Energy & Buildings 295 (2023) 113270

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

An investigation into the efficacy of the pulse method of airtightness testing in new build and Passivhaus properties

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ARTICLE INFO

Keywords:
The pulse technique
Enclosure airtightness
Steady fan pressurisation
Airtightness models
Air permeability
New dwellings
Passivhaus
The power law

ABSTRACT

The latest edition of the UK government's Approved Document L of the Building Regulations, which came into effect on the 15th of June 2022, for the first time included an alternative method of airtightness testing to the traditional fan pressurisation method (DLUHC & MHCLG, 2021). Unlike the fan pressurisation method, the pulse method operates at low pressures that are thought to be representative of natural infiltration. Despite government approval, responses to the Future Homes Standard consultation revealed that respondents did not have confidence in the method, particularly with very airtight properties, and others were concerned with the comparison between testing methods (MHCLG, 2021). In this paper, experimental investigations were performed involving the pulse method to assess its repeatability and accuracy. The results indicated an average repeatability of 4.96% from the mean for consecutive tests, and the pulse results extrapolated up to 50 Pa all fell within the fan pressurisation's 10% uncertainty range. In addition, two empirical models were applied to the data set to explore the conversion of air permeabilities between high and low pressures. The data showed strong agreement with the power law model and even stronger correlation with the conversion formula suggested in CIBSE TS23:2022 (Godefroy, 2021).

1. Introduction

1.1. Background

From 2025 all new dwellings in the UK must produce 75–80% fewer carbon emissions [17]. Reducing operational carbon through high fabric efficiencies is essential when building a zero-carbon ready home, especially as up to half of a building's heating demand is a direct result of infiltration losses [22]. Whilst a building's infiltration rate can be measured, most commonly through the tracer gas method, it is less complex and less time-consuming to instead determine the building's airtightness [12,10].

Whilst there are several methods of airtightness testing, two are now recognised by Approved Document L [19]. Prior to the June 2022 edition of Approved Document L, the only approved technique was the fan pressurisation method. The fan pressurisation method or the 'blower door test' has been used extensively for over 20 years, and uses a fan mounted in an external door of a building to create a high-pressure differential across the building envelope [6,5]. Typically, the test operates between 10 and 60 Pa to reduce interference from wind and buoyancy [14,25]. Criticisms of this method include its inability to maintain building integrity due to the fan being mounted in an external door of the test building, causing the leakage of this door not to be measured. Whilst the effect on the overall airtightness could be negligible in leaky buildings, it can have a significant impact on a building's airtightness in very airtight properties [25]. Furthermore, the method involves a complex and manual operation, and its unnaturally high operating pressures are unrepresentative of natural infiltration [7].

Unlike the fan pressurisation method, the approved alternative pulse method does not require skilled operation, operates at a lower pressure of 2–15 Pa and fully maintains building integrity [6,22]. The pulse method consists of a low-pressure pulse that releases a known volume of air into a building causing a temporary increase in pressure [22]. Air leakage through the building envelope causes the pressure to decrease, and as it does the air flow exhibits quasi-steady characteristics [15]. The pressure in both the air tank and the building are monitored continuously, allowing the pulse software to establish a correlation between the building's air leakage and the pressure differential [5,25].

Initially the pulse method was not considered suitable for very airtight properties and a minimum threshold of 1.5 $m^3/(h.m^2)$ at 50 Pa

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https://doi.org/10.1016/j.enbuild.2023.113270
Received 22 February 2023; Received in revised form 24 May 2023; Accepted 14 June 2023
Available online 19 June 2023
0378-7788/

was suggested [17]. This decision was based on early field trials of the pulse method which were unsuccessful for Passivhaus buildings [15]. Following evidence from the further testing of eleven Passivhaus properties this constraint was revoked [22].

Considering the methods operate in different pressure ranges, a reference pressure of 50 Pa is used for the fan pressurisation method, whilst 4 Pa is used for the pulse method. Conversion between high and low-pressure results is therefore required to enable comparison between the two methods and for compliance purposes. Due to uncertainties associated with extrapolation, accurate comparison is not without its challenges [4]. Whilst downwards extrapolation from fan pressurisation data is constrained by the origin as the lowest data point, extrapolating upwards from low pressure pulse data lacks a high-pressure data point [21]. Therefore, the agreement between the two methods can differ depending on the direction of extrapolation [22].

1.2. Empirical models

Empirical relationships have been established in order to relate the air leakage to the pressure differential as well as the air permeabilities at the two common reference pressures. The power law model is most widely used to represent the correlation between air leakage and pressure [26], and is given in equation (1), below.

$$Q = C \times \Delta p^{n} \tag{1}$$

Q is the air leakage rate (m^3h^{-1}), Δp is the pressure differential across the building's envelope (Pa), C is the flow coefficient ($m^3h^{-1}Pa^{-n}$), and n is the pressure exponent. Despite consistent critics of the model, it has shown to be both effective and accurate in a multitude of studies [9,13,20,26].

The power law equation requires calculation of the pressure exponent and the flow coefficient, and whilst the pressure exponent is constrained between 0.5 and 1, to determine their exact values, air leakage data is required over a range of pressures. Once determined, the air leakage can be estimated at any pressure. Dividing this by the building's envelope area will then produce the building's corresponding air permeability.

