Pulse tests in highly airtight Passivhaus standard buildings

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ABSTRACT

Due to the minimal energy requirement, the Passivhaus standard has been widely recognised and adopted to deliver low carbon buildings. To achieve this standard, the thermal and physical properties of the building envelope have to meet a stringent criteria. It has set out the highest requirement for the building airtightness, which requires the envelope to achieve an air change rate less than 0.6 h-1 when the building is subject to a pressure difference of 50 Pa. Building an envelope with such a high level of airtightness can be extremely challenging. However, with careful planning and conscientious implementation, the required airtightness can be achieved regardless of the construction method. Airtightness measurement plays an important role in the journey of delivering Passivhaus standard building as it allows the construction team to quality check its airtightness at the key construction stages and ensures its airtightness level meets the predefined target.

Current standard approach for measuring building airtightness is the conventional steady fan pressurisation method, which establishes a pressure difference across the envelop by drawing air out of or blowing air into the building and measures the corresponding air flow rate to establish the leakage-pressure correlation. Differing from this steady-state method by maintaining the building integrity and delivering a dynamic measurement, the novel Pulse technique releases compressed air from an air tank into the building over a short period of time and simultaneously measures the building and tank pressure responses to achieve the same purpose but at low pressures. Alongside the steady method, the Pulse technique has been used to measure the airtightness of 11 Passivhaus standard properties to understand its feasibility in measuring highly airtight buildings. The results show that measured airtightness ranged from 0.29 $m^3/h/m^2$ @50Pa to 1.19$m^3/h/m^2$ @50Pa. The average difference between the two methods at 4Pa is 0.0003 $m^3/h/m^2$ @4Pa (11%) and 0.12 $m^3/h/m^2$ @50Pa (18%) at 50Pa when using the Power Law as a means of extrapolation.

KEYWORDS

Passivhaus; Airtightness; Steady fan pressurisation; Low pressure Pulse technique

1 INTRODUCTION

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 (Cooper et al, 2020). This in turn creates an instant pressure rise within the test building which is then followed by a steady pressure drop where the pressure variations in both 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.

A typical pulse test measurement is shown in Figure 1. The readings of building pressure consist of three key stages; background pressure before the pulse, pressure variation during a quasi-steady period (where the percentage of unsteady flow caused by flow inertia is negligible), followed by background pressures after the pulse. In a standard pulse setting, the solenoid valve opens after sampling the background room pressure for 2s, releasing compressed air from the air tank into the test building for 1.5 seconds, closing again at 3.5s. This Pulse setting allows a similar pulse shape to be obtained in most domestic buildings (typically with airtightness levels >1.5 $m^3/h/m^2$ @50pa).

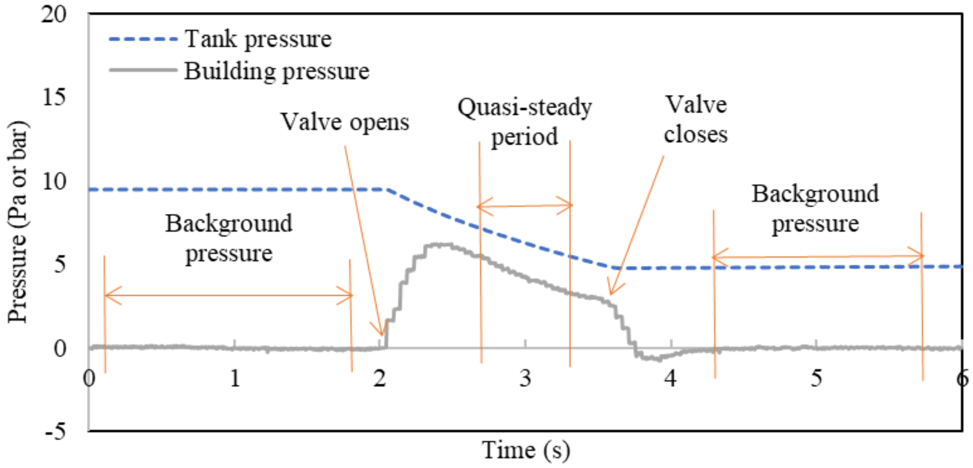

Figure 1: A typical pulse test by a pulse unit with 60 l tank (tank pressure measured in bar, building pressure in Pa) [Cooper et al, 2019]

When testing much more airtight dwellings, such as Passivhaus standard buildings, the pulse shape formed is different from that shown in Figure 1. It is seen that either the test property over-pressurises and saturates the room pressure sensor (±25Pa range) or there is a delay in the pulse peak leading to insufficient recording of the quasi-steady period in a standard pulse test setting. Figure 2 shows two typical examples of Pulse shapes experienced in highly airtight buildings.

