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Uncertainty in building fan pressurization tests: review and gaps in research

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Abstract

Building fan pressurization tests are based on a measurement method developed in the 1970s to estimate the airflow rate that penetrates the building envelope through unintentional openings. These tests are increasingly used for compliance checks with building energy performance requirements and may result in severe penalties. The uncertainty of the measurement results has therefore become a key concern in several countries. To address this concern, this paper gives an overview of the current knowledge regarding the sources of error that impact measurement uncertainty. We first analyse the sources of error due to the underlying model of fan pressurization methods, described in commonly used standards such as ISO 9972 and ASTM 779-19. We then examine the sources of error due to measuring equipment, protocol, and analysis. The papers reviewed are classified according to the major findings relevant to the uncertainty analysed, to provide a holistic approach to uncertainty sources which is missing from the literature. Overall, this review shows that several sources are well known and can be quantified or contained within existing methods; for instance, the uncertainty of airflow and pressure measurement devices. It also brings to light the fact that there remain many unanswered questions and gaps in research. One specific concern is the assumed homogeneity

in space and time of the differential pressures across leakage paths. Although the literature shows that this can dominate the uncertainty in the result, it provides little guidance on how to deal with the role played by this problem in uncertainty analyses.

Keywords: building envelope; airtightness; pressurization; measurement; sources; uncertainty

List of abbreviations

LBNL	Lawrence Berkeley National Laboratory
ResDB	Residential Diagnostics Database
ATTMA	Air Tightness Testing & Measurement Association
q	volume flow rate, in cubic meter per hour [$\text{m}^3 \text{h}^{-1}$]
Δp	indoor-outdoor pressure difference, in Pascal [Pa]
C	air leakage coefficient, in cubic meter per hour per Pascal ⁿ [$\text{m}^3 \text{h}^{-1} \text{Pa}^{-n}$]
n	flow exponent [no unit]
GUM	Guide to the Expression of Uncertainty in Measurement
ELA	Effective Leakage Area
CFD	Computational Fluid Dynamics
OLS	Ordinary Least Squares method
WLOC	Weighted Line of Organic Correlation method
IWLS	Iterative Weighted Least Square method

1 Introduction

1.1 Context

Nowadays, building airtightness tests are commonly performed in several countries, including Belgium, France, Ireland, UK, US, to assess the real performance of the building envelope at the time of its completion. These tests aim to characterize the total air leakage rate through building envelope unintended paths. These paths can be located on the main envelope area, on the wall, roof and floor junctions, on doors and windows, due to building components penetrating the envelope, trapdoors, electrical components, door/wall and window/wall junctions, wood-burners, chimneys, elevators, cooker hoods, etc [1]. The geometry of these paths varies from large and circular orifice to long and thin cracks, with direct leaks through envelope and others leaks that are indirect and unidentifiable. Thus, the properties of the airleakage rate through each path vary as they depend on their geometry.

The vast majority of these tests rely on a fan pressurization method according to ISO 9972 [2] or ASTM 779-19 [3], or slight variations from these standards. Several databases gather fan pressurization test results, in particular for research purposes, policy impact assessment or compliance checks. For instance, the walker's residential diagnostics database (ResDB) included 75,000 data in 2013 [4]; the ATTMA database in the UK included 192,731 records in 2017 [5]; and the national French database which contains measurements performed by qualified testers included about 219,000 tests in 2019 [1].

These building pressurization tests are increasingly used for checks of compliance with energy performance requirements. Failure to comply with the requirements may result in severe penalties [6]. For instance, in Belgium, when the test is not performed, default values are taken into account in the energy calculation, inducing a huge penalty on the calculation result that may reach 15%.

Consequently, the uncertainty of the measurement results has become a key concern in several countries including Belgium, France, and Ireland over the past few years. First, controlling and reducing the measurement uncertainty is essential to obtain reliable test results. Secondly, when tests are mandatory, the situation on the ground and more especially the weather conditions may induce significant errors, that need to be evaluated in order to correctly analyse the measurement result. This has led to more stringent requirements for improving test quality using instruments such as competent tester schemes, calibration rules, or testing guidelines [7]. Out of 11 countries analysed in 2014, Leprince and Carrié pointed out four countries (France, Denmark, UK, and Ireland) where competent tester schemes were supported by regulations. Since then, several countries have reinforced their existing schemes while others have engaged in initiatives to reduce measurement uncertainty in building pressurization tests [8]. To develop such schemes, one would ideally like to have an overall picture of the sources of error and their potential impact. This would help prioritize issues to be dealt with in a particular scheme. Nevertheless, to our knowledge, there are no pre-existing studies giving a holistic view of the variables that can affect the uncertainty of an airtightness measurement result. These schemes therefore include elements based on science and experience to limit overall uncertainty or on very specific aspects impacting the results such as the accuracy of the measuring instruments [9], regression analysis [10], and wind [11,12]. These, however, have been developed with only a very partial view of uncertainty sources

1.2 Background

In the sixties and the seventies, the first building airtightness measurements using pressurization techniques were performed with different prototypes of pressurization devices for heat losses concerns [13–17]. The fan pressurization method for measurements of whole-

house leakage became common practice in the 1980s first in Sweden [18] and the US [19]. In 1984, four national standards described a test pressurization method [20]: the Swedish SS 02 15 51 “Thermal insulation - determination of airtightness of buildings”, the Norway standard NS 8200 “Airtightness of buildings. Test method”, the American standard ASTM E779-81 “Standard practice for measuring air leakage by the fan pressurization method” and the Canadian standard “Determination of the equivalent leakage area of building by the fan depressurization method”. These standards included requirements regarding flow rate, pressure measurements and overall uncertainty. They also imposed wind speed limits that had to be verified before performing the test.

During a fan pressurization measurement, the *“building airtightness levels are measured by using a fan, temporarily installed in the building envelope (a blower door) to pressurize the building. Airflow through the fan creates an internal, uniform, static pressure within the building. The aim of this type of measurement is to relate the pressure differential across the envelope to the airflow rate required to produce it. Generally, the higher the flow rate required to produce a given pressure difference, the less airtight the building”* [21]. In the fan pressurization test method, the model considers that the airflows through the building envelope and building components can be represented by a single airflow rate through a single equivalent opening. In this model, the relation between this airflow through this equivalent opening and the indoor-outdoor pressure difference is simplified with the power-law relation given by Equation 1 [18]:

$$q = C * \Delta p^n \quad \text{Equation 1}$$

where:

q is the volume flow rate [$\text{m}^3 \text{h}^{-1}$]

Δp is the indoor-outdoor pressure difference [Pa]

C is the air leakage coefficient [$\text{m}^3 \text{h}^{-1} \text{Pa}^{-n}$]

n is the flow exponent [-].

The flow exponent n varies from 0.5 for a completely turbulent flow (dominated by inertial forces) to 1.0 for a completely laminar flow (dominated by viscous forces) [19].

The objective of the pressurization test method is to measure an airflow rate for a given indoor-outdoor pressure difference Δp . To impose this pressure difference, a fan extracts air from the house or supplies air to it to maintain Δp . In stable conditions, the building envelope air leakage mass flow is considered equal to the mass airflow rate through the fan. Thus, for a given pressure difference Δp , measuring the airflow rate through the fan leads to air leakage.

To determine the air leakage for a specific pressure difference Δp there are three options:

1. impose Δp and obtain the air leakage directly (in reality, due to weather conditions and measuring device resolution, it is almost impossible to impose a given Δp exactly);
2. impose Δp , measure the associated airflow rates, and consider a fixed value for the flow exponent n . The value of C can be obtained for any pressure difference. This is known as the one-point measurement method.
3. impose several pressure differences and measure the associated airflow rates to determine values of C and n from a regression analysis applied to $\ln(q)$ and $\ln(\Delta p)$.

The airflow rate can be extrapolated to a reference pressure difference. This is known as the multi-point measurement method. This method, described in ISO 9972 [2] and ASTM 779-19 [3], is currently the most used.

While alternative methods exist, such as the AC pressurization technique [22] and the pulse pressurization technique [23], this article focuses on fan pressurization methods, as they account for most of the airtightness measurements performed nowadays.

1.3 Objectives

The purpose of this paper is to identify and to quantify the key sources of uncertainty in a building fan pressurization test in order to prioritize research efforts to better understand and reduce uncertainties in such tests. This entails the following objectives:

- identify sources of uncertainties analysed in the literature;
- identify methods to quantify their influence on the uncertainty in the pressurization test result;
- evaluate the barriers and gaps in research either to reduce or to characterize this uncertainty.

In addition, a specific desired outcome of this review is to clarify a map of uncertainty sources in building pressurization tests.