Alternatively, the results of over 293,000 fan pressurisation tests have been analysed to produce a conversion equation that allows the air permeability at 50 Pa to be predicted from the 4 Pa permeability. The latest version of this, which is included in CIBSE's TS23:2022 [6], is given below.

$$AP_{50} = 5.2540\,AP_4{}^{0.9241} \tag{2}$$

1.3. Research gap

Even though CIBSE's latest guidance on airtightness testing [6] includes the pulse method as an alternative to the fan pressurisation test, it is comparatively new and is not currently widely implemented or well-known in the construction industry. Furthermore, the use of the pulse method in very airtight properties has been limited, with Part L's airtightness threshold overturned after a trial involving only eleven properties [18]. Despite government approval, responses to the Future Homes Standard consultation revealed that more respondents voted against the introduction of the pulse method into the building regulations [19]. Furthermore, it also suggested that some respondents questioned the pulse's efficacy in very airtight properties, and others raised concerns regarding comparison between the different airtightness methods [19]. To validate previous studies and increase confidence in the method, the collection of more data is crucial, particularly in Passivhaus and new build properties. An older model of the low-pressure pulse test was verified by BRE in 2019 [1]; however, the latest model has undergone hardware and software updates and is yet to be independently verified. Considering BRE previously found that both the equipment and set-up can impact the test results [6], independent trialling of the latest model should be carried out. Given two methods of testing that operate at different pressure ranges have been approved, there is now a greater need to accurately convert between low- and high-pressure results [19].

1.4. Research goals

The aim of this research was to investigate the efficacy of the pulse method of airtightness testing in new build and Passivhaus properties, with a focus on the exploration of the appropriateness of empirical methods used to convert airtightness data between high and low pressures. Through field trials, primary quantitative data was collected in order to achieve the research objectives below:

1. To verify the pulse method of airtightness testing is suitable for new build and very airtight properties.
2. To assess the airtightness gap between new build housing and Passivhaus properties using the pulse method.
3. To critically review the appropriateness of the power law model in describing the relationship between air leakage and pressure using pulse data.
4. To verify the conversion formula is an appropriate tool for converting air permeabilities between 4 and 50 Pa.

2. Methodology

In a similar approach to previous studies involving the pulse method that were carried out by the University of Nottingham [4,5,7,21,23,24,25], the author collected primary data using pulse equipment. New build and Passivhaus properties were the focus of this study, thus test properties were selected that met this criterion.

2.1. Test dwellings

Six new build dwellings were selected for validation of the low-pressure pulse and for the comparison against the fan pressurisation method. Fig. 1 shows examples of the properties used, two of which were designed to Passivhaus standards and four to the UK's Building Regulations 2010, incorporating the editions of the Approved Documents effective in November 2021. All properties were completed in 2022, their key parameters are included in Table 1.

Properties 1–4 were tested on an overcast day in August, whereas there were scattered clouds when the Passivhaus properties were tested. Table 2 shows the testing conditions of each property.

2.2. Equipment and testing protocol

To prepare for airtightness testing the properties had all trickle vents closed, ventilation systems turned off and temporarily sealed with tape, and drainage traps were filled with water. During the test all internal doors were kept open and loft hatches and external doors remained closed.

2.2.1. Pulse set-up

As illustrated by Fig. 2, the pulse set-up consisted of a 40-litre air receiver, a portable air compressor and a control unit. The air receiver was positioned in the centre of the properties' hallways and charged between 4 and 10 bars depending on the house type. Due to the lower air permeability of the Passivhaus properties the air receiver was charged to either 4 or 6 bars to prevent over-pressurisation of the building. On account of the buildings' volumes and expected air permeabilities, only one air receiver was required per property. In the standard houses the control unit was programmed to release two 1.5-second pulses of air, and for the Passivhaus plots one 4-second pulse of air was released per test. Previous trials found that in Passivhaus properties the pressure peak is reached after a longer period; thus, to ensure the steady state

Fig. 1. Test properties selected for this research. The image on the left shows the Passivhaus plots and the image on the right shows one of the standard plots. All standard plots had the same design and internal dimensions [16].

Table 1
Details of the test buildings. Envelope areas and volumes have been rounded to the nearest integer.

Test Building	Internal Volume (m^3)	Internal Envelope Area (m^2)	Construction Type	Storeys	House Type
Property 1	229	229	Brick and block cavity wall	2	End Terrace
Property 2	229	229	Brick and block cavity wall	2	End Terrace
Property 3	229	229	Brick and block cavity wall	2	Mid Terrace
Property 4	229	229	Brick and block cavity wall	2	Semi-detached
Passivhaus 1	229	235	Timber frame finished with timber cladding and masonry	2	Semi-detached
Passivhaus 2	229	235	Timber frame finished with timber cladding and masonry	2	Semi-detached

Table 2
Testing conditions of each property.

Test Building	Average Internal Temperature (°C)	Average External Temperature (°C)	Average Wind speed (m/s)
Property 1	26.6	21.1	3.6
Property 2	27.2	21.5	3.4
Property 3	26.0	22.2	2.0
Property 4	26.2	22.2	2.0
Passivhaus 1	28.5	21.3	3.6
Passivhaus 2	29.1	20.0	2.6

period is reached a longer pulse is required [22]. Each property was tested a minimum of three times using this set-up and following the pulse testing properties 1–4 were tested using the fan pressurisation method. Multiple tests were carried out on each property to assess the repeatability of results.

2.2.2. Fan pressurisation set-up

As shown by Fig. 3, a Minneapolis fan pressurisation unit was set up in the entrance doors of the properties for comparison with the pulse unit. All measurements of air flow, pressure and temperature were taken manually using a digital flow meter, pressure gauge, and thermometer. All tests were carried out in depressurisation mode across an approximate pressure range of 10–60 Pa. There was not enough time to carry out tests in both pressurisation and depressurisation modes to reduce the uncertainty in the fan pressurisation results.

