| $n$ | 0.611 | 0.755 | 0.566 | 0.63 | 0.583 | 0.496 | 0.612 | 0.623 | 0.621 | 0.622 | 0.681 |
| $r^2$ | 0.997 | 0.991 | 0.992 | 0.987 | 0.981 | 0.989 | 0.998 | 0.999 | 0.996 | 1 | 0.999 |
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 ‘40 l’ 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 ±5% of the mean $V_4$.

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 that there is a 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.

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 ($\sigma = 0.0032$) |
|---------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------------------------|
| $V_4$ (m$^3$/s) | 0.1166 | 0.1189 | 0.1219 | 0.1199 | 0.1182 | 0.1182 | 0.1241 | 0.1241 | 0.1148 | 0.1201                   |
| RPD (%)  | -2.94 | -1.01 | 1.47  | -0.16 | -1.55 | -1.60 | 3.37  | 3.34  | -4.39 |                         |

| Test ID | 10    | 11    | 12    | 13    | 14    | 15    | 16    | 17    | 18    |
|---------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| $V_4$ (m$^3$/s) | 0.1232 | 0.1207 | 0.1231 | 0.1194 | 0.1160 | 0.1157 | 0.1252 | 0.1194 | 0.1227 |
| RPD (%)  | 2.59  | 0.48  | 2.47  | -0.62 | -3.44 | -3.68 | 4.21  | -0.62 | 2.18  |

Note: Mean and RPD stand for ‘mean average’ and ‘relative percentage difference from mean’, respectively.
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 test run using the ‘40 l + 1/2”’ variant plotted alongside the ‘40 l’ 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 ‘60 l’ has a short period of flat reading at the peak. This was caused by the drift of the reference pressure going out of the scale of the pressure transducer. However, the test results are not affected, because this part of the pulse curve is not used for analysis. Further tests did not experience any out-of-scale issues.

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, where a larger tank gives lower percentage of unsteady flow.

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

The ‘pressure-leakage’ correlation curves measured by the tanks at low pressures are shown in Figure 11. The details, including \( Q_4 \) and its relative percentage difference (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.

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. The 60 l tank provides the closest measurement with increasing deviation as tank size reduces.

The pressure drops more quickly in a small tank than a large tank when the valve has the same size; hence a smaller valve (1/2”) was trialled with the 40 l tank to compare with the 3/4”. The percentage of unsteady flow was reduced to the similar level with the ‘60 l’ 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, on the building airtightness measurement. A recent study (Remi & Leprince, 2016) shows that 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 to 21.5 °C. Due to the development of the prototype, three versions of prototypes with tanks of two different sizes have been used for these monitoring tests; the full details are listed in Table 7.

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

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

The BD 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.

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

| Tank  | Test | Q_4 (m³/h·m²) | RPD (%) |
|-------|------|---------------|---------|
| 40 l  | 1    | 1.6948        | -4.62   |
|       | 2    | 1.8774        | 5.66    |
|       | 3    | 1.7645        | -0.69   |
|       | 4    | 1.7706        | -0.35   |
|       | 5    | 1.7900        | 0.74    |
|       | 6    | 1.7183        | -3.29   |
| 50 l  | 1    | 1.6296        | -3.12   |
|       | 2    | 1.5910        | -5.42   |
|       | 3    | 1.7618        | 4.74    |
|       | 4    | 1.7461        | 3.81    |
|       | 5    | 1.7318        | 2.95    |
|       | 6    | 1.7710        | 5.28    |
| 60 l  | 1    | 1.5724        | 0.75    |
|       | 2    | 1.5872        | -0.62   |
|       | 3    | 1.5790        | 0.61    |
|       | 4    | 1.5984        | -1.86   |
|       | 5    | 1.5907        | 2.78    |
|       | 6    | 1.5770        | 1.05    |
| 80 l  | 1    | 1.5738        | 1.87    |
|       | 2    | 1.5352        | -0.62   |
|       | 3    | 1.5543        | 0.61    |
|       | 4    | 1.5161        | -1.86   |
|       | 5    | 1.5877        | 2.78    |
|       | 6    | 1.5610        | 1.05    |

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

| Tank  | Q_4 (m³/h·m²) | RPD (%) |
|-------|---------------|---------|
| 40 l  | 1.770          | 11.5%   |
|       | 1.705          | 7.4%    |
|       | 1.589          | 0.1%    |
|       | 1.588          | 0%      |
| 50 l  | 1.7183         | 1.49    |
|       | 1.065          | 7.87    |
|       | 1.014          | 2.70    |
| 60 l  | 1.014          | 0.52    |
|       | 1.065          | 5.58    |
|       | 1.014          | 2.70    |
| 80 l  | 1.014          | 0.52    |
|       | 1.065          | 5.58    |