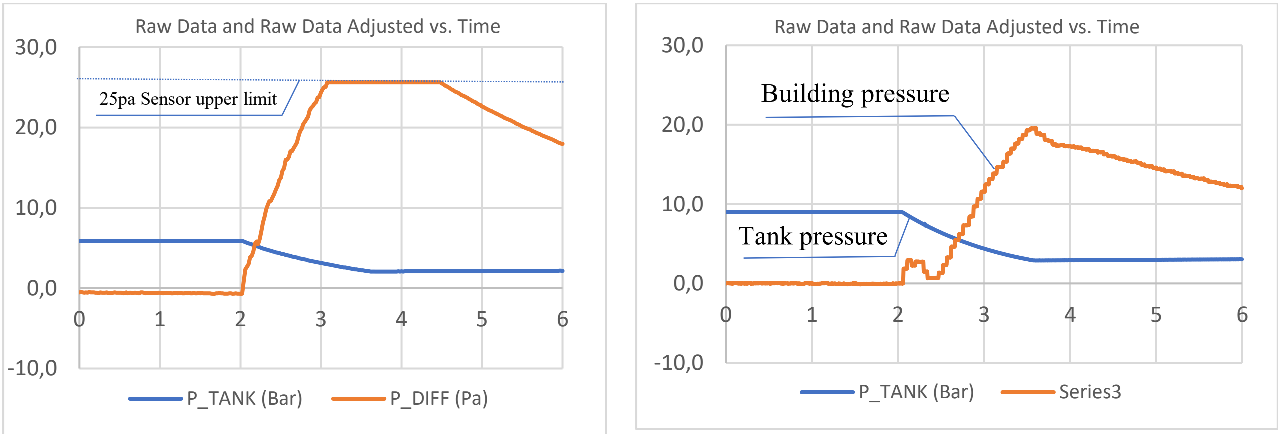

Figure 2: Example of unsuccessful pulse tests in highly airtight dwellings

The pulse shapes formed in each of the above tests are very different from that shown in Figure 1. In all such cases, we note it takes longer for the pressure pulse to reach the peak point with the rate of decay also becoming much more drawn out. This variation in shape is what has caused calculation failures for very airtight dwellings in early versions of the Pulse technology;

with timings becoming out of sync and the crucial 'quasi-steady' part of the measurement process not reliably captured. Acknowledging that this issue limits the operating range of the technology and would preclude the use of Pulse in Passivhaus buildings.

With a considerable body of data now at our disposal from our earlier field trials, an assessment of the impact of any proposed changes was able to be evaluated prior to undertaking any further field trial work. The two main changes made to the Pulse measurement device as a result of our investigations have been as follows:

- <u>Air receiver volume and air outlet nozzle orifice</u>
  A major hardware change based on the field trial data has been to reduce the size of the air receiver and to constrain outlet flow by fitting it with a reduced sized outlet nozzle. This has the effect of creating a similar flow regime to the original 60 litre air receiver unit but simply reduces the overall capacity. This in turn makes the unit physically smaller and quicker to charge whilst also improving performance in the lower pressure range without considerably compromising the upper range. Conversely, where Pulse was found to be out of range in more leaky properties, two 60 litre tanks (120L) would often be excessive and thus two 40 litre tanks (80L) also provides a good balance at this upper end, with further air receivers able to be added as required with no upper limit.

- <u>Valve opening time made adjustable</u>
  The second major change has been for the software to now enable a user adjustable valve opening duration. Much in the same way that a blower door fan operative may constrain flow by adding orifice plates to restrict the fan flow, a user of the Pulse system may now prolong the valve open period to ensure that a wider range of flowrate and Pulse shape is created. The logic here is that with the valve open for longer, the room pressure sampling duration is prolonged whilst the air flow rate of the Pulse itself also spans a wider range. Our revised user guidance is that standard Pulse valve open duration should be 1.5s for properties with a design airtightness of greater than 2 $m^3/h/m^2$ @50pa and for a 4 second valve opening recommended when testing properties with a design air tightness of less than 2 $m^3/h/m^2$ @50pa.

With each of these changes assessed, next was to build an updated test unit and to evaluate the performance of the updated solutions across a range of airtight dwellings. For this exercise we specifically sought certified Passivhaus dwellings wherever possible.