2.2.3. Calibration of pulse equipment

Calibration is a critical process to ensure the accuracy and reliability of measuring instruments. When comparing the calibration process of the fan pressurisation equipment with the pulse equipment, there are notable differences in their approaches. Both methods involve using reference instruments for calibration, but they focus on different aspects of the equipment.

In the case of the pulse equipment, which operates at a near ambient pressure of 4 Pa, calibration is conducted before and after each test based on the manufacturer's instructions. This calibration process aims to ensure accurate and reliable measurements. Build Test Solutions, the equipment provider, performs calibration checks by comparing the test unit with a master unit. The master unit is equipped with sensors calibrated by the United Kingdom Accreditation Service (UKAS). This traceability to UKAS standards adds to the confidence in the equipment's accuracy.

For detailed calibration instructions, it is advisable to consult the Pulse Instruction Manual and safety guidelines provided by the manufacturer [3]. These guidelines emphasise visually inspecting the equipment regarding its integrity and utilizing temperature and pressure calibration instruments that adhere to national standards for sensor calibration. Additionally, assessing the equipment for any damage or corrosion is crucial to maintain its performance.

By employing the pulse method, which combines precise equipment and calibration alongside multiple tests, airtightness measurements in new build and Passivhaus properties is practical, reliable, and compliant with industry standards.

2.3. Data analysis

2.3.1. Verification of the pulse method - repeatability

The relative percentage difference was used to determine the consistency of the pulse results. In equation (3), below, the average air permeability for each property was used as the 'Reference', and the difference between an individual test and the average air permeability as the 'Difference'.

$$Relative\ \ Percentage\ \ Difference\,(RPD) = \frac{Difference}{Reference} \times 100 \qquad (3)$$

BRE verified the pulse method's consistency using a maximum relative percentage difference of 5% which corresponded with the manufacturer's claim [1]. A similar approach was used in this report, and for any data sets that fell outside of this limit Chauvernet's criterion

Fig. 2. Pulse set-up.

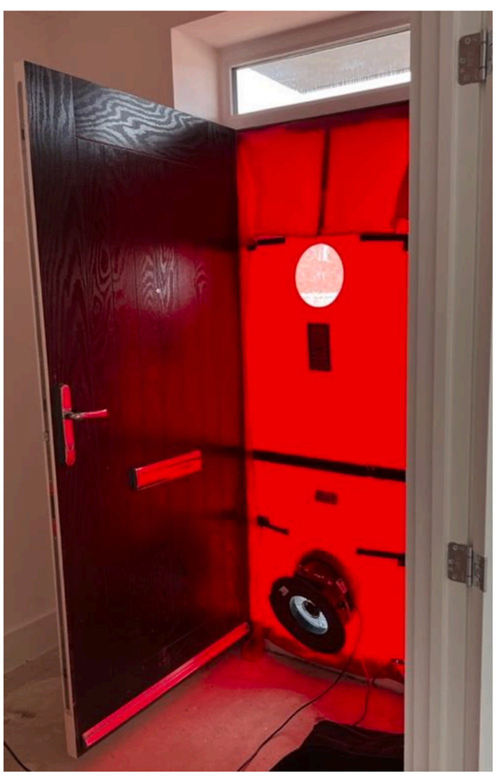

Fig. 3. Fan Pressurisation set-up.

was applied to determine if they should be rejected as outliers for the rest of the analysis [8].

2.3.2. Verification of the pulse method - accuracy

The accuracy of the pulse method was assessed through comparison with fan pressurisation results. Using the power law equation, the air permeabilities at 4 Pa were extrapolated to 50 Pa and vice versa.

2.3.3. Verification of the power law model

To determine if the power law was an appropriate model for the data sets, linear regression was used. The air flow and pressure data were plotted in logarithmic form to linearise the power law equation and determine the air flow coefficient and pressure exponent for each plot. The pressure exponents were calculated from the gradient of the log–log plot, and the air flow coefficient from the y-intercept. Considering the logarithm to base 10 was used throughout the analysis, the air flow coefficient was calculated using equation (4), below.

$$C = 10^{y-intercept} \quad (4)$$

For analysis of the pulse data sets, the minimum threshold of 0.96 for the coefficient of determination was used to establish if the model was appropriate. Each individual test had to pass this criterion in order to be deemed valid [6], and the same threshold was used when repeat tests were combined for the analysis of an individual property.

For the fan pressurisation data, due to the smaller number of data points, the threshold of the coefficient of determination was higher at 0.98 to be deemed valid as stipulated in CIBSE's TS23:2022 [6].

2.3.4. Verification of the conversion formula

To verify the conversion formula in equation (2), the conversion formula was applied to the measured air permeabilities at 4 Pa. Then the results were compared against measured permeabilities at 50 Pa, and the predictions made using the power law model. The difference between the predicted values and the measured values were analysed using the relative percentage difference method.

In addition, equation (2) was rearranged to also analyse the extrapolation down from high-pressure.

2.4. Limitations

Due to time and equipment availability the Passivhaus properties could not be tested via the fan pressurisation method. This would have aided in the determination of the pulse method's accuracy with respect to the Passivhaus plots and would have served as a useful addition to previous studies. Despite this, a robust analysis of the pulse method, power law model, and the conversion formula could still be executed.