### 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 (m³/h·m²) | Sub-RPD (%) | RPD (%) |
|--------------------|-----------|---------------|------------------|----------------|---------------|-------------|---------|
| 9 September 2014   | APU-50 (MK0) | 16/20         | 1.57             | SSE            | 1.014        | 0.52        | 2.70    |
| 16 September 2014  | APU-50 (MK0) | 17/20         | 0.9              | NE             | 1.065        | 5.58        | 7.87    |
| 26 November 2014   | APU-50 (MK0) | 7/21.8        | 0.23             | ENE            | 1.002        | -0.67       | 1.49    |
| 12 January 2015    | APU-50 (MK1) | 12/18         | 5.5              | W              | 0.953        | -5.44       | -3.39   |
| Mean Q_4 by APU-50 |           |               |                  |                | 1.008        |             |         |
| 17 August 2015     | APU-80 (MK2) | 21.5/23.5     | 0.45             | N              | 0.985        | 1.23        | -0.24   |
| 24 August 2015     | APU-80 (MK2) | 17/28.1       | 1.1              | NNE            | 0.926        | -4.79       | -6.17   |
| 8 September 2015   | APU-80 (MK2) | 17.8/18.1     | 0.23             | ENE            | 0.997        | 2.46        | 0.98    |
| 10 September 2015  | APU-80 (MK2) | 18/20.4       | 0.23             | E              | 0.973        | 0.04        | -1.40   |
| 18 September 2015  | APU-80 (MK2) | 19/23         | 0.6              | NNE            | 0.963        | -0.99       | -2.42   |
| 21 September 2015  | 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        |             |         |

**Note:** $T_o$ and $T_in$ are outdoor and indoor air temperature. $Q_4$ 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 $Q_4$ 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 $Q_4$ of each test against the mean $Q_4$ of all tests given by APU-50 and APU-80 combined.
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 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 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 BD Model-4 unit. For the BD test, only the pressurisation mode is plotted to keep consistency between the two techniques. A power law curve has been fitted to the BD 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 BD but with slightly smaller values. More details are presented in Figure 13, which shows \( Q_4 \) predicted by the BD, \( Q_4 \) (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.

\[
y = 0.0639x^{0.5771} \\
R^2 = 0.9983
\]

Figure 12. \( \Delta P \) vs. air leakage rate of repeated tests using the pulse configuration 40 l + 1/2", 50 l, 60 l, 80 l and blower-door in house No. 8 (BD in pressurisation mode).

Figure 13. The permeability at 4 Pa, \( Q_4 \) (m\(^3\)/h·m\(^2\)), predicted by the blower-door (BD) and measured by the APU (pulse).
Despite the wide range of difference between $Q_4$ given by both techniques, it shows that most of them follow a similar pattern and interestingly the APU gives lower $Q_4$ values than the BD in 8 out of 11 houses (average of both modes and pressurisation mode), 9 out of 11 houses (depressurisation mode).

The exceptions are house Nos. 2, 6 and 7, where the APU gives a higher $Q_4$ than the BD. However, in house No. 2, during the BD tests, it was noticed that the upper part of a loosely installed plasterboard panel, shown in Figure 14, opened when the BD 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 was not affected by the induced depressurisation. It can be seen to make a significant difference at low pressure. Interestingly, Johnston and Lowe (2006) found this issue to be one of the factors that affected the building airtightness.

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.
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 the depressurisation test, which, although arguably could be avoided in some cases, reflects the potential issues that the BD technique faces in reality.

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 BD. The prediction is made based on three pressure exponent ‘n’ values, including $n = 0.66$ (which has been regarded by previous research (Orme, Liddament, & Wilson, 1994) to be representative of most typical residential dwellings), the value measured by BD in pressurisation and depressurisation mode.

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 BD 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 BD in both modes. The $Q_{50}$ predicted in these ways does not provide sufficient accuracy for practical use. This is similar with the comparison at 4 Pa when the BD 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 BD 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 100 mm 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 $4.7909 \times 10^{-3}$ 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 BD 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.

5. Discussion of practicality and adaptability

5.1. 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 BD.

5.2. 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.

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      | $V_4$  | $-2.9\%$ | $16.5\%$ | $146.7\%$ | $-71.3\%$ | $27.1\%$ |
| APU     | $V_4$  | $4.77\%$ | $-3.47\%$ | $32.1\%$ | $9.7\%$ | $5.1\%$ |

Note: BD stands for blower-door; $V_4$ stands for air leakage rate @4 Pa pressure difference. For BD, $V_4$ is extrapolated from blower-door test. For APU, it is measured directly.
5.3. Operation and analysis

The APU provides efficient 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.

5.4. 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.

5.5. 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 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 ±5% of the mean and within ±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 BD technique has shown that the results measured in normal testing conditions are comparable with each other but an error up to ±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 that uncertainties cannot 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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