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Impact of wind on the airtightness test results

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Nomenclature

Roman symbols		
C	Air leakage coefficient	$m^3/(s \cdot Pa^n)$
C_p	Pressure coefficient	-
E	Error	-
n	Flow exponent	-
p	Pressure	Pa
q	Volumetric airflow rate	m^3/s
U	Wind velocity	m/s
Greek symbols		
Δp	Pressure difference	Pa
ρ	Air density	kg/m^3

Subscripts	
av	Averaged (pressurization – depressurization results)
BD	Induced by the pressurization measurement device (Blower door)
down	Downstream (leeward façade)
est	Estimated value
ext	Exterior
i	Interior of building
j	Index of leakage – external side
nowind	No wind condition
p+	Pressurization test
p-	Depressurization test
ref	Reference pressure
t	Total (up + down)
up	Upstream (windward façade)
0	Zero-flow pressure measurement

As a convention, to simplify notations in this paper for n<1 we assume that $X^n=\mathrm{sign}(X)*|X|^n$

1 Introduction

Building airtightness tests have become very common in several countries, either to comply with minimum requirements of regulations or programmes, or to justify input values in calculation methods. With more widespread use it has become increasingly important to understand and quantify the reliability of these tests.

There are four key sources of uncertainty in airtightness testing: measurement devices (accuracy and precision); calculation assumptions (e.g., reference pressure, regression analysis method); external conditions (impact of wind and stack effect); and human factors, such as consistent test apparatus installation.

While competent tester schemes and independent checking procedures show potential to contain errors due to human factors, there have been extensive yet inconclusive debates about how the building pressurisation test standard ISO 9972 should address other sources of uncertainties. As a result, no change has been made to address uncertainty since the last version of the standard which was published in September 2015.

Another issue is with limitations on allowable test conditions. With the present ISO standard, the zero-flow pressure shall not exceed 5 Pa for the test to be valid. Consequently, in moderately windy conditions, it may be impossible to perform a pressurisation test in accordance with the standard, even if an uncertainty analysis would show small test errors. On the contrary, the complexity of the wind impact during a test might lead to situations for which the 5 Pa requirements will be met, whereas the wind will induce an important error on the result [1].

This paper aims at:

- Presenting and discussing the calculation method of standard ISO 9972 regarding the uncertainty induced by wind.
- Gathering published knowledge and determining what further research is needed on the quantification of the wind impact on airtightness tests results. This includes numerical simulations, laboratory and on-site measurements studies.
- Giving guidance for minimizing and better estimating the wind impact on airtightness tests results.

2 Existing measurement standards

The international standard ISO 9972:2015, ASTM 779-19, and CGSB 149.10-2019 provide guidance for the determination of air permeability of buildings through the fan pressurization method. In those standards, the impact of the wind on the airtightness results is considered as follows:

Wind conditions

In ISO 9972, the wind speed must be recorded. A visual assessment with the Beaufort scale is considered sufficient. It is specified that a test is unlikely to meet zero-flow pressure requirements in case of a "ground wind speed" above 3 m/s, a "meteorological wind speed" above 6 m/s or if the wind reaches 3 on the Beaufort scale.

ASTM 779-19 states that strong winds shall be avoided.

Zero-flow pressure difference

The zero-flow pressure difference is the pressure difference between inside and outside when the building is not artificially pressurized, and is supposed to be an estimate of the magnitude of actual wind and stack effects.

The term "zero-flow pressure difference" is used in ISO 9972, but there is sometimes confusion about its actual meaning:

- pressure difference across the building envelope;
- or equilibrium internal pressure.

Theoretically, the zero-flow pressure difference across the envelope should be used to fix the lowest induced pressure difference. But monitoring and controlling the induced pressure during the test should be done by measuring the internal equilibrium pressure which is less sensitive to wind fluctuations than the pressure differences across the envelope [2].

In ISO 9972, the zero-flow pressure can be measured by temporarily covering the opening of the blower door and must be recorded over a period of at least 30 seconds with a minimum of 10 values. The following values are then calculated (see ISO 9972):

- the average of the positive values of zero-flow pressure difference, Δp_{01+},
- the average of the negative values of zero-flow pressure difference, Δp_{01-}, and
- the average of all values of zero-flow pressure difference, Δp_{01}.