The sample size of this research is comparable to those of previous reports, as BRE carried out a validation of the pulse method using only five properties [1]. However, a larger sample size would have produced more conclusive results. In addition, the fan pressurisation tests were carried out in depressurisation mode only. Averaging the results of pressurisation and depressurisation tests could have reduced uncertainty; however, there was insufficient time to carry out tests in both modes. Even though it was the author's first experience conducting airtightness testing, the data collection was strongly supported by airtightness testing professionals, thus preventing the collection of low-quality data. Finally, the uncertainties analysed in this report are derived from relative percentage differences rather than the error propagation of model, bias, and instrumentation errors. Error analysis on such basis was out of the scope of this study.

3. Results & discussion

3.1. Repeatability of the pulse method

Table 3 shows the air permeabilities and the maximum relative percentage differences for the pulse tests. In all cases for the Passivhaus properties and property 3, the maximum percentage difference is less then $\pm$ 5%. Three tests in the data set had maximum relative percentage differences greater than this threshold. For these tests Chauvernet's criterion was applied, but none were deemed to be outliers [8].

The pressure–time graphs of three data sets were analysed to determine if any of the three showed unusual characteristics that would have affected the resultant air permeability. Nothing conclusive was determined, as all plots appeared to be corrected with respect to the background pressure. Test 1 of property 1 and test 3 of property 4 did show unnatural plateaus for the background corrected curves, however further analysis indicated that the steady state data for determination of the air permeabilities was not being pulled from these regions. The greatest deviation from the average was seen in property 2, with a maximum relative percentage difference of 10.77% below the average. The pressure–time curve, shown in Fig. 4, appears quite noisy around the peak pressure of pulse 1 but otherwise the plot looks normal.

The Passivhaus properties were more consistent than the new builds despite using the same precision measuring instruments for the more airtight properties. Maximum relative percentage differences of 2.01 and 3.18 were found for properties 1 and 2, respectively, and half of the Passivhaus results had relative percentage differences below one percent. Combining the standard new build and Passivhaus data sets together the average maximum relative percentage difference is 4.96%, and 85% of the individual tests have a relative percentage difference below the 5% threshold stated by the manufacturer [6].

3.2. Accuracy of the pulse method

Perfect agreement between the predicted and measured air permeabilities is not expected due to the uncertainties associated with extrapolation; however, the properties should follow the same trend [4]. Table 4 shows that this is the case for this data set, with both airtightness methods ranking the properties in the same order of air permeability. Also demonstrated in Table 4, the properties appeared leakier in all cases when using the fan pressurisation method. This is unsurprising as air leakage pathways can be emphasised at higher pressures. According to the BS EN ISO 9972:2015, the uncertainty associated with the fan pressurisation method is 10% [2]. In every instance the extrapolated permeabilities fell within this margin.

3.3. New build vs. Passivhaus properties

Table 5 shows the directly measured air permeabilities at 4 Pa compared to the maximum and target air permeabilities determined from Approved Document L and Passivhaus standards [19,11] Considering Approved Document L does not state a target permeability at 4 Pa, the conversion formula was rearranged to convert this to a 50 Pa target. Furthermore, the target Passivhaus criteria was determined by converting the target of 0.6 h^{-1} to an air permeability using the plot's internal area to volume ratio. As the Passivhaus criteria is quoted to only one decimal place, the maximum air changes per hour that would pass is 0.649 h^{-1} (3d.p.). This also was converted to an air permeability.

From the given and derived thresholds, the Passivhaus properties are expected to be at least 10.56–15.70 times more airtight than the standard new builds. Whilst the standard new builds reached the threshold air permeabilities without exception, none of the Passivhaus properties reached the air permeability threshold. Thus, they were only 1.75–3.06 times more airtight than the standard new builds. The Passivhaus properties met the air permeability criteria at their stage 1 tests before the drylining, ceilings, services or floor coverings were installed, implying that the air barrier could have been compromised after this build stage. Whilst the plots had been designed to meet Passivhaus standards, it is apparent that the level of supervision and workmanship

Table 3
Air permeabilities and relative percentage differences of repeated tests.

Test Property	Pulse Method – Air Permeability at 4 Pa (m^3/m^2h)				Average Air Permeability (m^3/m^2h)	Maximum Relative Percentage Difference(%)
	Test 1	Test 2	Test 3	Test 4		
Property 1	0.86	0.94	0.94	n/a	0.913	-5.84
Difference	-0.053	0.027	0.027			
RPD (%)	-5.84	2.92	2.92			
Property 2	1.02	1.01	0.87	1.00	0.975	-10.77
Difference	0.045	0.035	-0.195	0.025		
RPD (%)	4.62	3.59	-10.77	2.56		
Property 3	1.01	0.97	0.97	n/a	0.983	2.71
Difference	0.027	-0.013	-0.013			
RPD (%)	2.71	-1.36	-1.36			
Property 4	1.13	1.09	1.2	n/a	1.14	5.26
Difference	-0.010	-0.050	0.06			
RPD (%)	-0.88	-4.39	5.26			
Passivhaus 1	0.37	0.37	0.38	0.37	0.373	2.01
Difference	-0.003	-0.003	0.007	-0.003		
RPD (%)	-0.67	-0.67	2.01	-0.67		
Passivhaus 2	0.54	0.52	0.51	n/a	0.523	3.18
Difference	0.017	-0.003	-0.013			
RPD (%)	3.18	-0.64	-2.55			

