Pulse tests in very air tight Passivhaus standard buildings

A report for:

The Ministry of Housing, Communities and Local Government

The Department for Business, Energy and Industrial Strategy

The Standard Assessment Procedure Scientific Integrity Group

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Testing carried out jointly by the University of Nottingham and Build Test Solutions
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Context

In December 2018, Build Test Solutions submitted a large evidence base to the Ministry of Housing, Communities and Local Government (MHCLG) concerning the performance of the low pressure pulse air leakage measurement technique. A major part of this submission was a report summarising the findings from a field trial where Pulse was tested alongside the incumbent blower door fan method across a large representative sample of 108 different dwellings.

Within this sample of 108 homes were five Passivhaus standard properties where the Pulse testing was declared as unsuccessful. This was due to the air release from Pulse causing an uncharacteristic pressure rise and decay curve due to the air tight nature of the building fabric, thus preventing the original algorithm from being able to reliably determine an air leakage rate.

MHCLG have subsequently launched the Future Homes Standard consultation concerning Part L and Part F of the Building Regulations for new dwellings. This proposes that the low pressure pulse technique becomes a recognised method for the purposes of compliance testing. The consultation does however also suggest that the method is actively limited by the regulations for testing dwellings where the designed air permeability is between 1.5 $m^3/h/m^2$ @50pa and the maximum allowable airtightness value in Approved Document volume 1. Our rationale for these limits not being imposed include:

1) A standalone Pulse unit is able to reliably measure in the sub 1.5 $m^3/h/m^2$ @50pa range and the units may be easily tethered to test buildings of all sizes and leakage levels. This report presents the findings from tests carried out across 11x certified Passivhaus properties where air leakage is considerably lower than 1.5 m3/h/m2 @50pa. More importantly is that technological advancement of the Pulse technique will continue and thus imposing limits within the regulations themselves feels cumbersome and inappropriate.

2) Trained, certified air tightness testers should themselves have the competence to select the most appropriate technology. Fan testing at very low leakage levels is in itself a specialist exercise, with 'mini low flow fans' used for such applications, often mounted in wooden panels fitted to windows due to the inability to get a good airtight seal in a doorway. The existence of the ATTMA TSL4 standard, written specifically for such reasons demonstrates this.

This short report specifically seeks to present our most recent field trial work, demonstrating that development steps made now enable the pulse method to reliably test in the sub 1.5 $m^3/h/m^2$ @50pa range.

Introduction

The pulse technique measures the building airtightness directly at low pressures by releasing a known volume of air into the test building over 1.5 seconds from an air receiver. This in turn creates an instant pressure rise within the test building which is then followed by a pressure drop where the pressure variations in both the building and receiver 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 flow from the air receiver is equal to flow out from the building fabric), 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 receiver 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 the majority of domestic buildings (typically with airtightness levels >1.5 $m^3/h/m^2$ @50pa).

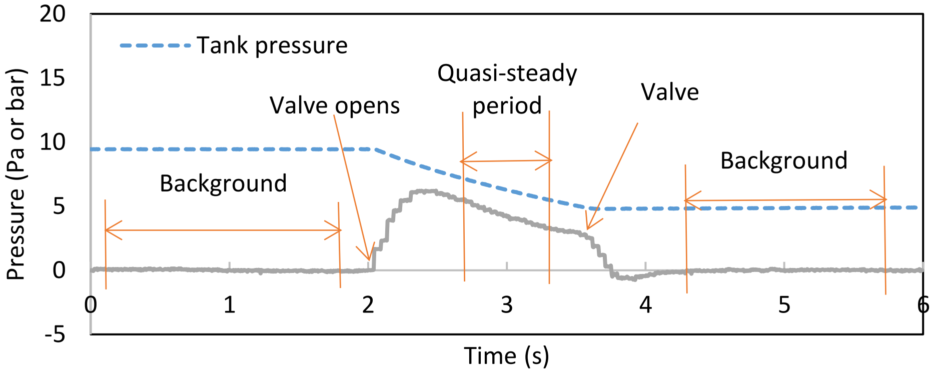


Figure 1 A typical pulse test by a pulse unit with 60 l receiver
(air receiver pressure measured in bar, building pressure in Pa)

When testing much more airtight dwellings, such as Passivhaus properties, the pulse shape formed is very 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 a failure to detect a quasi-steady air flow phase. Figure 2 below shows two typical examples of Pulse shapes experienced in highly airtight buildings.