The same measurements must be done at the end of the test (to obtain Δp_{02+}, Δp_{02-}, and Δp_{02}). If the absolute value of any one of these pressure differences is higher than 5 Pa the test is considered as not valid.

In ASTM 779-19, the zero-flow pressure is measured before and after the flow measurements, it is averaged on at least a 10s interval.
CGSB 149.10-2019 has an appendix of options for wind-pressure dampening for reducing test uncertainty. For time averaging, this standard recommends taking ten 10-second baseline pressure readings and increasing the required sampling time based on the variability between the ten measurements as follows:

- If the largest variation is ≤ 1 Pa the default 10 second time averaging is sufficient.

- For 1 Pa < variation ≤ 2 Pa use 20 second time averaging.
- For a variation >2 Pa use 30 second time averaging.

Pressure difference sequence

In ISO 9972, at least five approximately equally spaced data points are measured starting from approximately 10 Pa of indoor-outdoor pressure difference (Δp_i), with increments of at most 10 Pa and with a high-pressure point of at least 50 Pa. It is recommended to carry out two sets of measurements, for pressurization and depressurization.

In ASTM 779-19, induced pressure from 10 to 60 Pa with increments of 5 to 10 Pa are measured. Values are averaged over at least 10s. If this not possible, a partial range can be measured with at least 5 data points.

Pressure tap location

In ISO 9972, The pressure difference is usually measured at the ground level. It is required to ensure that the interior and exterior pressure taps are not influenced by the fan. It is recommended to protect the exterior tap from the sun and from the effects of air impinging on the open end (by using a T-pipe for example). It is good practice to place the end of the tap some distance away from the building and other obstacles. This suggests that ISO 9972 aims at testing equilibrium internal pressure.

On the contrary, the ASTM E 779 method suggests a pressure tap on each face of the building that is then averaged using a manifold. ASTM recommends when possible to collate the pressure tap at the bottom of the leeward wall. Both the American standard ASTM E 779-03 (§8.8) and Canadian standard CAN/CGSB-149.10-2019 (§6.2.2) are clear on the fact that the zero-flow pressure difference refers to the pressure difference across the building envelope.

CGSB 149.10-2019 also recommends using longer tubing (up to 30 m), the use of capillary tube and protecting the pressure tap using a drop cloth and avoiding practices that could increase the influence of wind, such as placing the outdoor pressure tap in a container or cavity.

Calculation of the air leakage rate

The average zero flow pressure difference Δp_0 (average between Δp_{01} and Δp_{02}) is subtracted from each of the internal pressure measurements (Δp_i). This would theoretically cancel the wind effect if:

1) the wind was steady in direction and velocity
2) and the flow was a linear function of pressure (n=1 in equation (1))

In real conditions, while imperfect, it reduces the impact of the wind on test results but does not eliminate it.

The ordinary least square technique is used to determine the air flow coefficient C and the air flow exponent n:

$$q_{BD} = C(\Delta p_i - \Delta p_0)^n \quad (1)$$

ISO 9972 claims that the overall uncertainty for tests in accordance with this standard can be calculated and is estimated to be under 10% for calm conditions and to reach 20% in windy conditions. Nevertheless, it may not take into account every source of uncertainty as discussed in [3].

The airtightness indicator is calculated from the determined C and n coefficients at a reference pressure which is usually 50 Pa but can also be 4 Pa, 10 Pa or 75 Pa.

3 Quantification of the impact of wind on the airtightness tests in literature

3.1 Simulation

3.1.1 Impact of steady wind

The impact of a steady wind on the airtightness test has been studied numerically. Although real winds are fluctuating in time and space, this is a first step to evaluate the impact of wind.

Bailly et al. [4] have studied with the software CONTAM the impact of wind depending on the airtightness levels with variable wind speeds (up to 9 m/s) and pressure (up to 70 Pa and -70 Pa) on three geometric models with different leakage distributions. They have concluded that:

- The wind could be responsible for significant errors on the estimation of Q_{4Pa_surf}, reaching more than 35% in some cases for an individual measurement of pressurization or depressurization with pressure conditions within the limits of the standard.
- Carrying out both pressurization and depressurization tests could reduce this deviation in a very important way.
- The pressure differences subtraction imposed by the protocol might not be the best one to reduce the measurement error.