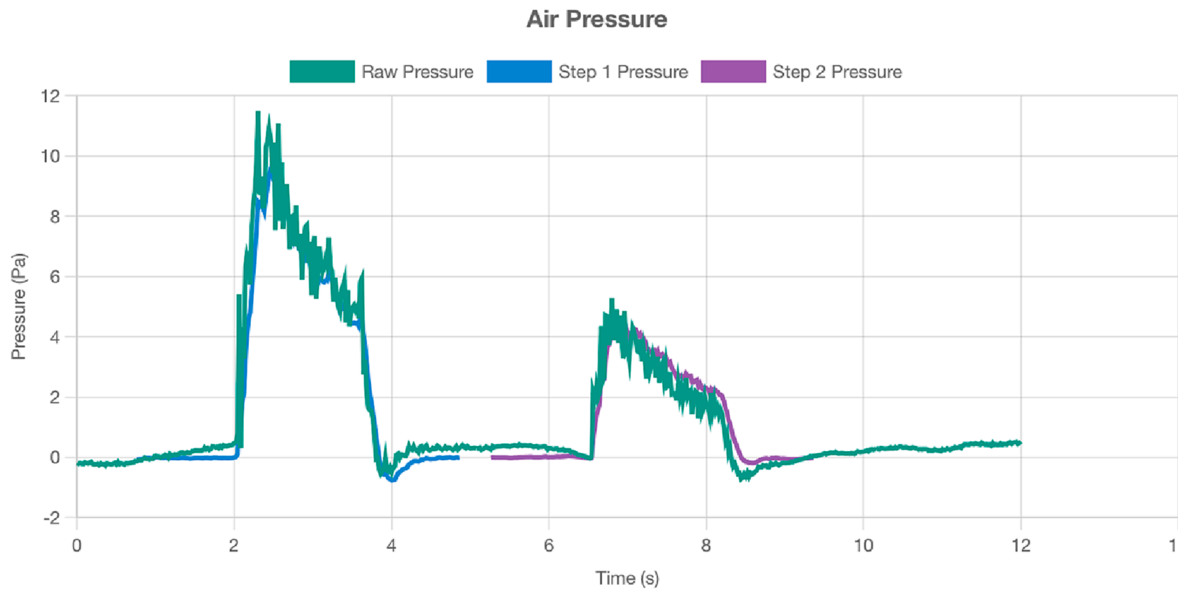

Fig. 4. Pressure - time graph for test 3 of property 2.

Table 4
A comparison of the measured air permeability at 50 Pa against the pulse data extrapolated to 50 Pa using the power law equation. [1]Due to an error experienced when exporting the data, property 2's fan pressurisation results the measured air permeability at 50 Pa is unknown.

Test Property	Mean extrapolated Air Permeability at 50 Pa (m^3/m^2h)	Measured Air Permeability at 50 Pa (m^3/m^2h)
Property 1	4.83	5.21
Property 2	5.13	Unknown [1]
Property 3	5.19	5.27
Property 4	5.92	6.12

Table 5
A comparison of the air permeability of new build and Passivhaus properties at 4 Pa.

Test Property	Mean Air Permeability at 4 Pa (m^3/m^2h)	Threshold Air Permeability at 4 Pa (m^3/m^2h)	Target Air Permeability at 4 Pa (m^3/m^2h)
Property 1	0.91	1.57	0.95
Property 2	0.98	1.57	0.95
Property 3	0.98	1.57	0.95
Property 4	1.14	1.57	0.95
Passivhaus 1	0.37	0.10	0.09
Passivhaus 2	0.52	0.10	0.09

required to fully execute the design exceeds that of a new build.

3.4. The power law model

Individual data sets for each property were combined to experimentally determine the air flow coefficient and pressure exponent that best describes the air leakage for each property.

3.4.1. New build properties

Properties 1, 3, and 4 had r^2 values greater than 0.96 when all their individual data sets were combined. Taking all four sets for property 2, at 0.943 this resultant r^2 value did not meet the threshold. Considering test 3 showed the greatest variance in terms of air permeability, it was apparent that this data set was significantly reducing the coefficient of determination. Excluding this data set and recalculating r^2 resulted in a value of 0.986 for property 2. A typical air flow-pressure curve for the standard properties is included in Fig. 5, with the power law model shown in green.

3.4.2. Passivhaus properties

Similar r^2 values were achieved for the Passivhaus plots; however, graphically the data sets show better correlation with the power law model. Unfortunately, in the case of Passivhaus 1, deriving a pressure exponent and flow coefficient from combining its data sets produced an invalid pressure exponent. Instead of falling between 0.5 and 1, the exponent was 0.498. There were no valid reasons to exclude any of the data sets; however, considering rounding the pressure exponent to two decimal places would make it valid, the author decided to accept it.

Fig. 6 shows the air flow pressure curve for Passivhaus 1. The plot for the second Passivhaus was comparable.

Every property had valid coefficients of determination, ranging from 0.997 to 0.999 for the fan pressurisation data and 0.963–0.986 for the pulse tests. At the high-pressure range, agreement with the power law model is better, and of the pulse tests, the Passivhaus properties exhibited marginally better correlation with an average r^2 value of 0.978 against 0.973 for the standard new builds. Despite the r^2 validity threshold being higher for the fan pressurisation method than the pulse, on average the r^2 value for the fan pressurisation method is 20% over the threshold compared to 18% of the pulse. All calculated r^2 values and coefficients are included in the Appendix.

3.5. The power law model vs the conversion formula

Extrapolation from 4 and 50 Pa using the power law equation has been compared to the conversion formula.