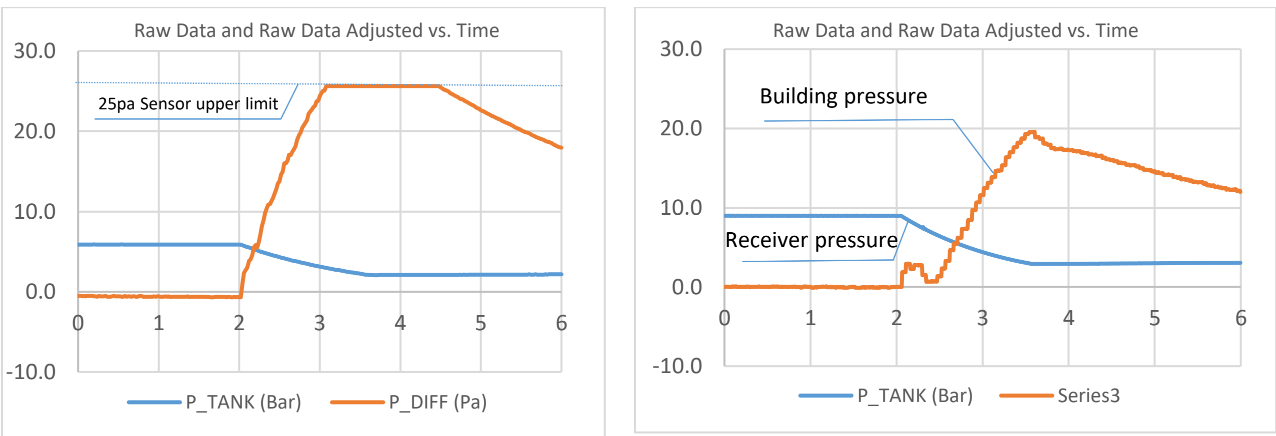


Figure 2 Example of unsuccessful pulse tests in highly airtight dwellings. Left, the peak pressure range is exceed. Right, the Pulse pressure rise and fall is slow and prolonged.

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 caused calculation failures for very air tight 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 limited the operating range of the technology and would preclude the use of Pulse in Passivhaus buildings, Build Test Solutions and the University of Nottingham sought to investigate what improvements could be made to the system.

Test Equipment Updates

With a considerable body of data now at our disposal from the 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:

- Air receiver volume and air outlet nozzle orifice
  A major hardware change based on the field trial data has been to reduce the size of the air receiver and to constrain the delivered flow by fitting it with a reduced sized outlet nozzle. This has the effect of creating a very 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 receivers (120L) would often be excessive and thus two 40 litre receivers (80L) also provides a good balance at this upper end, with further air receivers able to be added as required with no upper limit.

- Valve opening time made adjustable
  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, a user of the Pulse system may now prolong the valve open period to ensure that a reliable flow regime 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 velocity 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 air tightness of greater than $2m^3/h/m^2$ @50pa and for a 4 second valve opening recommended when testing properties with a design air tightness of less than $2m^3/h/m^2$ @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 air tight dwellings. For this exercise we specifically sought certified Passivhaus dwellings wherever possible.

Methodology

A total of 11 properties have been tested over the period October 2019 to January 2020 with a measured airtightness range of 0.29 $m^3/h/m^2$ @50Pa (0.48 ACH) to 1.19$m^3/h/m^2$ @50Pa (1.27 ACH) (or 0.05$m^3/h/m^2$ @4Pa (0.07 ACH) to 0.31$m^3/h/m^2$ @4Pa (0.33ACH)). In terms of size, these had an envelope areas ranging from 117m^2 to 681m^2 and building volume from 94m^3 to 637m^3. Overall 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.

Each of the properties were prepared according to the building preparation method 2 in BS EN ISO 9972:2015 [1], i.e. all intentional openings were sealed, the doors and windows closed, traps filled. 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; a problem experienced in past lab based testing of very airtight enclosures where agreement between the fan method and Pulse was being investigated.

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.

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	Fan mounted in canvas in the doorway, frame taped
003	Detached studio	138	94	Fan mounted in canvas in the doorway, frame taped
004	3-storey terraced house	344.4	360.6	Fan mounted in canvas in the doorway, frame taped
005	2-storey terraced house	244.4	186	Fan mounted in canvas in the doorway, frame taped
006	3-storey terraced house	344.4	322.5	Fan mounted in canvas in the doorway, frame taped
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	Fan mounted in fixed panel within window opening and taped
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

Photos illustrating a selection of the test setups can be found in Annex 1.