Not long after, Carrié and Leprince presented a mathematical model to calculate the error due to steady wind in building pressurization tests [5]. It was applied to a simplified one-zone building model with one leak on the windward side and one leak on the leeward side, and a range of input parameters including a leakage distribution ratio ranging from 0.1 to 160 and a wind speed ranging from 0 to 10 m/s. The maximum errors were identified, and the main results are (with criteria of ISO 9972 fulfilled):

- At 50 Pa (high pressure point), the error on the estimated airflow rate due to wind is relatively small: within 12% for wind speeds up to 10 m/s;
- At 10 Pa, the error can reach 60% for wind speeds up to 10 m/s and is therefore very significant at the low pressure point;
- The results are very sensitive to the leakage distribution for the low pressure point. In detached buildings, the surface of leeward walls and roof is usually around 4 times greater than the surface of windward walls. In case of rather evenly distributed air leakages, characterized by a ratio between leeward and windward walls from 3 to 8, the error drops below 3% at 10 Pa.

The uncertainty due to wind is compared to other sources of error, namely bias, precision and deviation of the flow exponent in [6] and [7]. It is found as additional results that:

- At the high pressure point, the uncertainty due to wind up to 6 m/s remains smaller than that due to other sources of uncertainties, whereas when a two-point pressurization test is performed to calculate flowrate at 4 Pa, the impact of wind may become dominant at 4 m/s;
- For single-sided dwellings or zones, to estimate flowrate at 4 Pa, it is better to perform:
    - up to 5 m/s, a 2-pressure point test and extrapolate with a calculated flow exponent;
    - above 5 m/s, a test at 50 Pa and extrapolate to 4 Pa with a default flow exponent;
- The low pressure point is more sensitive to bias and precision errors;
- Having a constraint either on the zero-flow pressure or on wind speed seems effective to control uncertainty (provided these quantities can be adequately measured);
- Averaging results between pressurization and depressurization is mostly beneficial at intermediate wind speed (around 4 m/s) when a reference pressure of 4 Pa is used;
- The error due to steady wind depends on the leakage distribution and is mostly critical for single-sided dwellings.

3.1.2 Impact of unsteady wind

Wind has not only a potential impact on airtightness tests because of its mean intensity but also because of its fluctuations in speed and direction.

In [8], Carrié and Mélois model pressurization tests with periodic wind applying quasi-steady compressible and isothermal models of a pressurization test. Their analyses show that the wind fluctuations can yield much larger uncertainties than the average wind alone. In addition, they have shown the significant impact of the wind frequency on the results and have confirmed that ignoring the zero-flow pressure uncertainty is inappropriate because of its significant contribution to the uncertainty of the leakage airflow rate error. They estimate the uncertainty on the air leakage coefficient for one-point pressurization tests at a given pressure station, but their models can be extended to multi-point tests.

In addition, the impact of unsteady wind on the air infiltration was recognized and studied experimentally from the start of air infiltration studies [9] [10], even if mean values are until now usually considered to facilitate calculations.

Wind frequencies and the induced pressure on buildings was studied first for wind load calculations [11].

Cockroft and Robertson [12] looked at the effects of turbulence-induced ventilation on single openings and Crommelin and Vrins [13] expanded this for different window opening types.

In 1991 Haghighat also used this knowledge and presented a power spectrum analysis approach to model pulsating air flows due to turbulent wind-induced pressures with an application for a single-opening and a two-opening cases [14]. He used the empirical formula of Davenport to describe the wind velocity spectrum resulting from a study of about 70 spectra of the horizontal components of gustiness in strong winds [15]. The peak of the wind spectrum was found within approximately 2 minutes, a measurement of unsteady wind should therefore last longer to capture this peak. One conclusion was that for the single-opening case the turbulence in the airflow rate is concentrated in the higher frequency range (around 0.1 Hz) whereas for the two-opening case it is around the same frequency range of the wind pressure (around 0.008 Hz), which means multi-openings configurations are also necessary for experiments.

In UK, Etheridge studied the effect of fluctuating winds in natural ventilation design, inducing unsteady flow effects, with a specific focus on the instantaneous flow rates [16] and the mean flow rates [17]. Even if the conclusions are not directly linked to the airtightness tests issue, the wind fluctuation models can be drawn upon:

- Real pressure data using full-scale wind pressure measurements on a test building with a pitched roof [18]
- Hypothetical gust in low wind speed conditions with smooth transition to the gust with time to avoid discontinuities.