2 Approach

The approach to achieve this goal is mostly based on a literature review and interviews with experts. Over 45 papers (Table 1) dealing with building pressurization tests methods and uncertainties were selected and analysed. Table 1 categorizes these papers according to their key topics related to development of methods and uncertainty evaluation of fan pressurization test.

Table 1: Studies analysed in this paper according to topics relevant for this review

Topics relevant to this review	References
Regulations and Tester's scheme	[6–8]
Development of tests	[1,5,13–18,24]
Standards and guides	[2,3,21,25–28]
Alternative methods	[22,23]
Uncertainty of fan pressurization test	[1,4,9–12,19,20,24,29–63]

The international Guide to the Expression of Uncertainty in Measurement (GUM) [25] proposes definitions and methods relating to measurement uncertainty evaluation which are considered as references for metrology experts. According to the GUM [25], “*the measurement uncertainty, associated with the measurement result, characterizes the dispersion of the values that could reasonably be attributed to the measurand.*” A second concept explained by the GUM [25] is the measurement error, which has two components: a systematic component, which can be reduced by the application of a correction, and a random component, which can be reduced with multiple measurements.

The GUM [25] lists several sources of uncertainty in a measurement, including “*inadequate knowledge of the effects of environmental conditions on the measurement or imperfect measurement of environmental conditions*” and “*approximations and assumptions incorporated in the measurement method and procedure*”. In 1984, Persily and Grot [29] classified the sources of uncertainties for a fan pressurization test into two different families: the sources due to the test conditions (including the weather and the building’s leakages) and the sources related to the measurements performed to determine airflow rates and pressure differences (including device selection and calibration). Sherman and Palmiter [30] identified three categories of error that can impact the uncertainty of an airtightness measurement:

precision errors, biases, and extrapolation errors. In 2012, Carrié and Wouters [31] proposed another classification with 5 families of sources: 1) building preparation; 2) reference values; 3) sampling assumptions; 4) device uncertainty and software errors; 5) wind and stack effect, reference pressure, data collection protocol, and analysis method. More recently, Hurel et al. have listed four key sources of error, with errors due to measurement devices, to calculation assumptions, to external conditions and then to human factors [63]. The literature provides neither an exhaustive list of errors nor a standard classification of these errors. Sections 3 and 4 below focus on multiple specific sources of uncertainty classified into two families: the uncertainties due to physical model assumptions (section 3) and uncertainties due to measuring equipment, protocol, and analysis (section 4). Each section summarizes a review of the present knowledge, including how these sources affect the hypotheses of an ideal pressurization test, and the test results when available. Where knowledge was insufficient to quantify and deal efficiently with a specific issue, priority research efforts in specific areas are suggested.

3 Uncertainties due to physical model assumptions

In this section, the impact of the model used when performing a fan pressurization measurement is discussed. First, section 3.1 focuses on the variability of the indoor-outdoor pressure difference. In section 3.2, the choice of the flow equation to characterize the link between the airflow rate and the pressure difference is discussed. Finally, section 3.3 is dedicated to the correction applied to measured pressure differences regarding the zero-flow pressure value as indicated by standards.

3.1 Variability of the indoor-outdoor pressure difference

The fan pressurization technique is based on the measurement of the indoor-outdoor pressure difference. Questions have been raised regarding the impact of the location and the nature of the taps used to perform this measurement, especially regarding the effects of wind for the external tap, and the homogeneity of the internal volume for the internal tap.

During an airtightness measurement, each measured airflow rate corresponds to one pressure difference between the inside and the outside, measured at a specific location. This location remains the same during the whole test. This pressure difference needs to be as stable as possible in order to apply Equation 1 simply. The impact of the weather on the pressure difference measurement, namely the impact of wind and stack effects, therefore needs to be avoided.

For the internal tap, two requirements exist in standards ISO 9972 [2] and ASTM 779-19 [3]. ISO 9972 [2] requires that the tap shall not be influenced by the pressurization device. As for ASTM 779-19 [3], it defines a single zone as “*a space in which the pressure differences between any two places differ by no more than 5% of the inside to outside pressure difference*”. Nevertheless, it specifies that for a pressurization test, “*all interconnecting doors in the conditioned space shall be open such that a uniform pressure shall be maintained within the conditioned space to within 10% of the measured inside/outside pressure difference*”. The ASTM 779-19 [3] requirement regarding pressure homogeneity is therefore less strict than its definition of a single zone. ISO 9972 [2] is less demanding: it only mentions as a *good practice* for tall buildings to measure internal pressure on both the lowest floor and the top floor. However, none of the standards gives guidance to deal with stack effect due to tubing deployed at an uneven altitude between the tubing ends

and the differential pressure sensors. Note that a difference of altitude between the external tap and the internal tap induces an additional pressure difference that is not corrected.

For the external tap, ISO 9972 [2] recommends protecting the tap from the effects of dynamic pressure, especially in windy conditions. ASTM 779-19 [3] recommends, when possible, locating the pressure tap at the bottom of the leeward wall. In 1990, Modera and Wilson [33] tested averaging the result given by four pressure probes on a single-family house on which continuous measurements were performed. The measurement results were estimated using the ELA (Effective Leakage Area) index. The scatter of ELA values at 4 Pa remained below 11% for wind speeds lower than $5 \text{ m}\cdot\text{s}^{-1}$. This measurement scatter was compared to measurement scatter from another campaign in which measurements were made according to the Canadian standard requirements without the spatial-averaging and time-averaging used by Modera and Wilson. The scatter obtained with the new technique was half the scatter obtained with the Canadian standard requirement. In contrast, in 2013, Brennan et al. [32] found from a repeatability campaign that any location of the external tap on the leeward side of the building was the best configuration (better than averaging one tap on each facade). During a repeatability study performed on passive house, Bracke et al. tested different locations of the external and saw no significant difference between the different positions [59]. In 2019, Delmotte [55] proposed an explanation of the physics that apply on-field during a pressure measurement, particularly regarding the impact of the wind. He gives recommendations regarding the location (away from the building and any obstacle) and the nature of the pressure tap (T-pieces for example). In 2019 also, Novak [49] studied the impact of the location of the external pressure tap from 9 tests performed on the same building. He noticed no significant impact of the location but all tests were performed at low wind speed: the dispersion of the values obtained for 4 different locations around the building is only $5.2 \text{ m}^3\cdot\text{h}^{-1}$, for a value of q_{50} around $245 \text{ m}^3\cdot\text{h}^{-1}$.

Overall, this review on this topic shows that there is no consensus on the location of the pressure taps to reduce the impact of wind and stack effects on the uncertainty of the measurement result. While avoiding the dynamic effect of the wind seems to be a common objective among professionals and scientists, no method has been clearly adopted. Some field studies put forward spatial averaging of different external taps, whereas other field data support a unique tap on the leeward side of the building. Note that the error due to dynamic pressure greatly depends on the building characteristics (especially the pressure coefficient of the facade depending on the exposure) and the wind conditions (speed, direction, and fluctuations). This could explain these diverging conclusions. Recently, Carrié et al. performed simulation regarding stack effect during airtightness test in high-rise buildings [62]. Their results led to first recommendations, especially regarding the definition of the minimum and the maximum induce pressure. Delmotte also performed simulations using Monte Carlo method to produce statistics regarding systematic errors, including the variation of the indoor-outdoor pressure difference [61]. His study also led to a recommendation to fix the lowest induced pressure difference considering the largest zero-low pressure difference in the building envelope, in order to reduce the steady wind and the stack effect error.

3.2 *Flow equation*

The pressurization test method is based on the assumption that the leakage airflow rate is a function of the pressure difference between inside and outside the envelope. This section discusses the impact of using the model described by Equation 1 regarding:

- the choice of a power-law equation versus a quadratic equation;
- the variation of the leakage coefficient C ;
- the variation of the airflow exponent n .

3.2.1 Power-law versus quadratic

In 1978, Nevander and Kronvall [18] presented the testing methods defined by a group in charge of coordinating research regarding building airtightness in Sweden. They described the relation between airflow through buildings and pressure differences as a power-law relation (Equation 1). In 1980, Sherman and Grimsrud [19] explained that:

- at very low pressure, as the flow is dominated by viscous forces, the flow is expected to be proportional to the pressure difference;
- at high pressure, as the flow is dominated by inertial forces, the flow is expected to be proportional to the square root of the pressure difference.