2 METHODOLOGY

A total of 11 properties have been tested over the period October 2019 to January 2020 with a measured airtightness range of 0.48ACH @50Pa to 1.27ACH @50Pa (or 0.07ACH @4Pa to 0.38ACH @4Pa) and building volume ranging from 94m^3 to 637 m^3. Here we specifically sought to measure as wide a range of property types as possible, ranging from new build certified Passivhaus properties through to Enerphit retrofits.

Figure 3: MVHR inlet and exhaust sealed both internally and externally

Each of the properties were prepared according to the building preparation method 2 in BS EN ISO 9972 (BS EN ISO 9972), i.e. all intentional openings were sealed, the doors and windows closed, traps filled. Mechanical ventilation with heat recovery unit is switched off and sealed with care, as shown in Figure 3.

During the blower door testing, the junction where the blower door frame and door frame meet was also sealed up using airtight tapes to minimize any leakage around the blower door unit itself, as shown in Figure 4; a problem experienced in past lab-based testing of very airtight enclosures where agreement between the fan method and Pulse was being investigated (Zheng et al, 2022).

Figure 4: Blower door fan setup in a doorway and taped from inside

Complete 40L Pulse setup

Window mounted blower door

Figure 5: Blower door fan setup in window opening

Once set, a blower door fan test was first carried out by a qualified test engineer in both pressurisation and depressurisation mode. The door fan was then packed away and pulse tests using the latest hardware and software configuration were carried out immediately afterwards in each property under the same building preparation. However, some of the buildings were tested using a window-mounted blower door unit by another onsite test engineer where the pulse test was performed with the blower door unit installed to minimise the envelope difference caused by the unit installation, as shown in Figure 5.

Table 1: Summary of tested dwellings

Property ID	Type	Envelope area (m^2)	Volume (m^3)	Setup Notes
001	Detached house	374	450	Fan mounted in canvas in the doorway, frame taped
002	Detached house	681	636.6	
003	Detached studio	138	94	
004	3-storey terraced house	344.4	360.6	
005	2-storey terraced house	244.4	186	
006	3-storey terraced house	344.4	322.5	
007	Flat	222.2	182.8	Carried out whilst door fan remained mounted in place of the window
008	Flat	213.4	125	Fan mounted in fixed panel within window opening and taped
009	Flat	123.2	138.3	
010	Flat	116.8	123.3	Carried out whilst door fan remained mounted in place of the window
011	0	344.2	322.5	Fan mounted in canvas in the doorway, frame taped

For the purposes of this report, all results are presented as volume of air leakage per hour per m^2 of floor area ($m^3/h/m^2$). This is in contrary to Passivhaus conventions where results are more commonly reported on the basis of volume of air leakage per hour per m^3 of building volume (ACH). The differences between the test methods reported herein are however relative and apply regardless of the result being cited as Air Permeability (AP) or Air Change per Hour (ACH). The main findings from the testing may be summarised as follows:

Table 2: Pulse results at 4Pa compared to blower door fan results extrapolated down to 4Pa:

Property ID	N4 (BDT)	N4 (Pulse)	N4 Difference	N4 Percentage Difference
001	0.11	0.09	0.02	27%
002	0.14	0.13	0.01	3%
003	0.11	0.10	0.01	10%
004	0.13	0.20	-0.07	33%
005	0.05	0.06	0.01	7%
006	0.12	0.14	-0.01	10%
007	0.08	0.09	-0.01	9%
008	0.04	0.05	0.01	7%
009	0.11	0.11	0.00	2%
010	0.11	0.11	0.00	0%
011	0.36	0.31	0.05	17%

Here, the Pulse device results are presented based on an air leakage measurement directly at 4Pa with the Power Law used to extrapolate a 50Pa door fan result to estimate what its leakage measure would have been if run at the same 4Pa pressure difference. The average difference across the dataset between the blower door fan technique and Pulse is -0.0003 $m^3/h/m^2$ @4Pa. In absolute percentage terms this equates to 11% which is broadly in line with expectation given the ISO 9972: 2015 declared measurement uncertainty of the fan method ±10%, Pulse measurement uncertainty at ±5% and the further uncertainty associated with Power Law extrapolation.

Overall, the agreement between the two methods at low pressure is encouraging, especially given the challenge of sealing the fan method in an opening to a level comparable to that of the opening itself being closed (as it is for Pulse testing). This strong level of agreement is thought to be largely down to our specific attempts to take blower door fan leakage measurements across as wide a pressure range as possible to minimise extrapolation uncertainty. For instance, most of our fan results tested down to as low as 15-20pa, minimising the level of extrapolation required.