More recently, in a CFD study, Kraniotis [19] simulated the impact of wind gustiness on infiltration rates with two levels of gust frequency expressed as a sinusoidal factor in the wind profile formula, and various cases of internal and external leakage distributions. It was shown that the ACH increases from about 100% during a windy day (mean velocity of 5 m/s) characterized by high-frequent gusts of 0.5 Hz compared to low-frequent gusts of 0.1 Hz. In this case, wind gusts can create high pressure differences of the same magnitude as an airtightness pressurization test at 50 Pa. Gusts are therefore marked out as potential critical factors under unsteady winds, as well as the internal leakages since a relatively tight partition element could result in lower ACH. It is also pointed out that wind gusts have a more significant impact for evenly distributed air leakages between the windward and the leeward sides.

In [20] and [21], Kraniotis suggests a multiple linear regression based on a limited number of samples for the ACH prediction that takes into account the gust frequency, the gust normalized cumulative strength, the wind direction, as well as the mean velocity. When tested with various time intervals (1s, 2s, 1 min and 10 min) for depicting the wind gust phenomena, it was shown that the ACH is more accurately predicted for 1s and 2s time intervals, when high-frequency wind gusts are taken into account, the most gust the wind has the more the interval matters.

3.1.3 Limits and further research needed

Including stack effect and multizone buildings for steady wind simulations

On the simulation of the steady wind impact on airtightness tests, it would be good to carry out further research to combine the impact of the wind and stack effect, which was also highlighted by [6] [14]. Information is also missing on the interdependency of different zones, for example a crawl space attached to a building, concerning internal pressures and air movements at different wind and temperature conditions.

A better characterization of unsteady winds

With regard to the impact of unsteady wind, one critical point for accurate simulations is a good wind description, as shown by Haghighat et al. [14]. A large number of experimental measurements of the wind behaviour at high frequency (with various turbulence, roughness, intensity) would be helpful both to calculate wind spectra and to identify relevant-for-infiltration indicators for characterizing dynamic winds and wind gusts. It is, however, not easy to determine where exactly these measurements should be made:

- At a height of about 10 m, the wind can be measured without the influence of the surrounding obstacles, but differs from the wind impacting the façades of a real building in their specific environments.
- On the other hand, around a given building the wind is different at each point in its surrounding and such specific measurements, despite their value for understanding the local phenomena and explaining the deviations from the generally predicted results, may not be helpful for generalisation attempts.

Detailed wind spectra measurements were made in various locations for other fields of research such as wind energy assessment with tower measurement in Western Nevada, USA [22]; estimation of the wind load impact on structures such as the ALMA antenna in Chile [23] or the comprehension of meteorological phenomena such as the cold-air pools in Salt Lake City [24]. These spectra may be partially helpful for studies on the wind impact on airtightness tests but one should note that each of them are specific and appropriate to the purpose of the study, for example in terms of the measurement height, frequency and the intensity of the wind recorded.

It is also needed to quantify the variability of air flow rates driven by wind. The wind pressure coefficients used to convert mean wind speeds and air leakage test results into air flows already include turbulent effects, but only for a "typical atmospheric boundary layer". The effects of windward obstacles, such as neighbouring buildings, trees etc. on both mean windspeeds and wind pressures have been investigated in wind tunnel studies (e.g. [25] and [26]), flow visualization experiments ([27], [28] and [26]) and development of simplified estimates of surface pressures [29]. The flow fields in most urban environments tend to be complex and highly dependent on the specific building geometries being studied. This makes it impractical to provide guidance or calculation procedures that would account for these effects in air leakage testing.

Additionally, even with the same mean velocity and low turbulence wind direction fluctuations changes the wind pressures. It could be argued that short term wind direction fluctuations are "turbulence". Panofsky and Dutton (1986) estimated crosswind RMS velocities of about 20% independent of longer scale wind direction changes [30].

Simulations on pressurized buildings

There is a need for directly modelling the impact of unsteady winds on airtightness pressurization tests results, with cases of over and under-pressurized volumes. This would also allow to identify characteristics and indicators of unsteady wind that are most critical for this specific issue and value thresholds associated with estimated induced errors. As an alternative, the impact of the unsteady wind numerically studied in terms of additional infiltration rates can be translated into additional external pressure field (positive or negative) on the envelope and compared to the internal pressure induced during an airtightness test. This was done by Kraniotis [20] but could be applied to the other studies focused on the infiltration rates.