From field measurements on buildings, Sherman and Grimsrud observed that the leakage airflow behaves similarly to turbulent flow: they therefore used a square-root relation in their model. In 1984, Etheridge [24] questioned the power-law relation and introduced a quadratic relation (Equation 2), which was already used for the characterization of components such as doors and windows. The mathematical formulation of the quadratic law is as follows:

$$aq^2 + bq = \Delta p \quad \text{Equation 2}$$

where a [$\text{Pa}\cdot\text{h}^2\cdot\text{m}^{-6}$] and b [$\text{Pa}\cdot\text{h}\cdot\text{m}^{-3}$] are constants.

q is the volume flow rate [$\text{m}^3 \text{h}^{-1}$]

Δp is the indoor-outdoor pressure difference [Pa]

Etheridge demonstrated that the power-law equation was more appropriate when all leaks in the buildings followed a power-law relation; and on the contrary, that a quadratic relation was more appropriate when all leaks followed a quadratic relation. He also concluded that whereas both approaches gave similar results at high pressure, low-pressure results could be very

different. He recommended that the coefficients of both relations should be calculated and quoted in pressurization test results.

In 1992, Sherman [39] demonstrated that the airflow through short circular pipes could be described using the power-law relation given in Equation 1. He explained that the application of this relation for building airtightness characterization assumed that all envelope leaks could be described as one unique circular leak. In 1998, Walker et al. discussed the choice of a better representation of the flow through building envelopes from field and laboratory measurements [34]. They concluded that the power-law relation was better for all of the configurations they tested in the field (on one house) and in a laboratory: with small cracks only, with both small cracks and large holes and for furnace flues. At the same time, Etheridge [35] kept defending the quadratic equation that he considered no harder to use and more practically adapted for fan pressurization tests. Later, Chiu and Etheridge performed CFD calculations to compare both methods on two models of cracks [36]. They evaluated the errors in infiltration prediction for the cracks they considered were two to three times larger with the power-law relation than with the quadratic equation at low pressure (between 4 and 10 Pa). More recently, Baracu et al. proposed a new relation: an extended power-law relation [37]. This relation is meant to better take into account the regime and the nature of the flow. According to experimental tests they performed on a passive house and numerical calculations, the extended power-law seems to be more accurate, but is still not suitable on site for large scale tests.

In all, the debate between power-law equation supporters and quadratic equation defenders is still active. Nevertheless, the power-law equation remains the relation used by airtightness testers. For this reason, the following subsections focus only on power-law based methods.

3.2.2 Variation of the leakage coefficient C

From Equation 1, it might be thought that the leakage coefficient C is a constant, but it is not.

First of all, the leakage coefficient C depends on the geometry of the orifices; more specifically the behaviour of components such as valves or seals. The behaviour of these components changes according to the intensity and the direction of the pressure difference. While ISO 9972 [2] recommends performing one set of measurements under depressurization and one set under pressurization, only one set is mandatory. This implicitly assumes that the behaviour of the building envelope can be characterized by measuring the airflow through leaks in only one direction, whereas the direction may change in real conditions depending on wind and temperature. Conversely, ASTM 779-19 [3] requires that data should be collected both from pressurization and depressurization. This appears more relevant since from 10 tests performed in repeatability conditions on a test house, Delmotte and Laverge [10] observed a significant difference between pressurization results and depressurization results. For the particular house tested in this study, all leakage airflow rates measured under depressurization (q_{50} from 698.6 to 738.0 $\text{m}^3 \cdot \text{h}^{-1} \cdot \text{Pa}^{-n}$) are lower than airflow rates under pressurization (q_{50} from 731.6 to 754.1 $\text{m}^3 \cdot \text{h}^{-1} \cdot \text{Pa}^{-n}$). This suggests that the ventilation behaviour of the building they tested was different under pressurization and under depressurization.

Secondly, for a fan pressurization test performed according to standards, the air leakage coefficient C needs to be corrected to take into account the impact of real conditions. In 2014, Carrié [38] determined the corrections that should be applied to the power-law coefficient C to take into account temperature and pressure conditions. These corrections stem firstly from differences between the conditions at the measuring device and the conditions at the leak, and secondly from differences between the real conditions and the reference conditions. According to his analysis, the C value depends on air viscosity, air density, and the flow

exponent n . The correction in ASTM 779-19 [3] includes the impact due to viscosity and density variations, but the correction in ISO 9972 [2] is incomplete: it does not include the viscosity correction. The impact of the correction greatly depends on atmospheric pressure, on the value of the exponent n and on the test mode (pressurization and depressurization). The absolute errors evaluated in this study varies from 0.0% to 11.6%. However, this may be, since it is easy to include in a measurement analysis, Carrié recommends applying this correction fully and systematically.

In all, the literature shows that the magnitude and direction of airflow, as well as temperature and pressure conditions can significantly affect the leakage flow coefficient. Information is also available to either reduce or correct the impacts of these parameters on the measurement result.

3.2.3 Variation of the airflow exponent n

For the multi-point test method described in ISO 9972 [2] and ASTM 779-19 [3], the method consists in evaluating one value for the leakage coefficient C and one value for the flow exponent n from pressure steps from 10 to 100 Pa. The test method assumes that the leaks are stable over the measurement period and that the n value is constant for all pressure differences applied during the test.

As the result can be extrapolated at several pressure differences including 4 Pa, the test method assumes that the n value is constant at an extrapolated pressure difference much lower than the test pressure stations. In such cases, the flow exponent may be poorly determined because of the extrapolation itself. This topic is discussed in section 4.4.

Another source of error linked to the flow exponent n lies in its variations with pressure. This subject has been investigated by Sherman in the specific context of laminar flow in short

pipes [39]. If n were constant, the power-law relation (Equation 1) would be absolute. Unfortunately, n depends on the pressure difference: therefore, this relation is a simplified model of the physical phenomena and may be responsible for errors.

This simplification was investigated in 2013 by Walker et al. [4] by evaluating the error due to a fixed exponent n for a one-point test method using a dataset of results of pressurization tests performed on six test houses from the Alberta Home Heating Research Facility in Canada. The one-point test method involves performing only one airflow rate measurement around 50 Pa and considering a default value for the flow exponent n , here 0.65. The coefficient C is calculated from the one-point measurement results and a q_4 or a q_{50} can be calculated from this C -value and the n -fixed-value. To evaluate the accuracy of this method and to compare it to the accuracy of the multi-point test technique, Walker et al. analysed 6007 tests performed on the 6 test houses in 97 configurations regarding open and closed flues, windows, and passive vents, in pressurization and depressurization. They evaluated first the variability of the exponent n due only to envelope behaviour: they considered only 301 tests for which the wind speed during the test was below 1.5 m s^{-1} . They evaluated that the standard deviation due to envelope behaviour was 0.063. Then, they evaluated the global variability of the n due to wind and envelope behaviour by analysing all measurements: the standard deviation was then 0.073. They concluded that the majority of the standard deviation for all tests is due to changes envelope exponents behaviour. Secondly, they evaluated the error due to the variability of the exponent n for a one-point test with a fixed value of n . They estimate that that fixing the n -value at 0.065 might induce an error between 15% and 21%. Nevertheless, note that the relative impact of the interpolation or extrapolation versus that of the pressure-dependence of the flow exponent is unclear in this study. A significant fraction of the standard deviation given by Walker and collaborators may stem from the statistical analysis beyond the pressure-dependence issue.

In summary on this topic, by construction Equation 1 does not account for the variability of the flow exponent n , but several authors suggest that this approximation might induce a significant error.

3.3 *Zero-flow pressure correction and measurement*

3.3.1 *A correction to eliminate the impact of wind*

During each step of the pressure difference sequence, the pressure difference between the inside of the envelope and the outside is measured. This pressure difference is due to the pressure applied by the pressurization device but also includes the natural pressure difference due to the wind and the stack effect. Wind and temperature conditions influence building airtightness measurement results because they affect the pressure difference seen by the leaks of the building envelope. As the duration of a pressurization test is around 10 minutes, the temporal variation of the temperature is most of the time too slow to have an impact on the result. On the contrary, the temporal variations of the wind may be fast enough to generate errors.