Of the notable outliers, property 004, goes to highlight that extrapolation isn't without its challenges. Here, the blower door fan pressurisation and depressurisation curves are on different paths, thus making the extrapolation down to 4Pa unreliable.

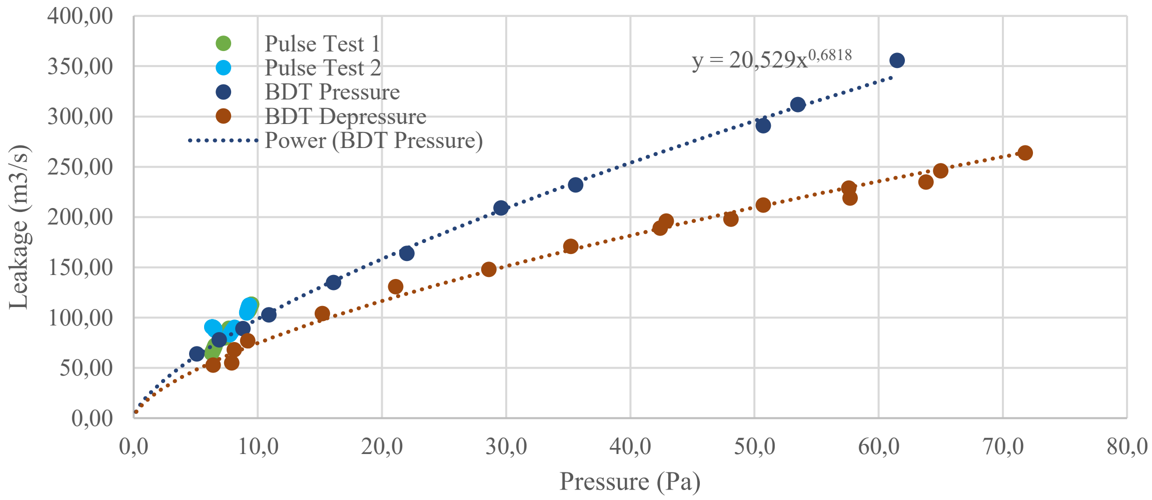

Figure 6: Property 004 blower door fan test power law extrapolation, with poor agreement between the pressurisation and depressurisation curves

Table 3: Blower door fan results at 50Pa compared with Pulse results extrapolated up to 50Pa

Property ID	N50 (BDT)	N50 (Pulse)	N50 Difference	N50 Percentage Difference
001	0.57	0.74	-0.17	22%
002	0.80	1.34	-0.55	41%
003	0.78	0.66	0.12	18%
004	0.73	0.82	-0.08	10%
005	0.45	0.50	-0.05	10%
006	0.78	0.74	0.04	6%
007	0.46	0.56	-0.10	17%
008	0.29	0.40	-0.11	28%
009	0.67	0.63	0.04	6%

010	0.65	0.80	-0.14	18%
011	1.19	1.53	-0.33	22%

In the above table, the blower door has been used to measure the air leakage directly at 50Pa and the Power Law has been used to extrapolate a 4Pa Pulse result to estimate what its leakage measure would have been if run at the same 50Pa pressure difference. The average difference across the dataset between the blower door fan technique and Pulse is -0.12 $m^3/h/m^2$ @50Pa. In absolute percentage terms this equates to 18% which again is broadly in line with expectation given the measurement uncertainty of the fan method ±10%, Pulse measurement uncertainty of ±5% and the uncertainty associated with Power Law extrapolation.

Note how the agreement between the two methods is notably worse when extrapolating in this upward direction. This is largely because there is absence of a known point at the high-pressure end for the leakage curve to follow while the origin provides a known point for the leakage-pressure curve to follow when extrapolation is done the other way around [Zheng et al, 2022]. There is also hydraulic dissimilarity between low pressure and high pressure, whereby it is widely recognised that n exponent values measured at low pressure and high pressure can be notably different, thus further compounding the uncertainties.

What is also particularly notable in the above table is the lack of a clear linear relationship between the results i.e. the fan method sometimes measuring the building to be more leaky, sometimes not. Factors beyond just extrapolation which can cause such uncertainty includes:

- Mounting of the blower door fan itself causing a door or window to potentially provide more or less leakage than the actual closed unit. In all of our test cases, the fan frame was actively sealed in place of a window or door opening in order to try to minimise this variation between its results and the Pulse test.
- Changes in weather conditions when conducting the comparative tests, particularly wind.
- Unreliable or inconsistent seating of window and door seals, especially in test scenarios where operatives were coming and going as part of the testing works. This was a particular issue with case P001 where all results are valid and repeatable but there is weak agreement between the two techniques.