A better knowledge of leakages behaviour according to wind variations

Finally, real air leakages do not all have the same behaviour under wind gusts. One can assume that when facing high frequency wind gusts, because of fluid inertia in cracks and boundary layer development, small undirect air paths induce a reduced and delayed response in flowrates compared to large and direct holes. In order to have accurate numerical simulations, there is a need for first monitoring differential pressures variations across a large range of air leakages and for various types of wind gusts.

3.2 Laboratory measurements

3.2.1 Review of studies

Zheng et al. [31] have tested the airtightness of a chamber with both the blower door and the pulse method under various leakage and wind conditions. The measurements were made outdoors, but a steady wind with various velocities was artificially produced by a fan, which resemble laboratory conditions. They found out that for airtightness tests at 4 Pa, high wind speeds (4 m/s – 9.5 m/s) in one direction induce 16% to 24% lower results of air permeability, whereas it becomes mostly insignificant under 3.5 m/s.

In [32], Mélois has developed an experimental set-up to estimate the impact of wind on the result of airtightness test (Figure 1). Part of the work performed aimed at reaching a realistic representation on a reduced-scale model. First measurements focused on the comparison of one-point, two-point and multi-points (ISO 9972) measurements. According to her result, under steady wind conditions, the ISO 9972 analysis is more appropriate than a 1-point method and a 2-point method for an airtightness indicator at 50 Pa. For an indicator at 4 Pa, the following results have been obtained:

- When leakage is mostly on the leeward side, the ISO 9972 measurement method is more reliable than a 1-point method and a 2-point method, for all wind speeds;
- When leakage is mostly on the windward side, a 1-point analysis with a pressure station at 50 Pa or 100 Pa gives lower error when the wind is above 4 m s-1.

Until now, to the best of our knowledge, there is no other laboratory measurements results published on the impact of wind on airtightness tests, but related studies have been published in the past decades.

One closely related field of research is the determination of the external pressure coefficients Cp on buildings. A large number of studies have been carried out in wind tunnels, mostly with reduced-scale measurements under steady wind conditions, to characterize the pressure on the envelope of typical geometries or specific constructions [33]. Most studies reproduce the vertical mean and turbulent wind profiles found in atmospheric boundary layers when measuring wind pressure coefficients suitable for ventilation calculations (as opposed to structural loads).

Akins et al. [34] measured surface pressures on a cube rather than a model house but their values of Cp are within the range of values presented elsewhere (1989 ASHRAE Handbook of Fundamentals [35], Liddament [36] and Wiren [25]) for isolated buildings. Akins et al. also covered the most comprehensive set of wind directions and thus their data is most useful in developing correlations of pressure coefficients with wind angles. Wiren also included tests of houses in rows (typical of most residential neighbourhoods) and for pitched roof surfaces [25]. Sheng at al. [37] have carried out reduced-scale wind tunnel measurements on a high-rise building. They managed to reproduce well the theoretical mean velocity, turbulence intensity and power spectra of the expected modeled atmospheric boundary layer (ABL) according to Eurocode 1 [38] using roughness elements. However, the lower the building, the more the environment is impacting the ABL and theoretical wind characteristics are less representative of reality.

Jafari et al. noted that if it is possible in wind tunnels to achieve similarity of the turbulence spectra, length scale and intensity for large structures as high-rise buildings, for low-rise buildings the similarity is often compromised by technical challenges [39]. As a consequence, the pressure coefficients measured in wind tunnels are less accurate. Hölscher and Niemann noted for example a peak pressure coefficient varying by 12% when increasing the building model height from 100 mm to 250 mm in six studies [40].

Van Beek et al. [41] could match wind tunnel and field tests results for wind gusts longer that 3s by applying a pressure correction based on the ABL turbulence. However, they concluded that for more extreme gusts (<3s) a spectral scaling of the ABL has to match the model scale since they interact with the ABL turbulence structures.

As for simulations, unsteady winds are also studied in laboratory for their impact on the natural ventilation. Chiu and Etheridge [42] have carried out measurements in wind tunnels to determine the impact of unsteady winds on the airflow in naturally ventilated buildings with stacks and detect flow reversal phenomena. Pressure fluctuations were generated in the tunnel but with the purpose to be close to what can occur at full-scale, without trying to reproduce specific characteristics of unsteady winds.