The pressurization test method requires that the pressure differences used to calculate leakage airflow rates are corrected by subtracting the natural pressure difference. This natural pressure difference is evaluated from two zero-flow pressure measurements: one performed before the pressure difference sequence and another after the sequence. ISO 9972 [2] requires that the zero-flow pressure is measured for at least 30 seconds (with a minimum of 10 values) and ASTM 779-19 [3] requires a 10-second interval. Firstly, the results of these two measurements are used to validate the test: both the zero-flow pressure differences measured before and after the test shall be below 5 Pa. ISO 9972 [2] detailed in notes two situations in which the limit of 5 Pa will unlikely be met: 1) with strong winds, i. e. *“if the wind near the ground exceeds 3 m.s-1 or the meteorological wind speed exceeds 6 m.s-1 or reaches 3 on*

Beaufort scale”, and 2) with important stack effect, i. e. “if the product of the indoor/outdoor air temperature differences (in Kelvin) multiplied by the height (in metres) of the building [...] gives a result greater than 250 m.K”. Secondly, the average of the results of these two measurements is used to correct the pressure difference measured during the sequence. Equation 1 is then corrected as indicated in Equation 3, where Δp_0 is the average indoor-outdoor pressure difference before and after the pressure sequence [Pa].

$$q = C * (\Delta p - \Delta p_0)^n \quad \text{Equation 3}$$

Etheridge and Sandberg [40] introduced this correction in 1996: they compared two theoretical curves of airflow rate depending on the pressure difference: one with neither wind nor temperature difference, and another with these two quantities non-zero. They calculated that the displacement due to weather conditions is constant: it should therefore be included in the equation to correct the result and eliminate the impact of the weather.

It can be shown that the zero-flow pressure correction using Equation 3 is strictly true for a network of parallel leaks, each with a flow exponent of 1. Nevertheless, this is only an approximation when the flow exponent differs from 1. Using Equation 3 as per ISO 9972 [2] or ASTM 779-19 [3] also implicitly assumes that the two series of 30 seconds – or 10 seconds – are representative of the natural pressure fluctuations during the test that lasts around 10 min.

The relevance of this correction with Equation 3 has been studied by Carrié and Leprince [42] in steady wind and isothermal conditions. They applied the zero-flow pressure correction and obtained significant errors due to wind: 12% for wind speeds up to 10 m.s⁻¹ at 50 Pa and 60% at 10 Pa. In other words, the zero-flow correction did not eliminate the impact of the wind. Later, Carrié and Mélois [56] modelled fan pressurization tests with a periodic wind. They also applied the zero-flow pressure correction, but they confirmed that this correction did not

eliminate the impact of the wind on the measurement result, as they calculated error due to wind up to 25% in their test conditions. The pressure differences induced by wind and stack vary spatially because of the variability of the spatial distribution of the wind pressures on facades; they also vary with time because of the time-dependence of the wind speed and direction as well as air temperatures. However, by construction Equation 1 does not account for these effects of spatial and time variations on the pressure seen by the leaks: it assumes that the effect of the pressures seen by the leaks on the leakage airflow rate can be viewed as a single pressure difference exerted on all leaks. Carrié and Mélois [56] suggest further research to contain the uncertainty due to fluctuations of the pressure signals. They mention using signal processing techniques to cross-analyse the wind spectrum and the measured values during the zero-flow pressure measurement to identify possible indicators that may determine the optimal duration of the measurement.

Overall, correcting Equation 1 to account for the zero-flow pressure as done in Equation 3 is convenient because it is simple and consistent when the flow measured through the blower door is zero. However, two uncertainty components stem from the zero-flow pressure correction: 1) the component due to the correction model itself, and 2) the component due to the estimation of the zero-flow pressure. The literature appears insufficient to be able to quantify these components in a practical manner for a general case.

3.3.2 Evaluation of the zero-flow pressure

In addition to the accuracy of the zero-flow pressure correction, the measurement of the zero-flow pressure itself has been investigated. During their repeatability study, Bracke et al. recorded the zero-flow pressure difference during 5 minutes and evaluate the maximal gap between different 30-seconds periods on one house, which was over 8 Pa [59]. In 2017, Delmotte [41] studied the impact of the assumption of a constant zero-flow pressure

difference on test uncertainty. He proposed a method to take into account the variability of the zero-flow pressure into the evaluation of the combined standard uncertainty of the induced pressure difference. He demonstrated that incorrect values for zero-flow pressure difference could lead to an error in the C and n values. Prignon et al. [43] went further on the quantification of the uncertainties in zero-flow and envelope pressures, using the experimental data from 31 tests performed on one building. They showed that the uncertainty on the zero-flow pressure measurement could significantly increase the uncertainty in pressure measurements, as they represents more than 75% of the envelope pressure uncertainties, and thus questioned the use of an ordinary least-square method. Nevertheless, this study did not confirm the better results obtained by Delmotte [41] with a bi-linear distribution of the zero-flow pressure values to correct the pressure measurements.

Prignon et al. reinforced their study with tests performed on 30 different buildings [57]. They conducted a statistical analysis to find variables with the most significant impact on the uncertainty on the pressure measurement due to the uncertainty of the zero-flow pressure. This analysis showed that increasing the duration of the zero-flow pressure measurement lead to reducing the uncertainty due to zero-flow pressure approximation. The authors gave the limitations of their work, mainly due to the size of their building sample and the need for field data to validate the model they created.

Based on numerical analyses on an idealized building, Carrié and Mélois [56] have shown that wind frequency was an important parameter to be considered in order to correctly assess the zero-flow pressure. This seems logical because if the sampling time is smaller than the period of the variations, the measurement will capture only one part of the change in the signal.

4 Uncertainties due to measuring protocol, equipment, and analysis

4.1 *Building preparation*

Performing a fan pressurization test requires specific work to prepare the building that includes installing the pressurization devices and closing and/or sealing components such as ventilation openings, fire-guards, smoke-guards, and letter boxes. How the building is prepared depends on the purpose of the test. For example, if the test aims at characterizing the envelope with its unintentional openings only, intentional natural ventilation inlets/outlets have to be sealed. Conversely, they would not be closed if the intention is to characterize the permeability due to all openings. This is the reason why ISO 9972 [2] defines three methods of preparation.

Leprince and Carrié compared the building preparation rules for 11 European countries from a questionnaire addressed to national representatives of airtightness testers [44]. They showed that most of the countries included specific requirements that might have a significant impact on the measurement result. Any comparison from one country to another should therefore be performed with caution.

In 2010, Rolfsmeier et al. [45] studied the difference between tests performed by 17 testers on the same building. The error on the test result varied from 7% to 63% when there was no specific work to prepare the building, whereas it stayed below 6% when the building was correctly prepared. Of course, for a specific measurement, the error is probably strongly dependent on building characteristics and applicable rules. Nevertheless, this study demonstrates that significant errors can be attributed to building preparation even when the testers apply the same rules. In 2016, Bracke et al. evaluated the difference between test results depending on the disconnection of the ventilation system for a passive house [59]. In

their case, this choice can lead to an additional airflow equal to $4.3 \text{ m}^3 \cdot \text{h}^{-1}$, or 17.6% of the total leakage.

4.2 *Sampling procedure*

For large buildings such as multi-family dwellings, ISO 9972 [2] offers the possibility to evaluate building airtightness by performing a pressurization test on only a part of the building. In Europe, different sampling methods are based on the total number of apartments or the total envelope area [46]. Performing a test by sampling implicitly means that the results obtained on the building parts are representative of the building as a whole and can be used to assign an airtightness rating for the whole building. Nevertheless, three parameters will affect the representativeness of the building parts. First, when the sampling procedure concerns a group of apartments with identical design, there are often differences from one apartment to another during the construction phase. These may be due, for example, to a change of construction companies, a change of workers, a change of material, or a change of internal partitioning required by the owner. All these changes may have an impact on the envelope airtightness. Secondly, a group of apartments may be considered as being similar but not identically designed: the number of rooms, the surface area of the windows and the wall surface area may change from one apartment to another. Representative sampling might therefore be difficult to achieve in this case. In turn, this might generate uncertainties on the results attributed to all apartments. Thirdly, when the sampling represents a part of one building, isolating this part completely might not be possible and the resulting ventilation behaviour might not be representative of the whole building.

Moujalled et al. evaluated the impact of different sampling methods for 10 multi-family dwellings [47]. They measured the airtightness of each apartment. They also performed a measurement of the common areas and a global measurement of the whole building. They

tested three different sampling methods. Their analyses showed that the sampling method gave results similar to the whole building measurement result only when all apartments presented uniform airtightness performance. They also showed that a leakage in the common areas could have a significant impact on air permeability of the whole building when they included the lift shaft and basement parking. Novak [48] conducted a similar study to test the sampling rules applying in the Czech Republic on one multi-family building. He showed that measuring only apartments could not lead to a correct estimation of the airtightness of the whole building because of the leakages between apartments and in the common parts of the building.

In turn, it appears that a sampling method to estimate the overall airtightness of a large building is often necessary for practical and financial reasons. However, none of the studies quoted above gives any guidance to help estimate the uncertainty induced by the sampling method, although their results show that this may be very significant.

4.3 Pressure measurement and airflow measurement uncertainties

During a fan pressurization test, two measurements are performed at the same time: an internal-external pressure difference measurement and an airflow measurement through the pressurization device (the fan). The uncertainties due to these measuring instruments must obviously be considered.