3.5.1. Extrapolation from 4 Pa

Table 6 shows the measured and predicted air permeabilities at 50 Pa alongside the relative percentage differences. For the standard plots, without exception the conversion formula underestimates the air permeability, whilst the power law equation overestimates it. On average, the relative percentage difference for the conversion formula is less than the power law equation. Despite this, the relative percentage differences presented in section 3.1 from repeat testing the pulse unit are comparable to those in Table 6, implying that extrapolation has not compounded the uncertainties in either method. The relative percentage

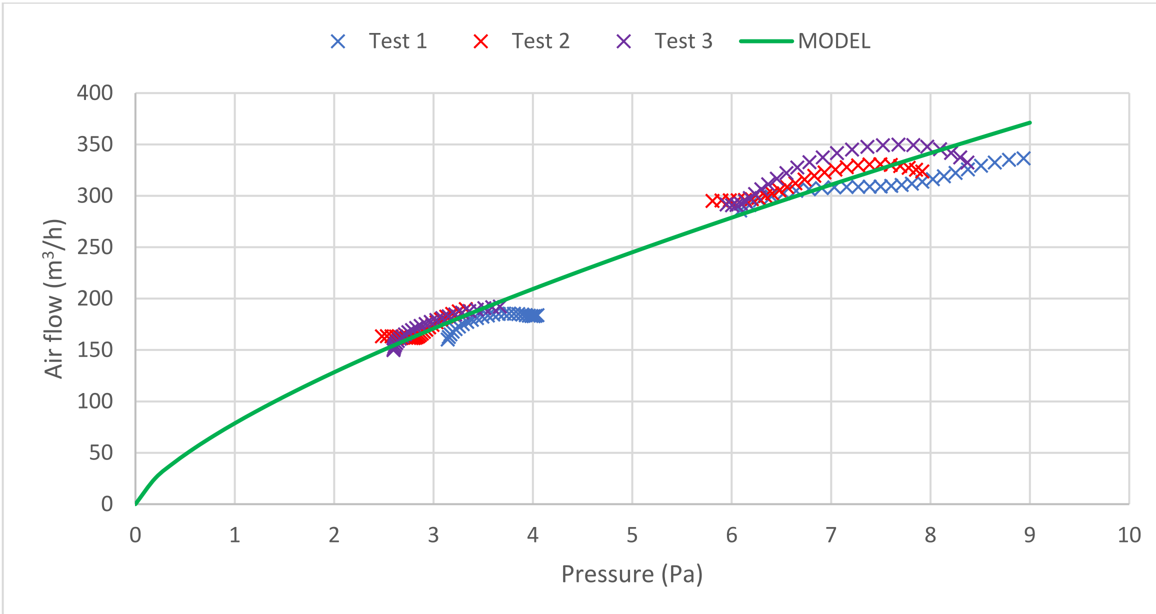

Fig. 5. Air flow plotted against pressure for property 1.

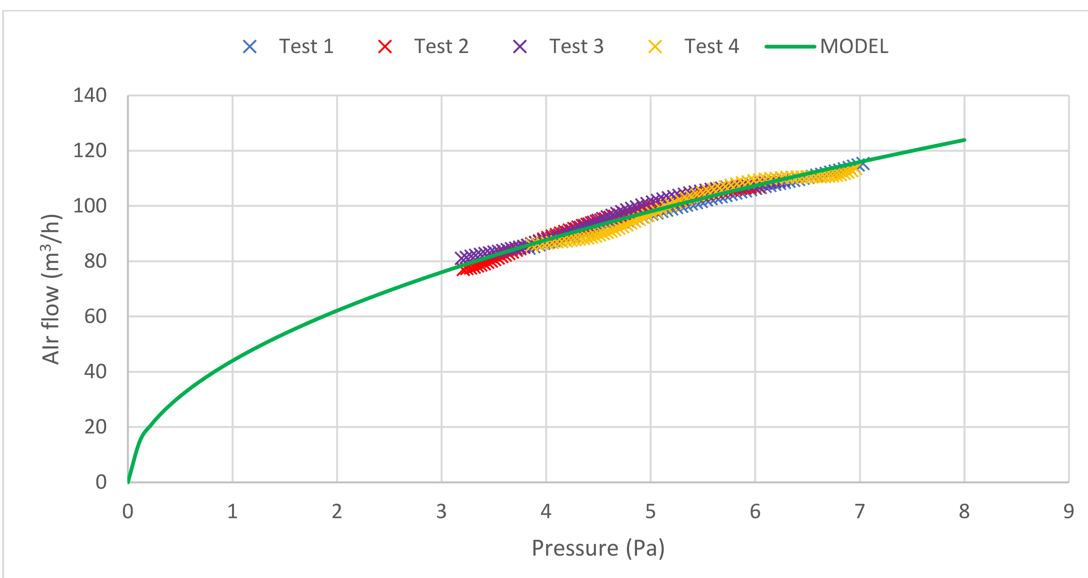

Fig. 6. Air flow plotted against pressure for Passivhaus 1.

difference between the measured data and the power law's predictions was significantly better than found in previous studies [23], with an average of 5.54%.

Conversely, with the Passivhaus plots the conversion formula predicts a higher air permeability than the power law equation. Whilst there is not any fan pressurisation data for comparison for these plots, it is clear that these predicted results are not in close agreement. The conversion formula predicts an air permeability greater than 60% larger for Passivhaus 1 and over 30% larger for Passivhaus 2. Whilst the Passivhaus properties' air flow-pressure graphs appear to show strong correlation with the power law model, as they only show the low-pressure range, extrapolation to 50 Pa can be difficult due to the absence of high-pressure data points [22].