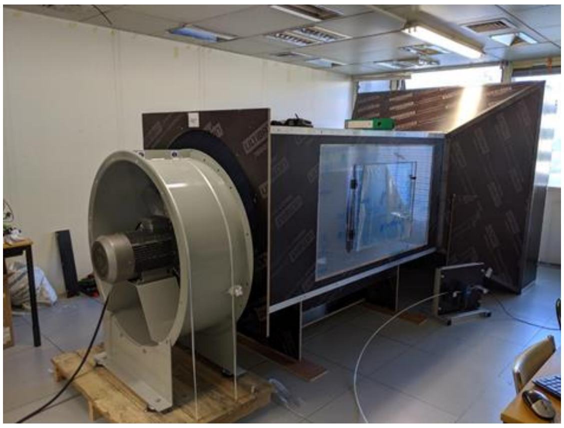

Figure 1: Wind tunnel developed at ENTPE, France, to test the impact of wind on building airtightness test

3.2.2 Limits and further research needed

Laboratory measurements have the advantage of easily allowing parametric studies, by changing for example the wind speed, wind turbulence, the geometry of the building and of the openings, etc. However, wind is artificially created in wind tunnels and it is not possible to reproduce the exact spectrum of a given natural wind. The experimental studies of Van Beek et al. [41] and Jafari et al. [39] have both pointed out the difficulty of reproducing the turbulence spectra in wind tunnel for the determination of pressure load due to unsteady wind. They recommended to match the spectral scaling of the ABL respectively for gusts shorter than 3s (with the possibility of applying corrections for longer gusts) and for reduced frequency between 0.01 and 1. There is a need for similar additional studies to define clearly how the unsteady wind should be modelled in wind tunnels for the study of its impact on airtightness pressurization tests: what parameters are most significant, what corrections could be applied to offset modelling assumptions and in which conditions.

The study of buildings in the laboratory requires the use of reduced-scale models. The resulting geometry simplifications can be a limit for the accuracy of the results, as well as the scale effect, especially for wind gusts under 3s [41]. The equality of the Reynolds number can hardly be achieved in wind tunnels for low-rise buildings and the violation of the geometric scaling leads to a mismatch of the turbulence spectra [39]. It is therefore not possible to duplicate the integral scale of the turbulence [43] and it is not clear yet from the literature which of the peak of intensity or the high-frequencies should be more correctly reproduced to capture unsteady wind loads.

Moreover, as for simulations, the wind tunnel experiments focus on the wind-driven air infiltration and airing, but the stack effect is also of importance. Hayati [44] noted that if the stack effect mechanism was out of his study's scope, it is often at least as important as wind as airing driver and should consequently be included in further studies.

Despite these difficulties, laboratory measurements can allow studies at the air leakage scale to characterize the differential pressures variations across a large range of air leakages and winds, as mentioned in paragraph 3.1.3.

Finally, leakages should be modelled with accurate C and n coefficients. As shown by equations (7) and (11) in annex, the error induced by a steady wind is theoretically zero for n=1.

3.3 On site measurements

3.3.1 Review of studies

On-site full-scale measurements have the advantage of studying the wind impact under real conditions, with both natural wind and a real full-scale building. They are more and more used worldwide, in particular for validating model-scale results.

In [1], series of in-situ measurements of wind and pressurization tests were conducted in a test module located in an open terrain. The findings reveal that the variance of the orthogonal components of wind velocity, and therefore turbulence intensity, is proportional to uncertainties of pressurization tests. The change in wind direction showed generally less correlation with the calculated uncertainty, compared to the wind speed. Furthermore, the results show that the variation in wind direction is inversely proportional to the uncertainty: when wind direction changes a lot (and therefore the pressure distribution around the building), the test becomes more reliable. As expected, when the wind blows against the fan, or a big leakage, the main source of error is due to this direct flow of wind on the fan (or on a big leakage), it overlaps any other source of error related to wind.

Walker at al. [45] [46] have analyzed over 6000 blower door measurements from six test houses tested in various configurations by opening and closing flues, windows, passive vents to get a wide range of airtightness levels, leakage distribution and air flow paths. With up to 100 tests by configurations and using on-site wind measurement at 10 m they could study the errors induced by fluctuating wind pressures. They found out as main conclusions, which are rather consistent with the more recent simulation results mentioned above [6], that:

- For low wind speeds below 3 m/s, multi pressure point testing is recommended and is about 10% better at estimating the equivalent leakage area at 4 Pa than single-point testing, mostly because of the error due to the fixed exponent assumption.
- For wind speeds above 6 m/s, single point testing at 50 Pa is recommended, since it is less subject to wind pressure fluctuations errors.
- An average of pressurization and depressurization tests results should be used, otherwise the additional uncertainty is estimated at about 12%.