In 1984, Persily focused on errors due to calibration [50]. To ensure sufficient fan capacity, most blower doors measure airflow rates using a calibration formula to relate airflow rates to fan speed and pressure difference. The calibration formula depends on air density, which varies with pressure difference, temperature, and humidity. He calculated that the difference between the calibration conditions and the test conditions regarding temperature and pressure difference could induce differences of up to 10% on air density.

In 1991, Murphy et al. investigated the reproducibility and the repeatability of pressurization measurement from a series of measurements performed on four houses according to the method described in the ASTM standard [9]. Three operators performed 144 tests with four blower doors. Before each test, the blower door was completely disassembled. To maintain repeatable conditions, wind velocity and direction were measured and tests were performed only for wind velocity lower than 2.24 m s^{-1} (5 mph). To evaluate the repeatability of the tests, Murphy et al. compared the airflow-pressure curves obtained on the same house by the same operator. For each operator, the curves intersected a nearly identical point at high-pressure, but they differed by 20% at 4 Pa. The same tendency was observed for reproducibility: 7.5% at 50 Pa and 23.5% at 4 Pa. The bulk of these errors was attributed to the measuring devices.

In 1994, Sherman and Palmiter [30] estimated the global uncertainty of an airtightness measurement from calculations considering different sources. They first considered a systematic error equal to 2.5 Pa for pressure measurement that may be due to non-linearities in the gauge, calibration errors, hysteresis, and sticking problems. They also considered a bias error of 5%. For the airflow estimations, as these are usually performed from pressure drop measurements across a calibrated plate, they considered both bias error and precision error equal to 5%, to take into account the error relating to the determination of the plate properties. With this, they evaluated the overall uncertainty of an airtightness measurement by performing an error propagation analysis. At 50 Pa, the uncertainty due to measuring device uncertainties was estimated to be around 7%, whereas it reached 40% at 4 Pa. Carrié and Leprince [42] also considered bias and precision errors for both airflow measurement (95% confidence interval = 2% for precision error and 4% for bias error) and pressure measurement (95% confidence interval = 0.5% for precision error and 0.15% for bias error). For both a one-

point test and a 2-point test, the combined uncertainty for no wind at 50 Pa was around 5%. This estimate included only uncertainties due to measuring instruments.

Therefore, although measurement techniques and data acquisition techniques have developed considerably between 1984 and 2016, the drop in the uncertainty contribution of the measurement devices appears modest on the strength of the studies mentioned above. Clearly, this cannot be neglected in an uncertainty analysis. Fortunately, this contribution can be assessed using standard uncertainty analysis techniques extensively described in the GUM [25].

To contain those instrument errors, note that both ISO 9972 [2] and ASTM 779-19 [3] include requirements regarding measuring device uncertainty. For pressure difference instruments, standard ISO 9972 [2] requires an accuracy of 1 Pa on the range [0-100 Pa] while ASTM 779-19 [3] requires an accuracy of 5% or 0.25 Pa, whichever is the greater. Regarding airflow measurement, ISO 9972 [2] requires an accuracy of 7% while ASTM 779-19 [3] requires an accuracy of 5%.

Nevertheless, another subject of concern is the quality of the calibration. It seems that this is hardly ever analysed and yet it might induce significant uncertainty. In 2019, Leprince et al. [54] analysed the quality of the calibration performed on fans of various blower doors. They found that some laboratories had a low measurement capability index, which could give a large degree of uncertainty for the calibration result. Requirements regarding measurement calibration should therefore include requirements regarding either the quality of the calibration or the method used to include the uncertainty of the calibration itself in the total uncertainty estimation. Otherwise, the calibration might lead to significant errors due to the measuring device.

4.4 *Regression analysis methods*

When all data from measurements are collected, the airtightness of the building envelope is determined from a mathematical model. While ASTM 779-19 [3] requires the use of an unweighted linear regression technique to estimate the leakage coefficient C and the airflow exponent n , ISO 9972 [2] requires only a least squares method. In addition, ISO 9972 [2] includes an informative annex that recommends using an ordinary (unweighted) least squares method and provides all the equations for estimating C , n , and uncertainties. This technique is therefore widely used in practice.

In 2011, Delmotte and Laverge conducted a pressurization test campaign to evaluate the repeatability and the reproducibility of the test protocol with the currently used manufactured blower doors under low wind speed conditions [10]. They first performed 10 tests on one house under repeatability conditions, in terms of both pressurization and depressurization, with 10 pressure stations from 10 to 100 Pa. They calculated the standard deviations of three extrapolated airflow rates at 4, 50, and 100 Pa. For both depressurization and pressurization, the scatter was greatest at 4 Pa, with a standard deviation of 5.2% and 5.1% respectively. It decreased at higher pressure: 2.0% and 1.2% at 50 Pa, and 1.7% and 1.4% at 100 Pa. Delmotte and Laverge identified two main causes: variations due to weather at low pressure, and errors due to the non-weighted regression which were maximal at the lowest and the highest pressures.

Delmotte and Laverge proposed new calculations using weighted regression. These calculations led to lower standard deviations at low pressure and no significant change at high pressure. Ten other pressurization tests were performed on the same house by 10 different laboratories, under reproducibility conditions. Similar tendencies were observed. For both depressurization and pressurization, the scatter was greatest at 4 Pa, with a standard deviation

respectively 7.9% and 11.1%. It decreased at higher pressure: 2.5% and 2.9% at 50 Pa; 2.9% and 3.2% at 100 Pa.

Note that in 1994, Sherman and Palmiter [30] already questioned the use of an unweighted regression analysis highlighting the fact that this method assumes that uncertainties on pressure difference are negligible, which is not correct. At that time, they already recommended performing a weighted analysis.

In 2012, Okuyama and Onishi [58] explained that a weighted method should be used to take into account possible sudden changes from one measurement point to another, and so attribute a small weighting to measured values with a large error. They compared the results obtained from two different weighted methods (by residuals and by measurement uncertainty) to the results obtained from the unweighted method in different scenarios that included varying C value and wind turbulence. They concluded that the weighted method by residuals was more appropriate for airtightness measurement. In 2013, Delmotte [51] pointed out that the ordinary least squares method (OLS) is applicable only when the values of airflow rates are equally uncertain and the uncertainties on pressure differences are negligible. When the first assumption regarding airflow rates is not met (which may be the case in practice), he explained that a weighted least squares method should be used. When the second assumption is not met either, another method is needed. In 2017 [41], he analysed the suitability of a third method for airtightness measurement: the weighted line of organic correlation (WLOC), which considers both pressure difference and airflow rate uncertainties. Including also an evaluation of the uncertainty on the zero-flow pressure difference, he obtained a better repeatability standard deviation for the low-pressure stations than with the method described in the standards. In 2018 and 2019, Prignon et al. [43,52,57] performed a new zero-flow pressure uncertainty evaluation from field data and confirmed that the uncertainty of the zero-

flow pressure was not negligible. They confirmed that OLS was inadequate for airtightness measurement; only methods considering the zero-flow pressure uncertainty shall be used. This includes the WLOC method or iterative weighted least square (IWLS) method. More recently, Prignon et al. studied [53] the impact of the linear regression technique regarding the uncertainty of airtightness measurement results. They used data from the field to evaluate the impact of changing the linear regression technique, both on the airtightness results and on the uncertainties evaluation. They compared OLS, WLOC, and IWLS methods. They found that whereas the three methods give similar results regarding the average value of the airflow rate (for all pressure difference) and standard deviation (for pressure difference close to the centroid of the pressure sequence, here 50 Pa), IWLS and WLOC compared to OLS led to: 1) reduce the standard deviation of both in pressurization and depressurization, 2) reduce the uncertainty for the airflow rate for pressure differences away of the centroid of the pressure sequence, and 3) better estimate the uncertainty of the measurement result. Consequently, they suggest using WLOC or IWLS instead of OLS. In 2020, Kölsh and Walker used the data from tests performed previously on the Alberta Home Heating Research Facility in Canada to compare results using OLS and WLOC [60]. For half of the 7405 tests (109 different configurations) included in their study, the value for C and n obtained by OLS are different than the values obtained using WLOC. They observed that using a WLOC significantly reduces the variances in the tests results by 32% for n value and 22% for C value. They also showed that the bias due to wind at 4 Pa and 10 Pa are significantly higher for OLS than for WLOC.

