Determining infiltration from the Pulse tests – the establishment of an evidence base of utilising a low-pressure approach for measuring building airtightness and energy modelling

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ABSTRACT

Building air infiltration rate is required as an important input in the calculation of building heat loss. Tests to directly measure infiltration rates are complex and time-consuming to perform, and are therefore usually substituted with an airtightness test as a more efficient alternative. An empirical ratio, or sometimes an infiltration model, is then used to predict the building infiltration rate from the measured airtightness value. For instance, in the United Kingdom the building air permeability measured by a steady pressurisation test and reported at 50 Pa (Q50) uses the so-called divide-by-20 rule to obtain the air infiltration rate. The blower door test, as a standard and widely accepted steady pressurisation method for measuring the building airtightness, takes the measurement in a range of high pressures (typically 10-60 Pa), which are regarded as being much higher than that experienced by buildings under natural conditions. Hence, an extrapolation is required and error could incur. The low-pressure Pulse technique has been developed to take measurements at low pressures (typically 1-10 Pa) directly and it therefore avoids the extrapolation process. However, it has been often asked how the test results given by the two different airtightness test methods compare with each other and how the Pulse test result can be used in the building energy assessment. A field trial study using the blower door, Pulse and tracer gas methods were carried out in over 100 dwellings to (tracer gas tests were conducted in 21 of them):

- identify the correlation between the test results given by the Pulse and blower door methods
- establish the correlation between the Pulse test results and infiltration rate to allow the infiltration rate to be predicted when the pulse test is carried out

The results showed that there is a strong correlation (a factor of 5.3) between measurements given by the blower door and Pulse methods and an initial Pulse-infiltration correction range (from 5 to 11) has been obtained.

KEYWORDS

Air infiltration rate, Airtightness, Pulse, Blower door, Tracer gas

1 INTRODUCTION

There has been increased focus on the energy use in the buildings as it is responsible for 36% of global final energy consumption and this goes up to 50% for the developed countries (Lombard 2008, IEA 2013, UNEP 2013). The relative proportion of energy losses associated with air infiltration has increased as the building thermal insulation has been improved over the last few decades. Airtightness fundamentally determines the level of infiltration occurring through building fabric and affects the building ventilation. The term, air leakage, is also used to describe how poor the building envelope is sealed and often contributes to 'unnecessary ventilation', which could account for over 60% of the energy wastage in commercial and residential buildings, through the loss of conditioned air (Orme 2001).

In the process of evaluating the energy consumption associated with infiltration, the measurement of building airtightness is a common approach taken to provide an estimation of the annual infiltration rate. Fundamentally determined by the airtightness, infiltration can also be affected by various building and climate-dependant factors, such as building construction, local terrain, shielding factor, wind conditions and ambient temperatures. The correlation between them can be addressed either by empirical models or numerical models (Younes 2011, Sherman 1987, Sherman 2009). For instance, a leakage-infiltration ratio was proposed between 1970s and 1980s as a quick estimation for infiltration when a building airtightness measurement was available and this approach was preferred by some professionals and researchers due to being easy and quick to use. The well-known leakage infiltration ratio is the divide-by-20 rule, which however was regarded as a crude way of predicting the infiltration rate because it can be affected by other aforementioned factors and this rule was lack of supporting research (Meier 1986). However, it has been adopted by the UK government as a standard method for calculating the annual infiltration rate based on a steady pressurisation test. The blower door method is the most commonly used steady pressurisation method and is therefore used widely to establish the infiltration models.

The novel Pulse pressurisation technique for measuring building airtightness at low pressures (Zheng 2019: Future Cities and Environment), which has gone through various stages of developments over the last 16 years from a cumbersome and heavy unit (Carey 2001, Cooper 2004, Cooper 2007) into a more portable and quick-to-use version (Zheng 2017, Cooper 2019). However, as a viable method for measuring building airtightness, the Pulse technique cannot be used to infer the building infiltration rate because an established correlation between the Pulse test and building infiltration rate is not available.