Table 4: Blower door fan results at 50Pa:

Property ID	AP50 (BDT Pressurisation)	AP50 (BDT Depressurisation)	BDT Difference	BDT Percentage Difference
001	0.54	0.60	-0.06	11%
002	0.84	0.75	0.09	11%
003	0.75	0.81	-0.06	8%
004	0.86	0.61	0.24	28%
005	0.47	0.44	0.04	8%
006	0.83	0.73	0.10	12%
007	0.45	0.47	-0.02	5%
008	0.30	0.27	0.03	10%
009	0.66	0.68	-0.02	3%
010	0.67	0.64	0.04	5%
011	1.11	1.27	-0.16	14%

Although limited repeat-testing was conducted across the test properties due to time constraints, blower door fan testing was carried out in both pressurisation and depressurisation mode for all properties as required under standard Passivhaus conventions. Whilst neither the UK Building

Regulations nor the referenced approved procedure stipulate which mode is to be used for compliance reporting purposes, it is widely acknowledged that there can be variation between the two approaches for a wide range of reasons. Across these particular highly airtight 11 test cases, the average difference between the blower door fan pressurisation and depressurisation tests is 0.02 $m^3/h/m^2$ @50Pa. In absolute percentage terms this equates to 11% which is similar to the level of agreement seen between the two different test techniques and is again very close to expected levels of measurement uncertainty cited by the ISO 9972: 2015 standard. The closest match between both modes was 3% and biggest discrepancy was 28%. This isn't to discredit the fan method, rather to simply highlight that when working to measure such fine margins, even the established incumbent method has a level of associated uncertainty before further compounding with extrapolation.

3 CONCLUSIONS

Overall, the revised and updated Pulse unit has been tested across 11 very airtight dwellings, demonstrating an ability to reliably measure such properties just as effectively as the incumbent fan-based technique. There are however an inevitable number of challenges associated with working at this extreme end of the airtightness spectrum, especially when trying to compare methods whereby neither measure directly at the same pressure difference and where the fan technique must penetrate the envelope as part of the test procedure. Nevertheless, the average difference between the two methods at 4Pa is 0.0003 $m^3/h/m^2$ @4Pa (11%) and 0.12 $m^3/h/m^2$ @50Pa (18%) at 50Pa. Therefore, it seems reasonable to make the following conclusions:

- Pulse can measure very airtight dwellings just as reliably as the steady fan technique.
- Contrary to the previous BTS field trial-based recommendation of using a fixed conversion factor of 5.3 to convert a Pulse 4Pa result to a 50Pa air leakage value (Zheng and Cooper et al, 2019), this testing of very airtight dwellings illustrates how use of such a single number is not reliable across the full spectrum of buildings. The same applies to the divide-by-20 rule applied to all blower door fan results, as previously reported. Our recommendation having now conducted these additional tests is that the power law equation as detailed in the proposed updated TM23 document is used for all extrapolation purposes.
- Measurement of very airtight buildings is fraught with challenges, regardless of the measurement method being used. As ATTMA have already demonstrated with its TSL4 guidance document, expert preparation, specialist equipment and perfect conditions are all required in order to get a remotely reasonable assessment of air leakage from the technologies available on the market today. This, we believe, should be recognised by UK Government by continuing to support innovation in this field and by encouraging the development of further guidance and best practice.

4 ACKNOWLEDGEMENTS

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5 REFERENCES

Cooper E., Zheng X.F., Wood C.J. Numerical and experimental validations of the theoretical basis for a nozzle based pulse technique for determining building airtightness. Build. Environ. (2020), p. 107459

Cooper E., Zheng X.F., Wood C.J., et al. Field trialling of a Pulse airtightness tester in a range of UK homes. Int. J. Vent., 18 (1) (2019).

BS EN ISO 9972. Thermal performance of buildings-Determination of air permeability of buildings-Fan pressurisation method. BSI Standards Publication (2015)
Zheng X.F., Hsu Y.S., Pasos A.V., Smith L., Wood C.J. A progressive comparison of the novel pulse and conventional steady state methods of measuring the airtightness of buildings. Energy and Buildings, Vol. 261, 15 April 2022, 111983.
Zheng X.F., Cooper E., Zu Y.Q., Gillott M., Tetlow D., Riffat S., Wood C.J. Experimental Studies of a Pulse Pressurisation Technique for Measuring Building Airtightness. Future Cities and Environment (2019), 5(1): 10, 1–17.