4.5 *Reference values for derived quantities*

The last step in the process of an airtightness measurement is the calculation of derived quantities, i.e., the final measurement results. The most commonly used derived quantities include the air change rate at 50 Pa (n_{50} used for example in Germany), the specific leakage

rate at 50 Pa (q_{E50} used for example in the UK), or the specific leakage area at 4 Pa (ELA_{E4} used for example in the US). They involve three key reference values: the internal volume, the envelope area, and the floor area. Errors on these reference values are sources of uncertainties on the measurement results. To contain deviations, ISO 9972 [2] gives recommendations to calculate these reference values, including the following simplifications:

- The internal volume is calculated without subtracting the internal walls and floors, and the volume of the furniture;
- The floor area is calculated according to national regulations;
- The envelope area is calculated using internal dimensions, without subtracting the area at the junction of internal walls, floors and ceilings with exterior components.

Clearly, the underlying assumptions behind these simplifications should be assessed in the light of the context and purpose of the measurement to be performed.

In addition, evaluating the reference values brings in another component of uncertainty. Mathematically, this component is straightforward to include in an uncertainty analysis; however, the difficulty lies in assessing the uncertainty of the reference value itself. We are only aware of the French approach to this problem.

In this country [27], when the reference value is given by national regulations, the uncertainty of this value is considered equal to zero; when the reference value is calculated by the tester, the uncertainty associated with this value is from 3% to 10%, depending on the reliability of the drawings and the feasibility of the on-site measurements. It is a rough approach based on expert-statements which was found necessary because the significant contribution made by this component of uncertainty.

5 Discussion

The previous sections of this paper show that there are a number of aspects that can influence the results of an airtightness test by fan pressurization, although the key principles behind this method might seem simple and clear at first sight. There exists a significant body of literature addressing uncertainty in these tests. To give a quick overview of the literature analysed in this paper, Table 2 classifies the papers into three families and gives the major findings of the authors. Overall, there are a number of exploratory studies looking at specific cases and conditions and showing the significant influence of several parameters. Nevertheless, in general, the literature provides little guidance on how to deal with the contribution of these parameters in uncertainty analyses. None of the papers analysed address uncertainty in pressurization tests as part of a holistic approach.

The representation of the sources of uncertainty during a fan pressurization test shown in Figure 1 is an attempt to help fill this gap using a holistic approach. It summarizes the different sources of uncertainties for all variables used to calculate the result of a fan pressurization test. Figure 1 lists all sources due to the test procedure at each step of the measurement on the left (the preparation of the test, the pressure sequence and the calculation of the test results), and the external sources due to weather on the top (wind and temporal variations of the temperature). For each of the three main steps, different stages when uncertainty source can occur are identified in the second column, and the associated sources of uncertainty are named in column 3. Then Figure 1 connects the different sources of uncertainty with each value used in the test procedure, from the measured temperature and the zero-flow pressure difference, to the calculated test result, including the measured airflow rates and pressure differences, and the calculated C and n value. Figure 1 detailed all the

uncertainty connection for a test performed in pressurisation. As the diagram is the same in depressurisation, only the result appear is this figure in order to make it readable.

There are several sources of uncertainty that seem sufficiently documented to be readily included in uncertainty analyses. These sources include:

- Measuring device accuracy and calibration quality. Both aspects are covered in the GUM [25], but our review shows issues with the calibration quality in particular. One reason lies in the large range of airflow rates covered by standard pressurization devices to avoid switching devices in the field. Note that these sources of errors may require additional research work to be dealt with in an uncertainty analysis. If so, it would be mostly to match existing knowledge to the specific features of building airtightness tests;
- Temperature and pressure corrections to be applied to the airflow rate and the leakage coefficient. The corrections are well documented. It is unclear why they are only partially applied in ISO 9972 [2]. Note that these do not concern stack effect issues, which are discussed below.

As for the reference values, these carry an uncertainty component that is mathematically straightforward to address; however, the failure to properly include this component in uncertainty analysis seems to be due to the lack of statistical data relevant to specific types of measurements in specific contexts.

Similarly, it seems that the availability of field data relevant to specific contexts is often the major barrier to giving guidance to quantify the uncertainty originating from preparing the building. This uncertainty entails uncertainty components due to sampling and preparation of the part of the building to be measured (e.g., sealing unintentional openings). This issue seems to be properly understood now, although dissemination is always welcome to consolidate

good practice. In any case, it is clear that given the significant errors found in the literature with the sampling procedures, an estimation of the uncertainty due to sampling should be included in the uncertainty analysis of a pressurization test. Nevertheless, we are aware neither of guidance on this subject, nor of methods or data that could be used to derive this guidance. Note also that additional work on the sampling issue could be inspired by European standard EN 14134 [26] on performance measurement and checks for ventilation systems. This standard provides the sampling error associated with the size of the sample, depending on the total number of apartments or houses.

It may be relevant to pursue research work on regression methods. The ordinary (unweighted) least squares method has been widely used for decades; however, because fundamental assumptions are violated in its application to pressurization tests, a more appropriate mathematical analysis should apply. Methods such as WLOC and IWLS seem promising. With today's available computing power, it is unclear to us why these methods are not in use, since they would involve only a modest or no additional burden on the tester if included in software analysis tools for these tests.

The power-law model is another potential research subject because two components that are often seen as constants, namely the flow coefficient and the flow exponent, are in fact parameters that can vary during a pressurization test. As each opening air leakage coefficient depends a) on the intensity and the direction of the pressure difference, and b) on the density and viscosity of the air, the air leakage coefficient considered in Equation 1 also depends on these variables. In practice, this can be partially overcome by: 1) using a correction that includes the air density and viscosity; 2) using measurements performed in depressurization and in pressurization. The first point is documented as mentioned above. As for the second point, it is difficult to infer general conclusions from pre-existing work because the cases

investigated remain limited compared to the variety of cases that can be encountered in the field. Note also that bi-directional measurements are not mandatory in ISO 9972 [2] because some building designs prevent testing in pressurization and depressurization modes. To give just one example, this may be the case with a stretched ceiling where the ceiling bows down significantly when depressurizing the building.

As for the flow exponent, it remains unclear to the authors whether its recognised variations with pressure can lead to a significant uncertainty component. This remark extends to the choice of the power law versus the quadratic law where there remain active debates amongst the scientific community. Unfortunately, the discussions we are aware of do not always make clear the influence of the purpose of the measurement on the possible outcomes. In fact, different conclusions may be reached depending on whether the test is performed to verify if the envelope meets a requirement, or whether it primarily aims to estimate the infiltration airflow rate. In the first case, the chosen method for the test needs only to be consistent with the requirement. In the second case, it is preferable to choose a method that is most accurate near the operating pressures. This may appear to be favourable to the quadratic law that should be more accurate at low pressures; however, its cost-benefit over the power law remains unclear.

This review also shows that the reasons and limitations of the zero-flow pressure approximation are very poorly understood among both professionals and scientists. In fact, because the relation between the airflow rate and the pressure difference is not linear (except if $n=1$), the zero-flow pressure correction is only an approximation. Therefore, two uncertainty components stem from the zero-flow flow pressure correction: 1) the component due to the correction model itself: 2) the component due to the estimation of the zero-flow pressure. If these components were known, there would be little difficulty in propagating their

influence in an uncertainty analysis; our review shows, however, that there is a clear need for further research for proper characterization of these components. This is linked to the spatial and temporal fluctuations of the differential pressure across the leaks during the measurement.

In fact, looking back at Figure 1, temporal fluctuations and spatial variations of differential pressures remain in a group of uncertainty sources that have not yet been mentioned in this discussion, together with the duration of the measurement.

Concerning spatial variations, wind is clearly identified as a major problem, with different views on ways to minimize its effect, namely on the location of the pressure taps (average over the four walls, positioned to the leeward). Also, in addition to the temperature effect on the leakage flow coefficient and airflow rate which can be corrected, temperature differences may drive significant changes in pressure differentials across the envelope. ISO 9972 [2] and ASTM 779-19 [3] attempt to solve this issue by restricting the range of validity of the measurements with criteria on the homogeneity of the pressure difference across the leaks or between spaces in the part of the building to be measured. Furthermore, the zero-flow pressure requirement in ISO 9972 [2] is also meant to restrict changes in pressure differences across the leaks. In practice, these criteria disqualify many buildings from being tested according to these standards, in particular, high-rise buildings or buildings tested in windy conditions. Unfortunately, we have not found relevant literature addressing the uncertainty component associated with these spatial variations in a global uncertainty assessment.

On temporal fluctuations, there is also a clear need for research linked to signal processing techniques. With the uptake of relatively low-cost sensors and high-frequency data acquisition systems, analysing the pressure signal together with the wind spectrum could be helpful in deriving methods to better characterize the differential pressures, including the zero-flow pressure.