This paper reports the findings of onsite measurements of building airtightness and infiltration rate of over 100 dwellings (21 dwellings for infiltration measurement) using the blower door, Pulse and tracer gas methods. The leakage-infiltration relationship is appraised herein based on the field trial data to provide evidence-based information for the policy makers and fellow researchers. This also allows us to gain insights into the correlation between building air leakage given by the Pulse test and the infiltration rate by the tracer gas test. This field trial will also help us understand how the Pulse test relates with the blower door test. A comprehensive analysis accounting for the factors that affect the infiltration rate based on theoretical models is beyond the scope of this paper and will be presented in later publications.

2 EQUIPMENT, SETUP AND TEST PLAN

In this field trial, three sets of equipment were utilised including blower door unit, Pulse device and tracer gas kit, as listed in Table 1. All test equipment has been inspected by BRE, UoN and iATS[1] at different points throughout the field trial with UKAS calibration certificates held for all the equipment, sensors and supporting environmental condition sampling devices.

Table 1 List of main testing equipment

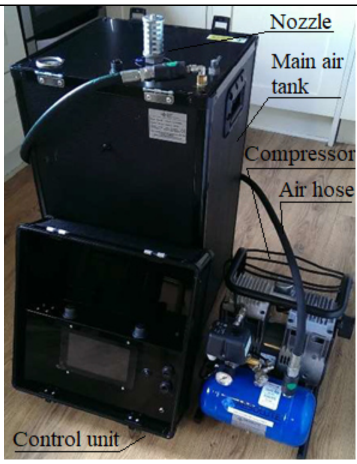
Item	Description	Serial Number
Pulse 585	Main 58.5L Pulse unit, ¾” air release valve	1021422
Pulse 398	39.8L Pulse unit, ½” air release valve	1021423
Energy Conservatory Model 3	Standard model	11233
Energy Conservatory Duct Blaster	Mini model	15752
Testo 511	Absolute pressure meter	39115414/803
Testo 110	Thermometer with thermistor type probe	33975032/707
x7 Sontay 0-5000 ±30 ppm CO_2 sensor	CO_2 concentration measurer	GS-CO2-1001-HR-LCD-1-7

[1] BRE: British Research Establishment; UoN: University of Nottingham; iATS: Independent Airtightness Testing Scheme Ltd

x6 PT-100 temperature sensors	Temperature sensors with a frequency of 1 measure per second	N/A
WindSonic RS232 solid state ultrasonic anemometer	Wind speed and direction with a frequency of 1 measure per second	18040109
DataTaker DT-85 Data logger	Data acquisition, recording rate at 1 second intervals for all connected sensors	112225

The three main testing devices are listed in Table 2 to illustrate the setup of the equipment in a test house. The building preparation complied with the standards (ATTMA TSL1, BS EN ISO 9972).

Table 2 Equipment and setup for the three testing methods

PULSE-60	Duct Blaster B	Sontay CO_2 sensor with mixing fan
		
Pulse unit	Minneapolis blower door	Tracer gas equipment

Where possible, the backdoor was chosen for the blower door installation due to less fittings in the doorframe and consideration of being accessible to other testers at the front door. The PULSE-60 was placed in the centre of the living room. In the setup of tracer gas test, the building was divided into 6 zones with one CO_2 sensor installed in each zone and placed 1.5 metre above the floor level (ASTM 2011).

A field trial plan and a testing sequence were developed to maintain the overall testing consistence throughout the field trial. It sets out the target sample size and the overall schedule of works. The conventions below were followed:

- Tracer gas testing was carried out according to ASTM E741
- Both blower door and Pulse tests were carried out according to ATTMA TSL1 2016 edition and to BS EN ISO 9972:2015 “Method 2”
- Additional Pulse testing was carried out in “Method 1” defined in BS EN ISO 9972:2015
- “Method 1 (unsealed)” and “Method 2 (sealed)” refer to sealing protocols outlined in BS EN ISO 9972:2015.

The testing sequence is described in Table 3. Tier 1 refers to Pulse vs blower door testing. Tier 2 refers to Tier 1 testing plus tracer gas testing. The timings are indicative of the typical length of time required for testing. In some of the tracer gas tests, over-night monitoring was implemented to obtain a satisfactory decay of tracer gas concentration.