Another on-site study has been carried out by Rolfsmeier and Simons [47] on a tall building of about 60 m. As illustrated in Table 1, two pressurization tests were carried out in different weather conditions. It was shown that by averaging the results of pressurization and depressurization tests, it was possible for this building to obtain reproducible measuring results, despite very high winds on the first test. It is mentioned that the impact of the wind was reduced by averaging the measured values of 3 test points located on different sides of the ground floor.

Table 1: Airflows V50 of the airtightness test under two different weather conditions [47]

	TEST 1 (Wind 4 Bft; ΔT= 9 °C) Airflow V_{50} (m³/h)	TEST 2 (Wind 0-1Bft; ΔT= 14 °C) Airflow V_{50} (m³/h)	*Difference*
Negative pressure	5567	4833	-13%
Positive pressure	4219	4859	+15%
Mean value	**4893**	**4846**	**-1%**

Figure 2 : Building tested by Rolfsmeier and Simons [47]

3.3.2 Limits and further research needed

On-site measurements results are giving precious indications on the impact of natural wind on real-scale buildings, in particular the on-site study of Walker et al. [45] on airtightness pressurization test results. It is, however, difficult to draw general conclusions from the study of only 6 houses located in the same place. Moreover, the opening and closing of elements, such as big as windows, to artificially vary the airtightness level of the buildings may not be representative of reality, since large openings have no resistance to the airflow.

The same limitation applies for the study of a 60 m tall building [47], with the difficulty of drawing general conclusions based on one specific case. As discussed in annex, averaging pressurization and depressurization results reduces the error but depending on the leakage distribution, the wind velocity and the tested pressures, it seems that the error can still be significant.

As a result, there is a need for a significant number of additional similar measurements in various locations, with a large range of wind characteristics and on various types of buildings geometry, leakages and leakage distributions.

4 Minimizing and better estimating the wind impact on airtightness tests results

4.1 Pressure difference measurement method

The Δp_0 measurements allow both to avoid tests in case of strong wind and stack effects (Δp_0>5Pa) and to minimize these effects with a subtraction on each pressure measurement during the pressurization test. If the interest is focused on wind, one should note that it gives information on the average response of the building rather than the impact on pressure differences at individual air leakages. This subtraction would therefore be appropriate for linear behaviour (n=1) but in reality, because of the non-linearity and as discussed in annex, it is possible to measure a Δp0 (induced pressure) of zero, but still have a significant error due to wind in the flowrates estimation. Moreover, as mentioned in §3.1.2 this is optimal for rather steady winds, but less appropriate to cancel the effects of wind gusts as detailed below.

Fluctuations during the test:

The monitoring time of the zero-flow pressures is usually very short compared to the duration of the pressurization test, and may miss the peaks of wind intensity and changes in wind speed and direction.

It could be useful to detect strongly fluctuating wind which induce higher uncertainties by quantifying the variability in the Δp0 and each pressure station measurements. For example, a standard deviation or a maximum difference could be calculated on the values used for the average calculation. A corresponding threshold value for which the test is not valid could also be defined.

However, the big errors occur when the wind speed and direction during the zero-flow measurement is not the same as during the actual measurement. These differences get bigger at higher wind speeds. One could add a third zero-flow pressure measurement in the middle of the test, however, since by definition zero-flow pressure cannot be measured simultaneously with the pressurization test, it would lengthen the test duration and therefore potentially making it worse.

In case of large variations between the beginning and the end of the measurement an option could be to estimate the zero flow pressure at a given moment (for each measurement points) through a linear regression instead of only calculating the average of the two readings.

The only way to detect those fluctuations would be a monitoring of the wind during the entire test.

Figure 3 shows a wind spectrum recorded in Brooklyn the total length of the test shall be included in the spectral gap: between 10 minutes and 1 hour.