Finally, this review mentions the existence of testers' schemes that help to reduce errors due to tester practices. The use of software to perform the measurement, both to drive the blower door and to perform the mathematical analysis, can obviously eliminate many errors. Errors may still arise due to involuntary software errors, but these can be reduced by means of a validation process for the software. For instance, in France, Cerema provides a tool [28] to help editors verify that their software meets the requirements of ISO 9972 [2] and the French technical report FD P50-784 [27]. Other voluntary errors might occur which can be partially contained in a testers' scheme with appropriate controls. Nevertheless, all of the aspects mentioned in this last paragraph do not seem relevant for an uncertainty evaluation of an airtightness test.

Table 2: A summarized review of studies regarding fan pressurization test uncertainty

Authors	Ref	Family of uncertainty source	Sub-family	Detailed sub-family	Type of study					Conclusion related to this review
					Review	Theoretical	Calculations	Laboratory tests	Field tests	
A. K. Persily	[11]	O-U	-	-					X	- evaluated a 15% error on airflow rate for wind speed above 2.5 m s ⁻¹
A. K. Persily, R. A. Grot	[29]	O-U	-	-					X	- evaluated that uncertainties are largest outside of the range of the measured data and smallest around the middle of the measured pressure differences - evaluated that a combination of pressurization and depressurization data reduced the uncertainties
M. H. Sherman, L. Palmiter	[30]	O-U	-	-				X		- recommended performing a weighted analysis
F. R. Carrié, P. Wouters	[31]	O-U	-	-	X					- identified sources of uncertainty
Hurel et al.	[63]	O-U	-	-	X					- identified sources of uncertainty and presents existing works on the impact of the wind during fan pressurization tests
T. Brennan et al.	[32]	IMA-U	Variability of Δp	-					X	- estimated that an external tap on the leeward side of the building is the best configuration
M. P. Modera, D. J. Wilson	[33]	IMA-U	Variability of Δp	-					X	- evaluated a scatter for $ELA_4 \leq 11\%$ for wind speed $\leq 5 \text{ m s}^{-1}$ with time-averaged and space-averaged pressure measurement - evaluated a scatter with average technique = half scatter with the conventional method
P. duPont	[12]	IMA-U	Variability of Δp	-					X	- estimated that the error due to wind is from 24% to 74% with wind velocity from 2.24 m s ⁻¹ to 4.47 m s ⁻¹ (5 mph to 10 mph) in depressurization tests

J. Novak	[49]	IMA-U	Variability of Δp			X	- identified no significant impact of the tap location for 4 different locations: maximum gap of 5.2 m ³ .h ⁻¹ , for a value of q ⁵⁰ around 245 m ³ .h ⁻¹ .	
Bracke et al.	[59]	IMA-U	Variability of Δp			X	- identified no significant impact of the tap location	
Carrié et al.	[62]	IMA-U	Variability of Δp			X	- recommendations regarding the definition of the minimum and the maximum induce pressure due to stack effect	
C. Delmotte	[55]	IMA-U	Variability of Δp	-		X	- estimated that the location of the external pressure tap may induce a significant overestimation of the induced pressure (up to 13%)	
C. Delmotte	[61]	IMA-U	Variability of Δp	-		X	- recommends to fix the lowest induced pressure difference considering the largest zero-low pressure difference in the building envelope, in order to reduce the steady wind and the stack effect error.	
M. H. Sherman, D. T. Grimsrud	[19]	IMA-U	Flow equation <i>Power-law vs quadratic</i>			X	- observed that the leakage airflow behaves similarly to turbulent flow: for this reason, they used a square-root relation in their model.	
D.W. Etheridge	[24]	IMA-U	Flow equation <i>Power-law vs quadratic</i>			X	- questioned the power-law relation and introduced a quadratic relation - concluded that when both approaches give similar results at high pressure, low-pressure results can be very different. He recommended that the coefficients of both relations should be calculated and quoted in pressurization test results.	
I.S. Walker et al.	[34]	IMA-U	Flow equation <i>Power-law vs quadratic</i>			X	X	- concluded that the power-law relation is better for all configurations that they tested on the field (on one house) and in a laboratory
D.W. Etheridge	[35]	IMA-U	Flow equation <i>Power-law vs quadratic</i>	X	X			- defended the quadratic equation that he has considered no harder to use and more practically suited to fan pressurization tests
Y.H. Chiu, D.W. Etheridge	[36]	IMA-U	Flow equation <i>Power-law vs quadratic</i>			X		- calculated that errors in infiltration prediction are two to three times larger with the power-law relation than with the quadratic equation
T. Baracu et al.	[37]	IMA-U	Flow equation <i>Power-law vs quadratic</i>		X		X	- proposed a new relation: an extended power-law relation that takes into account the regime and the nature of the flow.
M. H. Sherman		IMA-U	Flow equation <i>Power-law</i>					- demonstrated that the airflow through short circular pipes can be

	[39]			<i>vs quadratic</i>	X		described using the power-law relation
C. Delmotte, J. Laverge	[10]	IMA-U	Flow equation	C variation		X	- observed that all leakage airflow rates measured under depressurization are significantly lower than airflow rates under pressurization
P. duPont	[12]	IMA-U	Flow equation	C variation		X	- observed that errors fell from 1% to 10% with an average result of combined pressurization and depressurization tests
F. R. Carrié	[38]	IMA-U	Flow equation	C variation		X	- justified that the impact of the incomplete correction depends on the atmospheric pressure and leads to a few percent difference in the airflow rate
I. S. Walker et al.	[4]	IMA-U	Flow equation	<i>n variation</i>		X	- evaluated that an error of 0.1 on the n-value may induce an error of 29% on q_4
M. H. Sherman	[39]	IMA-U	Flow equation	<i>n variation</i>		X	- explained that as n depends on the pressure difference, the power-law relation is a simplified model and thus may be responsible for errors
D.W. Etheridge, M. Sandberg	[40]	IMA-U	Δp_0	wind impact		X	- observed that the displacement due to weather conditions on the airflow rate curve is constant: it should therefore be included in the equation to correct the result and eliminate the weather impact.
F. R. Carrié, V. Leprince	[42]	IMA-U	Δp_0	wind impact		X	- evaluated the error due to wind when the zero-flow pressure correction is applied: 12% at 10 m s ⁻¹ at 50 Pa and 60 % at 10 Pa
F.R. Carrié, A.B. Mélois	[56]	IMA-U	Δp_0	wind impact		X	- observed that the error due to the wind is not eliminated by the zero-flow pressure correction
Bracke et al.	[59]	IMA-U	Δp_0	Δp_0 evaluation		X	- evaluate the maximal gap between different 30-seconds periods on one house, which was over 8 Pa
C. Delmotte	[41]	IMA-U	Δp_0	Δp_0 evaluation		X	- proposed a method to take into account the variability of the zero-flow pressure in the evaluation of the combined standard uncertainty of the induced pressure difference
M. Prignon et al.	[82]	IMA-U	Δp_0	Δp_0 evaluation		X	- estimated that the uncertainty on the zero-flow pressure measurement can significantly increase the uncertainty in pressure measurements

M. Prignon et al.	[43]	IMA-U	Δp_0	Δp_0 evaluation	X	X	- estimated that measuring the zero-flow pressure difference for more than 30 seconds leads to a small reduction of the zero-flow pressure measurement uncertainty
V. Leprince, F.R. Carrié	[44]	PEA-U	Building preparation	-	X		- observed that building preparation varies from one country to another
Bracke et al.	[59]	PEA-U	Building preparation	-		X	- evaluated the difference between test results depending on the disconnection of the ventilation system for a passive house: 4.3 m ³ .h ⁻¹ , or 17.6% of the total leakage
S. Rolfmeier et al.	[45]	PEA-U	Building preparation	-		X	- estimated that the error on the test result varies from 7% to 63% depending on building preparation, and stays below 6% when specific attention to building preparation is given
W. Walther, B. Rosenthal	[46]	PEA-U	Sampling procedure	-	X		- observed different sampling methods in Europe based on the total number of apartments or the total envelope area
B. Moujalled et al.	[47]	PEA-U	Sampling procedure	-		X	- observed that samples give a similar result to overall building tests only when apartments present uniform airtightness performance - observed that leakage in common areas may have an important impact on the air permeability of the whole building
J. Novak	[48]	PEA-U	Sampling procedure	-		X	- observed that measuring only apartments cannot lead to a correct estimation of the airtightness of the whole building
W. E. Murphy et al.	[9]	PEA-U	Δp and Q	-		X	- estimated repeatability: for each operator, the airflow-pressure curves differ by 20% at 4 Pa whereas they intersect at a high-pressure difference - estimated reproducibility: 7.5% at 50 Pa and 23.5% at 4 Pa
M. H. Sherman, L. Palmiter	[30]	PEA-U	Δp and Q	-	X		- estimated uncertainty due to measuring device uncertainties = 7% at 50 Pa, 40% at 4 Pa
F. R. Carrié, V. Leprince	[42]	PEA-U	Δp and Q	-	X		- estimated uncertainty due to measuring device uncertainties = 5% at 50 Pa
A. K. Persily	[50]	PEA-U	Δp and Q	-		X	- estimated that the difference between calibration conditions and test conditions could lead to differences of up to 10% on air density