Table 3. Field trial procedure and timings

Activity	**Est.time (mins)**
Attend property, meet representative on site. Photograph property. Set up laptop	60

Deliver Tracer Gas kit to property (Tier 2)	5
Deliver Blower Door kit to property	5
Deliver Pulse kit to property	5
Set up and start charging Pulse	2
Measure up property, calculate building volume and envelope area	25
Seal up: Method 2, document with photos	15
Pulse Test: x3 Method 2, recharge	5
Set up blower door	10
Blower door test: Method 2, pressure and depressure	25
Pack down blower door	10
Tracer Gas Test, Method 2 (Tier 2)	240-360
Remove sealing	10
Pulse test: x3 Method 1, drain	15
Pack down Pulse equipment, return to vehicle	5
Pack down tracer gas, return to vehicle (Tier 2)	10
Return blower door equipment to vehicle	5
Tier 1 Total (hours)	3.3
Tier 2 Total (hours)	7.5-9.5

3 CASE STUDY BUILDINGS AND ENVIRONMENTAL CONDITIONS

3.1 Case study buildings

A large representative sample comprising 108 homes has been tested. These comprised a wide range of new build and existing homes of varying degrees of performance, built form, age and size with testing carried out in a variety of environmental conditions throughout 2018. Overall, the sample is well balanced with an almost equal share between new building and existing properties. Although any pre and post works testing was beyond the scope of this particular field trial study, other property types tested include properties that have undergone extensive retrofit, Passivhaus and Enerphit.

As well as leakage, another important measure of the full operating range of the Pulse test system is in the size of the properties the device is able to pressurise. In terms of general overall representation, the English Housing Survey (EHS) unfortunately doesn't report the distribution of property volumes in England but 76% of homes are reported to have a floor area of up to 109 m^2 which if multiplied by a typical floor to ceiling height of 2.5m, equates to approximately 275 m^3. Of the homes tested under the field trial, 69% (74 properties) fall within the bracket of less than 300m^3.

Table 4. EHS 2017 percentage distribution of property size bands

Floor Area band	Approximate upper volume (m^3)	Percentage of English housing (%)
less than 50 m^2	125	9.7
50 to 69 m^2	173	21.2
70 to 89 m^2	223	29.0
90 to 109 m^2	273	16.3
110 or more m^2	500 (based on 200m^2 TFA)	23.7

These EHS statistics are further reinforced by the distribution of a 1000 EPC survey assessments where the mean volume is approximately 200m^3. A further 31% of the sample (34 properties) were tested with a volume of greater than 300m^3. Pulse has therefore demonstrated a clear ability to test across a full spectrum of building sizes, with the ability to tether multiple tanks offering similar system flexibility to the blower door technique where different size fans and flow restrictor rings were used.

3.2 Weather conditions

The field trial was undertaken from January 2018 to November 2018 with the order of testing dictated by the availability of properties, meaning that the weather conditions in which tests were carried out were random. However, tests were only performed when wind conditions met the requirement set in BS EN ISO 9972.

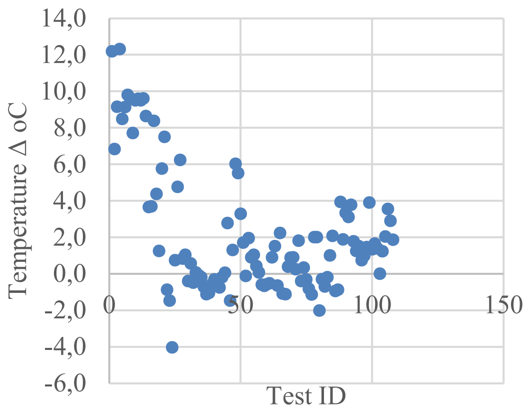


Figure 1 Distribution of temperature differential between indoor and outdoor across the sample