Results and discussions

For the purposes of this report, all results are presented as volume of air leakage per hour per m^2 of floor area ($m^3/h/m^2$) to two decimal places. This 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:

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

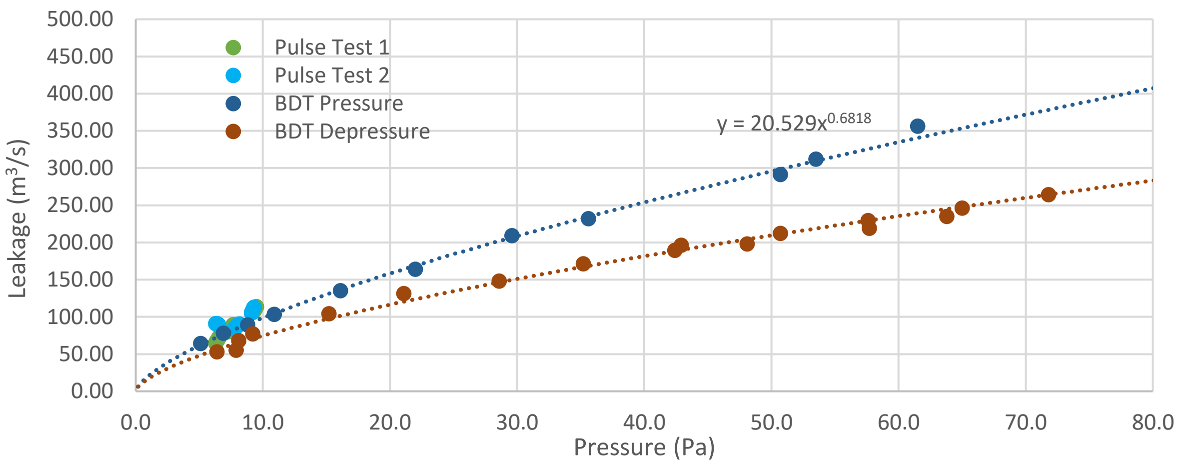
Property ID	N4 (BDT)	N4 (Pulse)	N4 Difference	N4 Percentage Difference
001	0.11	0.09	0.02	27%
002	0.14	0.13	0.00	3%
003	0.11	0.10	0.01	10%
004	0.13	0.20	-0.07	33%
005	0.05	0.06	0.00	7%
006	0.12	0.14	-0.01	10%
007	0.08	0.09	-0.01	9%
008	0.04	0.05	0.00	7%
009	0.11	0.11	0.00	2%
010	0.11	0.11	0.00	0%
011	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 in order to estimate what its leakage measurement 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 in order 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. Properties 007 to 010 show particularly strong agreement and these are all cases where the fan method was sealed in a fixed board in the window rather than using a canvas sheet in a doorway.

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, hence the 33% discrepancy for this particular case.



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

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 in order 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 -0.12m^3/h/m^2 @50Pa. In absolute percentage terms this equates to 18% which again is broadly in line with expectation given the combined measurement uncertainty of the fan method ±10%, Pulse 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 due to the fact that 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. 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 being a particular issue with case P001 where all results are valid and repeatable but there is weak agreement between the two techniques.

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, 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 very airtight 11 test cases, the average difference between the blower door fan pressurisation and depressurisation tests is $0.02m^3/h/m^2$ @50Pa. In absolute percentage terms this equates to 11% which is similar to the level of agreement seen between the two different test techniques above and is again very close to expected levels of measurement uncertainty cited by the ISO 9972:2015 standard. The closest match between both modes being 3% and biggest discrepancy 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.

Summary and recommendations

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 performance 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 $0.0003m^3/h/m^2$ @4Pa (11%) and $0.12m^3/h/m^2$ @50Pa (18%) at 50Pa when using the Power Law as a means of extrapolation. Our arising recommendations to UK Government are therefore:

1. Pulse can measure very airtight dwellings just as reliably as the incumbent blower door fan technique and setting a lower operating limit of $1.5m^3/h/m^2$ @50Pa is not necessary.

2. 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, this testing of very air tight 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 a means to infer infiltration rates, 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.

3. 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.

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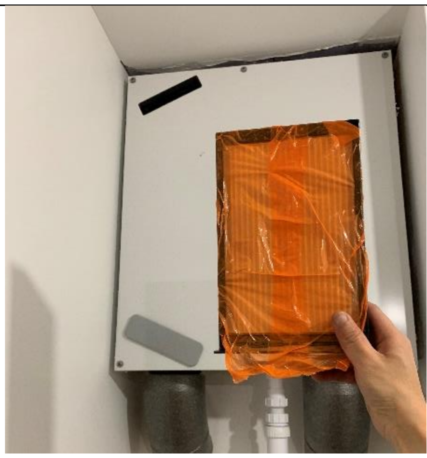
[1] BS EN ISO 9972. Thermal performance of buildings-Determination of air permeability of buildings-Fan pressurisation method. BSI Standards Publication (2015)

Annex 1 – Examples of equipment set-up scenarios

Blower door fan setup in a doorway and taped from inside

Complete 40L Pulse set-up used in this configuration for all test cases

Blower door fan mounted and sealed in a panel cut to the size of the window opening



MVHR units switched off with both inlet and exhausts either sealed internally or externally

	
Very low flow min fan required for the fan tests, with large restrictor plate fitted	Enerphit retrofit property
	
3 Storey house in Colchester	Low rise block of Passivhaus flats
	
Pulse and blower door fan testing in a small 94m^3 art studio	