V. Leprince et al.	[54]	PEA-U	Δp and Q	Calibration		X	- observed that low calibration quality induces high uncertainty for the calibration result
C. Delmotte, J. Laverge	[10]	PEA-U	Regression methods	-		X	- estimated that weighted regression leads to low standard deviation of the result at low-pressure reference
C. Delmotte	[41]	PEA-U	Regression methods	-	X		- observed better repeatability for low pressure using a WLOC
M. Prignon et al.	[43]	PEA-U	Regression methods	-		X	- explained that as the uncertainty on the zero-flow pressure measurement is not negligible the OLS is not appropriate
C. Delmotte	[51]	PEA-U	Regression methods	-	X		- explained that as the uncertainty on the zero-flow pressure measurement is not negligible the OLS is not appropriate
M. Prignon et al.	[52]	PEA-U	Regression methods	-		X	- estimated that WLOC and IWLS show lower standard deviation and better uncertainty evaluation than OLS
M. Prignon et al.	[53]	PEA-U	Regression methods	-		X	- observed that WLOC and IWLS lead to lower standard deviation of n and of C than OLS - observed that WLOC and IWLS lead to lower uncertainty of airflow rate at a pressure remote from the centroid of the pressure sequence - observed that WLOC and IWLS lead to a better estimate of measurement uncertainty
M. Prignon et al.	[57]	PEA-U	Regression methods	-	X	X	- explained that WLOC and IWLS should be considered instead of OLS
Kölsh and Walker	[60]	PEA-U	Regression methods	-		X	- 7405 tests (109 different configurations) : value for C and n obtained by OLS are different than the values obtained using WLOC for half of the tests. WLOC significantly reduces the variances in the tests results by 32% for n value and 22% for C value and the bias due to wind at 4 Pa and 10 Pa are significantly higher for OLS than for WLOC.
H. Okuyama, Y. Onishi	[58]	PEA-U	Regression methods	-	X	X	- estimated that a weighted method by residuals is more appropriate than un-weighted uncertainty methods and uncertainty methods weighted by measurement

Key: O-U: Overall Uncertainty

IMA-U: Intrinsic Model Assumption Uncertainties

PEA-U: Protocol, Equipment and Analysis Uncertainties

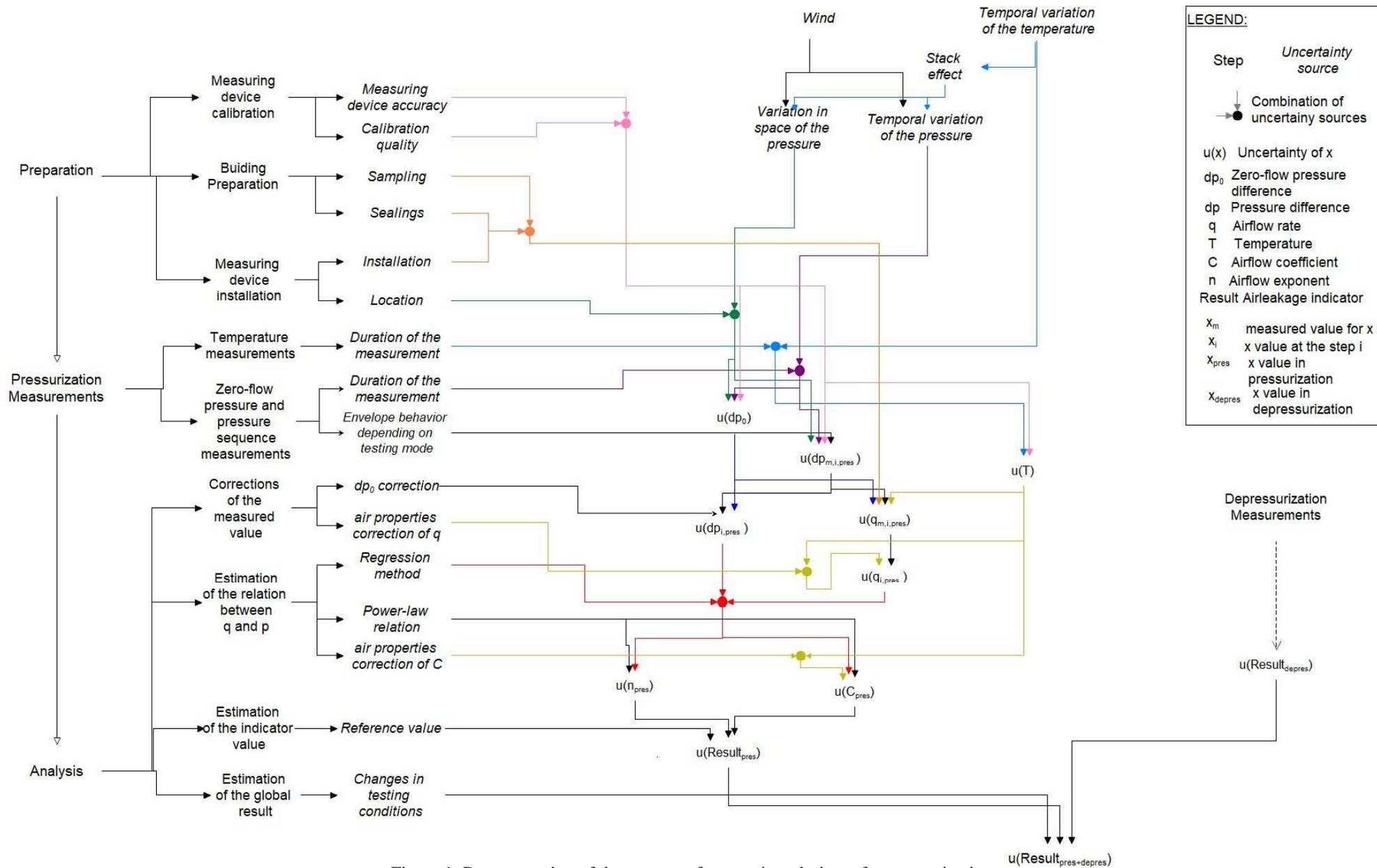


Figure 1: Representation of the sources of uncertainty during a fan pressurization test

6 Conclusion

The building fan pressurization test method aims at characterizing the permeability of a building by matching the parameters of a power-law relationship to a series of measurements of leakage air flow rates and differential pressures. Characterizing the uncertainty associated with this test method is key in many applications, including research and compliance to regulatory requirements. Our literature review shows that it is convenient to classify the sources of uncertainty into two major categories: a) errors stemming from the physical model assumptions and b) errors due to the instruments, the measurement protocol, and the analysis.

In the latter category, existing methods can deal with sources of error that lie in the measurement itself, i.e., the uncertainty of the instruments and the actions undertaken by the tester. This can be either with schemes to contain them when possible and justify neglecting them; or by quantifying them as part of a global uncertainty analysis. These methods include state-of-the-art guidance on measurement uncertainty evaluation or requirements and recommendations in standards or testers' schemes. From our review, there does not seem to be major obstacles to implement these methods in practice. In contrast, uncertainties arising from building preparation, reference values, and more particularly, sampling can remain difficult to address because the lack of field knowledge on relevant building stocks can prevent from setting proper rules to contain or characterize associated errors.

As for physical model errors, building pressurization tests assume that the leakage airflow rate through all leakage paths can be viewed as that flowing through a single opening according to a power law. Although the test method gives corrections to account for the heterogeneity of the differential pressures across the leaks or the temperature and pressure dependence of the power-law model, there remain errors. This literature review shows that these model errors can dominate the uncertainty in the results when wind or stack effects

compromise the assumed homogeneity of the differential pressures across the leaks. Although this problem is well-identified, there remains a considerable need for research both to reduce its impact with modified protocols and to quantify the corresponding uncertainties as part of a holistic approach to uncertainty assessment. This work may entail exploratory theoretical and experimental work in order to better understand the heterogeneity in space and time of the differential pressures, and to correct them more effectively than with the present zero-flow correction.

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