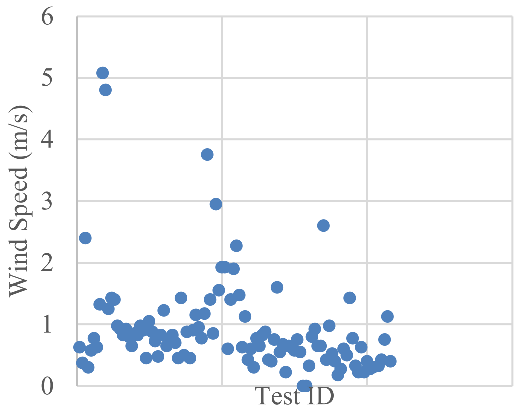


Figure 2 Distribution of ground level wind speed conditions across the sample

The outdoor temperatures ranged from 4 °C to 23.4 °C, and the indoor temperatures ranged from 11.5 °C to 23.4 °C. Figure 1 presents the spread of temperature differential between inside and out across the test sample. Ground level wind speed was also monitored and shown in Figure 2.

4 RESULTS AND ANALYSIS

4.1 Air leakage characteristics of the sample

The sample of the dwellings tested in the field trial provided a good spread of airtightness level, from very airtight to leaky, as shown in Figure 3 and Figure 4. It is considered to be a good representation of the leakage range experienced by airtightness testers covering highly leaky pre-retrofit buildings and the majority, as driven by the current building regulations, around the value for a typical new build property (3-5 $m^3/(h \cdot m^2)$ @50Pa). This is supported by the ATTMA lodgement statistics reported by Love (Love et al 2017) that most of the sample falls between 3 and 5 $m^3/(h \cdot m^2)$.

Of the 108-property sample, there was only 1 property where the blower door was unable to be used due to the lack of a suitable location to mount the door fan in the building envelope. There were nine properties where the Pulse testing was unsuccessful, five of which were Passivhaus standard properties tested early on in the field trial. In the particular Passivhaus tests it was found that, a standard 58.5L Pulse unit was oversized and thus over pressurising the building beyond the scale of (±25Pa) of the building pressure sensor. Conversely, two properties were so leaky that they were beyond the capability of two tethered Pulse tank units, leading to a failure of achieving a 4Pa pressure rise. For the final two, software malfunction led to the data being compromised with inadequate feedback presented to the tester when testing on site.