3.5.2. *Extrapolation from 50 Pa*

It has been found that extrapolating fan pressurisation data down from 50 Pa has shown greater agreement with pulse data than the extrapolation in the reverse direction [22]. As shown in Table B1 of the Appendix, both the conversion formula and the power law model overestimated the air permeability at 4 Pa. Considering these formulas utilised fan pressurisation data which suggested the plots were leakier than the pulse in section 3.2, this is unsurprising. However, on a similar basis, when both models used the pulse data, the expectation would be an underestimation of the air permeabilities. This was not the case for the power law model, suggesting it overestimates air permeability to a greater degree than the pulse method underestimates air permeability relative to the fan pressurisation method. Whilst the magnitudes of the differences are smaller than reported in section 3.5.1, when converted to percentages, the relative percentage differences are greater. Despite

Table 6
Comparison of the air permeability at 50 Pa via the interpolation of fan pressurisation data against that predicted using the power law equation and the conversion formula in conjunction with the pulse method. There are no fan pressurisation results for property 2 due to an error that occurred when the file was saved. Due to time constraints the Passivhaus properties were not tested via the fan pressurisation method. AP_4 is the air permeability measured by the pulse method at 4 Pa.

Column ID	1	2	3	4	5
Column Formula	A	B	(B-A)/A × 100	C	(C-A)/A × 100
Test Building	Measured fan Pressurisation data	Extrapolated from pulse data	Relative Percentage difference (%)	Derived using AP_4 and the conversion formula	Relative Percentage difference (%)
	Air Permeability at 50 Pa (m^3/hm^2)	Air Permeability at 50 Pa (m^3/hm^2)		Air Permeability at 50 Pa (m^3/hm^2)	
Property 1	5.17	5.44	5.33	4.84	−6.35
Property 2	Incomplete	5.42	Incomplete	5.29	Incomplete
Property 3	5.28	5.53	4.73	5.18	−1.87
Property 4	6.08	6.48	6.55	5.90	−2.94
Passivhaus 1	Incomplete	1.35	Incomplete	2.17	Incomplete
Passivhaus 2	Incomplete	2.24	Incomplete	2.92	Incomplete

knowing the end point when extrapolating to low pressures, this data suggests that in terms of relative percentages the power law model is more accurate when extrapolating to high pressures.

Before extrapolation errors are taken into consideration, the fan pressurisation method has an uncertainty of 10%, compared to the pulse's 5%. As the accuracy of the extrapolated result is dependent on the accuracy of either data set, one would anticipate the extrapolation of the fan pressurisation data to give rise to the largest percentage error. The standard properties do suggest that this is the case. However, with the lack of fan pressurisation data for the Passivhaus properties, one cannot be sure that this same trend would be exhibited in very airtight circumstances. Moreover, ignoring extrapolation errors the methods' combined uncertainty is 15%[6], thus aligning with even the largest relative percentage difference in Table B.1.

4. Conclusions and recommendations

4.1. Conclusions

Through collection and analysis of primary data this research supports the notion that the pulse method is an appropriate method of airtightness testing in new build and in Passivhaus properties. Similarly, the air leakage data collected indicated the power law model and the conversion formula were appropriate methods for the conversion between high and low pressures.

Whilst the fan pressurisation method has been the primary method of airtightness testing for years, its unnaturally high pressure, the disruption of the building envelope during testing, and complex operation has generated the desire for alternative methods. In comparison to the fan pressurisation method, the pulse method has advantages of quick and simple use with little manual input required by the operative. It also maintains the building's integrity throughout the test procedure, operates at ambient pressures whilst minimising the effects of background pressures through its dynamic testing process.

The repeatability and accuracy of the pulse test has been demonstrated; hence the UK government supported its usage in part L of the building regulations without limitations. However due to limited existing data in new build and Passivhaus properties this research aimed to demonstrate its suitability under such circumstances. The repeatability of the pulse method was investigated and an average relative percentage difference of 4.96% was found for the data set. Despite this average falling within the manufacturer's stated uncertainty, 15% of the individual tests did not fall within this range. Two thirds of these had a relative percentage difference less than 6% and thus just fell outside the manufacturer's uncertainty range. Furthermore, the results of Passivhaus plots were more consistent than the standard new builds, thus reducing the overall average for the data set.

In all instances the extrapolated air permeabilities fell within the reported 10% error range for the fan pressurisation method, indicating the pulse method was indeed accurate. However as this was not a direct comparison at 4 Pa, errors of the pulse results will be amplified by extrapolation. Fan pressurisation tests could not be carried out for the Passivhaus plots for comparison due to equipment availability and time constraints.

The design criteria indicated the Passivhaus plots would be 10.56–15.70 times more airtight than the standard new builds, when in actuality they were only 1.75–3.06 times more airtight. Considering this was due to the Passivhaus plots not reaching the target air permeability, it highlights the challenge in constructing a Passivhaus design, and in fact the term Passivhaus cannot truly be used to describe these plots.

With regard to the power law's appropriateness in modelling the relationship between air leakage and the pressure differential, both the Passivhaus and new build properties exhibited good correlation with r^2 values of 0.997–0.999 with the fan pressurisation method, and 0.963–0.986 with the pulse method. The lower r^2 values for the pulse method indicates that the power law equation does not fit the data as well at lower pressures. In addition, the Passivhaus properties showed slightly better agreement with the model than the standard new builds, with an average r^2 value of 0.978 against 0.973. Moreover, when comparing the measured air permeability to power law predictions at 50 Pa, the average relative percentage difference was 5.54%. Considering these uncertainties were comparable to those found in section 3.1, using multiple leakage-pressure curves to determine power law coefficients did not appear to compound the error. In comparison, the average difference between predicted and measured air permeabilities at 4 Pa was 9.65% indicating the power law model is less accurate when extrapolating down to low pressures.

Finally, the conversion formula showed greater correlation with the data than the power law equation, irrespective of the direction of extrapolation. Since the power law model is widely accepted as an empirical representation of the air leakage against a building's pressure differential, these results indicate the conversion formula is also appropriate for the conversion of air permeabilities from low to high pressure and vice versa.