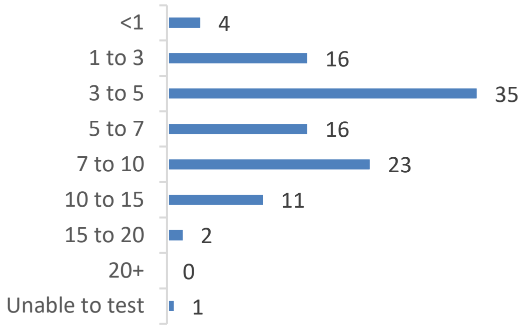


Figure 3. Spread of air permeability @50 Pa

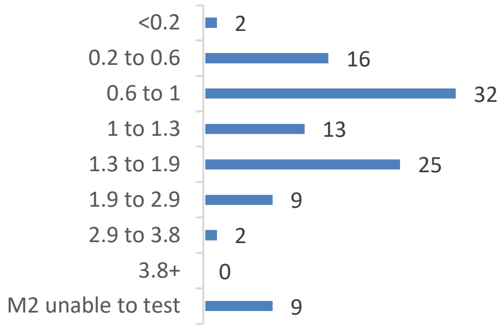


Figure 4. Spread of air permeability @4 Pa

4.2 Pulse vs. BD

Although the Pulse test is designed to take measurements of building air leakage at low pressures, its comparison with that of the steady pressurisation test at 50 Pa is often asked. Due to lack of direct measurement, errors will occur in the prediction of air leakage rate from one level to the other under natural conditions, as reported by Cooper in a field trial study (Cooper 2016). However, direct comparison at 4 Pa is possible to achieve in a sheltered environment where the wind and buoyancy effects are reduced, thereby making it easier for blower door to obtain accurate readings at low pressures. Initial findings showed that both methods provide measurements of Q_4 that are in close agreement under sheltered conditions when direct measurement is made (Zheng 2017). Theoretically, there should be a defined relationship between the blower door result at 50 Pa (Q_{50}) and a Pulse test result at 4 Pa (Q_4) provided the leakage characteristics of the test building stays unchanged when pressurised to different pressure levels (i.e. determined by the pressure exponent in the power equation). This Q_{50}/Q_4 relationship has been looked into in a series of experimental studies carried out in 16 buildings (Cooper 2019, Zheng 2019: Future Cities and Environment). It was found that the average value of Q_{50}/Q_4 (5.26), interestingly is in close agreement with the ratio (5.30) calculated using the average pressure exponent (0.66) in the power law equation obtained by steady state tests to a large sample size of dwellings in a number of countries reported by Orme (Orme, 1998). Nevertheless, the sample size of the test buildings needs to be increased in order to gain a more comprehensive and confident insights. The field trial reported herein provides a decent size of test sample, which should add sufficient weight to any finding that this study might provide.

For a direct conversion factor to be deemed viable, the data must fit well to a linear relationship. The quality of the relationship is governed by the r^2 value, which represents how far the data points deviate from the attempted fit within a confidence bracket. In this comparison the blower door results presented are the average value of the pressurisation and depressurisation tests undertaken, although it is not specified in any regulations that this approach should be undertaken it is regarded as best practise and should provide a more accurate measurement.

It has been shown that, in general, pressurisation tests tend to result in a higher air permeability (i.e. leakier) measurement than depressurisation tests when carried out in the same building. In a pressurisation test, the fenestrations such as windows, attic hatches are pushed away from the frame, creating leakage, while the opposite is true for depressurisation tests. In the field trial, the air permeability as measured by a pressurisation test was 5% larger on average than the result by depressurisation. This effect should be negated by using the average measurement of a depressurisation and pressurisation test. As shown in Table 5, the average value of Q_{50}/Q_4 is 5.33, which corresponds to a pressure exponent value of 0.663, thereby giving a close agreement with the value reported in the previous study (Orme, 1998).

Table 5. The conversion factor from Blower Door to Pulse

BDT	Q_{50}/Q_4 Conversion	Pressure exponent (n)
Pressurisation	5.41	0.668
Depressurisation	5.24	0.656
Average	5.33	0.663