4.2. Future research

Considering the lack of fan pressurisation data for the Passivhaus plots in this study, further research on the application of the conversion formula and power law equation should be undertaken using fan pressurisation data at 50 Pa as a reference. In contrast to previous studies [22], this data suggests the power law equation is more accurate when extrapolating to higher pressures. Due to this disparity, further research is required. Whilst this study was focussed on more airtight properties, validation of the pulse method in scenarios that warrant the linkage of multiple air receivers would complement this research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The author wants to thank Build Test Solutions and St. Modwen Homes, without whom this research would not have been possible.

Appendix

Table A1
Comparison of the air permeability predicted by the pulse method against the conversion formula and the fan pressurisation method. There are no fan pressurisation results for property 2 due to an error that occurred when the file was saved. Due to time constraints the Passivhaus properties were not tested via the fan pressurisation method. AP_4 is the air permeability measured by the pulse method at 4 Pa.

Test Building	Low-pressure pulse						Conversion Formula	Fan Pressurisation
	Pressure range (Pa)	r^2	n-value	Air flow coefficient (m^3/hPa^n)	Interpolation using the power law equation	Extrapolation using the power law equation	Derived using AP_4 and the conversion formula	Interpolation using the power law equation
					Air Permeability at 4 Pa (m^3/hm^2)	Air Permeability at 50 Pa (m^3/hm^2)	Air Permeability at 50 Pa (m^3/hm^2)	Air Permeability at 50 Pa (m^3/hm^2)
Property 1	2.48–8.94	0.967	0.706	78.686	0.92	5.44	4.84	5.17
Property 2	1.93–7.71	0.986	0.666	91.538	1.01	5.42	5.29	Incomplete
Property 3	1.99–8.34	0.974	0.683	87.398	0.98	5.53	5.18	5.28
Property 4	1.58–6.51	0.963	0.690	99.724	1.13	6.48	5.90	6.08
Passivhaus 1	3.19–7.03	0.971	0.498	43.980	0.38	1.35	2.17	Incomplete
Passivhaus 2	3.65–8.88	0.985	0.570	55.070	0.53	2.24	2.92	Incomplete

Table A2
Comparison of the air permeability predicted by the fan pressurisation method against the conversion formula and the pulse method. There are no fan pressurisation results for property 2 due to an error that occurred when the file was saved. AP_{50} is the air permeability measured by the fan pressurisation method at 50 Pa.

Test Building	Fan Pressurisation						Conversion Formula	Low-pressure pulse
	Pressure range (Pa)	r^2	n-value	Air flow coefficient (m^3/hPa^n)	Interpolation using the power law equation	Extrapolation using the power law equation	Derived using AP_{50} and the conversion formula	Interpolation using the power law equation
					Air Permeability at 50 Pa (m^3/hm^2)	Air Permeability at 4 Pa (m^3/hm^2)	Air Permeability at 4 Pa (m^3/hm^2)	Air Permeability at 4 Pa (m^3/hm^2)
Property 1	19.1–61.1	0.999	0.642	95.962	5.17	1.02	0.98	0.92
Property 2	Incomplete	Incomplete	Incomplete	Incomplete	Incomplete	Incomplete	Incomplete	1.01
Property 3	11.2–60.2	0.998	0.607	112.383	5.28	1.14	1.01	0.98
Property 4	11.7–50.0	0.997	0.660	105.245	6.08	1.15	1.17	1.13

Table B1
Comparison of the air permeability at 4 via the interpolation of pulse data against that predicted using the power law equation and the conversion formula in conjunction with the fan pressurisation method. There are no fan pressurisation results for property 2 due to an error that occurred when the file was saved. AP_{50} is the air permeability measured by the fan pressurisation method at 50 Pa.

Column ID	1	2	3	4	5	6	7
Column Formula	A	B	B-A	(B-A)/A × 100	C	C-A	(C-A)/A × 100
Test Building	Interpolated from pulse data	Extrapolated from fan pressurisation data	Difference between interpolated and extrapolated air permeabilities (m^3/hm^2)	Relative Percentage difference (%)	Derived using AP_{50} and the conversion formula	Difference between interpolated and predicted via the conversion formula (m^3/hm^2)	Relative Percentage difference (%)
	Air Permeability at 4 Pa (m^3/hm^2)	Air Permeability at 4 Pa (m^3/hm^2)			Air Permeability at 4 Pa (m^3/hm^2)		
Property 1	0.92	1.02	0.10	10.87	0.98	0.06	6.52

(continued on next page)

Table B1 (*continued*)

Column ID	1	2	3	4	5	6	7
Column Formula	A	B	B-A	(B-A)/A × 100	C	C-A	(C-A)/A × 100
Test Building	Interpolated from pulse data	Extrapolated from fan pressurisation data	Difference between interpolated and extrapolated air permeabilities (m^3/hm^2)	Relative Percentage difference (%)	Derived using AP_{50} and the conversion formula	Difference between interpolated and predicted via the conversion formula (m^3/hm^2)	Relative Percentage difference (%)
	Air Permeability at 4 Pa (m^3/hm^2)	Air Permeability at 4 Pa (m^3/hm^2)			Air Permeability at 4 Pa (m^3/hm^2)		
Property 2	1.01	Incomplete	Incomplete	Incomplete	Incomplete	Incomplete	Incomplete
Property 3	0.98	1.14	0.16	16.32	1.01	0.03	3.06
Property 4	1.13	1.15	0.02	1.77	1.17	0.04	3.54

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