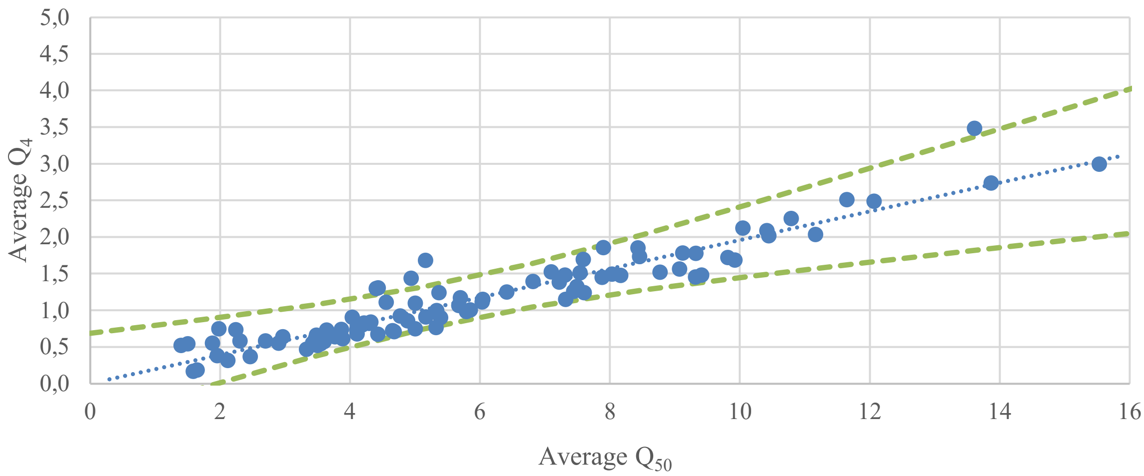


Figure 5. Relationship between measured Q_{50} and Q_4 values

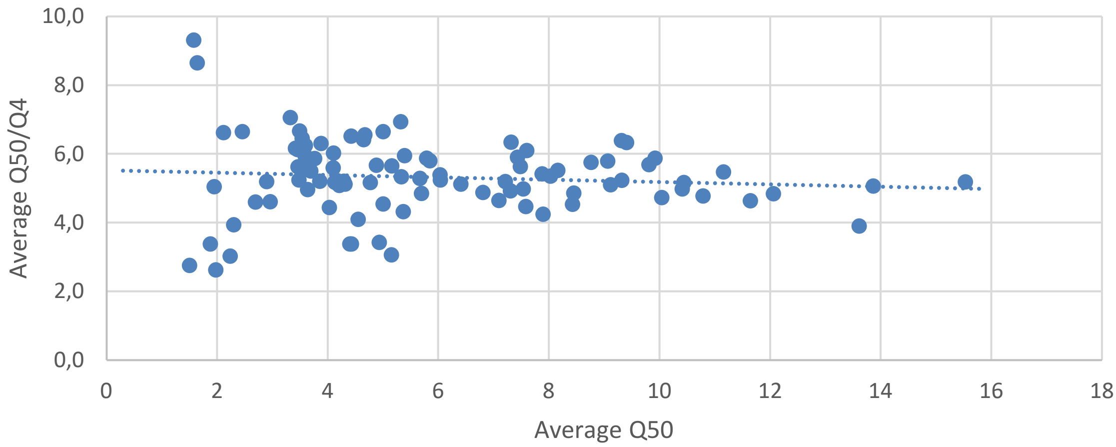


Figure 6 relationship between Q50/Q4 and building leakage

Overall, despite different testing approaches, a high degree of agreement has been observed between Pulse and blower door tests carried out in the field trial and supporting tests, thus giving confidence that a conversion factor can be used to compare the two measurements.

Absolute agreement between the two testing methods is not expected, because both have intrinsic uncertainties in their measurement due to sensor accuracy and system noise, which could be further enlarged by a number of specific differences in the nature of testing between the two tests, mainly including:

- The fan test technique is doorway mounted which itself leaks to varying degrees depending on positioning and testing mode (i.e. pressurisation or depressurisation)
- Pulse measures at 4Pa and tends not to exert pressures any higher than 15Pa in obtaining a measurement. This typically results in a difference in flow characteristics through gaps

and cracks in the fabric between Pulse and the blower door, leading to differing pressure exponent 'n' values.

4.3 Airtightness vs. Infiltration

It is widely acknowledged throughout industry and in supporting literature that a 50 Pa pressure is much higher than the pressure differences that drive infiltration under natural conditions. 4 Pa is regarded more representative of infiltration pressure. Nevertheless, in the absence of an adequate relationship linking the infiltration and airtightness, it is difficult to estimate the annual air infiltration rate with a good level of confidence using a measurement of airtightness.

Developing a more robust infiltration model was not the objective of this field trial. It was only intended to run a series of tracer-gas-decay tests alongside the blower door and Pulse to assess the validity of the current method adopted in the UK for evaluating the infiltration rate (SAP 2012) and explore correlations that the Pulse test might have with the blower door test and the tracer gas test.

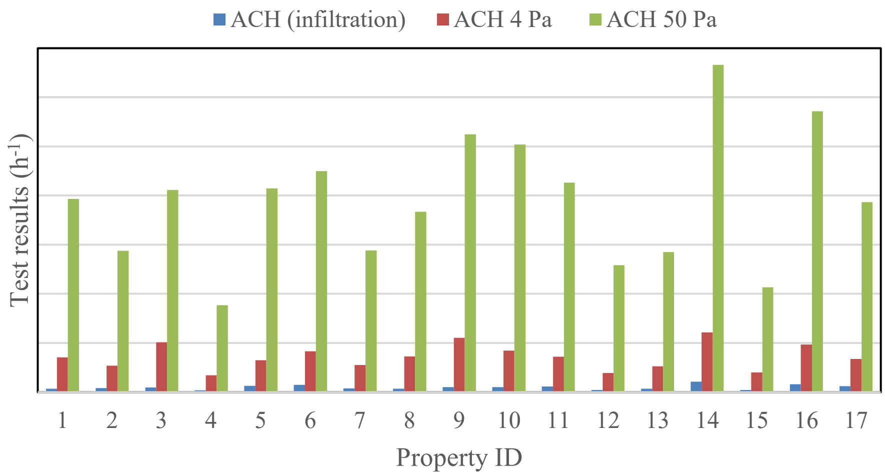


Figure 7. Directly measured air change rate (h^{-1}) by tracer gas decay, Pulse (4Pa) and blower door (50Pa)

Of the total 21 tests, 17 tests are deemed to have delivered reliable results, which are presented in Figure 7. Table 6 summarises the leakage infiltration ratios obtained in the tests using tracer gas decay, blower door and Pulse. Due to variations in building and testing conditions, the ratio varies from house to house. The ACH4/ACH ratio ranges from 5.26 to 11.40 with an average value of 8.16 while the ACH50/ACH ranges from 30.72 to 66.88 with an average value of 44.4.

Table 6. Ratios of air-change rate of 17 dwellings obtained in tracer gas and airtightness tests

Airtightness-infiltration correlation	ACH4/ ACH	ACH50/ ACH
Mean	8.2	44.4
Minimum	5.3	30.7
Maximum	11.4	66.9
Standard error	0.54	2.65

ACH, ACH4, ACH50 are infiltration rate, air change rate at 4 Pa and air change rate at 50 Pa measured in tracer gas test, Pulse test and blower door test, respectively.

Therefore, the divide-by-20 rule as currently used in the SAP (UK) to calculate the infiltration rate from measurements quoted at 50 Pa is far from the reality observed in this study. A ratio below 30.7 was not observed in any of the field trial properties, and the average of the results presented here would appear to better fit a divide-by-44 rule. This differs slightly from the ratio reported by Pasos et al (Pasos, 2020) due to different number of buildings included in this paper. Similarly, an approximate approach can be taken with the Pulse technique, where a ratio would more likely suit a divide-by-8 rule. As the Pulse result is measured at a pressure level much closer to the ambient condition and therefore makes Pulse a test method suited to measurement of infiltration.

5 CONCLUSIONS

The sample of field trial test properties has been shown to be representative of a range of dwelling sizes, forms, construction, ventilation system types and air leakage levels. The distributions based on these characteristics have also been shown to correlate with other studies and datasets relating to the profile of the UK housing stock.

With six Pulse and two blower door tests at each property in 108 dwellings and a tracer gas test at each property in 21 dwellings, this field trial presents a great opportunity of studying the relationship between leakage and infiltration in a range of dwellings using tracer gas method, blower door and Pulse techniques. The leakage-infiltration correlation has been assessed and the initial results showed that the leakage infiltration ratio produced by the blower door and tracer gas test deviated from the current divide-by-20 rule by over 100%. Discussions on the validity of divide-by-20 rule might not have much international significance due to the fact it has been discarded by the country where it was originated and the use of it has not been widely adopted. However, the field trial provides valuable insights into the leakage-infiltration ratio from an experimental perspective and therefore it allows us to have an updated understanding of it in the UK context and can be used as a benchmark for the countries that are currently establishing or going to establish the relevant standard. The results also showed that there is a clear linear relationship (a conversion factor of 5.30) between the measurements given by the Pulse technique and blower door method and encouragingly the linear relationship largely agrees with the average pressure exponent reported in the previous studies. For the Pulse technique, a divide-by-8 rule would provide a quick estimation of the annual infiltration rate if a simple leakage-infiltration ratio is sought in future.

The authors appreciate the practical value of using a leakage-infiltration ratio to provide a quick estimation of the annual infiltration rate when a measurement of building airtightness is made, and recognises the necessity and importance of looking at the leakage-infiltration correlation in a holistic way, which accounts for the factors affecting the infiltration rate to reflect the as-built infiltration behaviour.

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