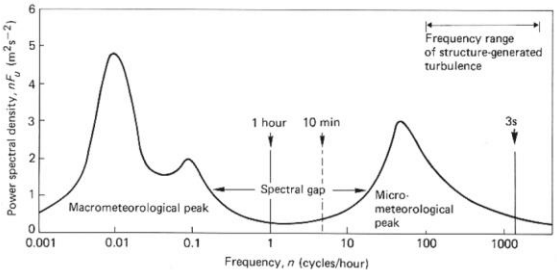

Figure 3 : Van der Hoven wind spectrum recorded in Brooklyn [48]

Zero-flow and pressure station measurements frequency and duration:

A better understanding of the wind and the building behaviour would allow to define an appropriate monitoring time and also acquisition frequency.

Parmentier et al. carried out full-scale tests to measure the wind effect on low-rise buildings [49]. They mentioned that the time duration of the records should be defined by a spectral analysis of the wind with a recommended acquisition frequency between 10 and 40 samples per second. This allows to capture accurately the observed wind event.

However, the building can be considered as a low-pass filters so winds variations at a frequency above 1 per seconds are unlikely to have any impact on the internal pressure. Nevertheless, high frequency change in the wind may have an impact on the measured external pressure (depending on the external gauge location) and therefore create noise on the measured pressure difference.

Regarding the duration of the measurements, Prignon et al. suggested that the approximation period should be increased to 60 s on medium-wind days (to reduce the uncertainty by 11%), and to 90 s on high-wind days (to reduce the uncertainty by 9%) [50]. However, this improvement depends on the duration of the fan pressurization test itself and, at some point, increasing the duration of the measurement would not reduce the uncertainty anymore because the test would then be measuring changes in mean wind speed and direction rather than fluctuations about a mean.

Research is still needed to determine the best frequency and duration of pressure measurement, however the following advice could be given for the data acquisition:

- A duration between 30s and 60s for each pressure station (including zero-flow pressure)
- 1 data per second
- Each data being the average of at least 10 points within a second (to flat the noise due to high frequency wind on outdoor pressure).

Derived parameters

Estimates of turbulence intensity and peak pressures may be useful guides to indicate the magnitude of test uncertainty or whether a test result is likely to be acceptable within certain error bounds. Only averages of at least 10 values are considered in the standard for the Δp0 measurements, which means potential peaks of wind intensity can be underestimated in magnitude. For a proper correction purpose, it seems therefore appropriate to have pressure measurements during the airtightness test similar to the zero-flow pressure measurement, namely an average of the same number of values over the same time interval. Delmotte pointed out that the uncertainty calculation in the standard does not take into account the effect of averaging the zero flow pressure measurements and suggested a corrective formula [3]. Prignon et al. quantified with field tests that uncertainties in zero-flow pressure represent more than 75% of the envelope pressure uncertainties whatever the wind conditions [50].

4.2 Location of pressure taps

The location of the external pressure probe is of importance since p_{ext} is used as reference for every relative internal pressure measurement, including Δp_0. Existing standards have different recommendations for pressure tap location as discussed in §2.

Novák [51] conducted airtightness measurements on a single-family house 9 times and calculated five air flow rates (q_{50}) based on each of the 4 external pressure taps located on the different sides of the house (ground level, at 5-8 meters from the façade) and on the averaged value. The wind conditions were rather similar the 9 days, with low wind around 2-3 m/s and he concluded that under these conditions the location of the external pressure tap was not impacting the repeatability. He however stressed out that the use of T-pieces, the longer periods of record, as well as the distance of the pressure taps from the façades could also explain this result.

On the other hand, Delmotte stated that, because of the wind, the nature and the location of the pressure taps play a crucial role in the measurement uncertainty [2]. He tested numerically the impact of placing the external tap in free field, on the windward roof and on the leeward façade for a residential building. If for light wind of 1 m/s no impact was noted, for a wind of 4 m/s an error of 13% was found for the leeward façade compared to 2% for the other two locations. He confirmed the recommendations of ISO 9972 (also discussed in annex) on how to place the pressure taps and advises to use an exterior pressure tap designed to measure the static pressure only.

In [52], Modera and Wilson analyzed field testing results to show:

- a slight negative bias in leakage area measurement with increasing wind speed,
- that using four pressure taps averaged together gave less bias than a single pressure tap.

Recommendation for the location of the external probe

Pressure measurement device (indoor and outdoor) shall remain at the same location during the whole test (including the zero-flow pressure measurement).

The probe should measure the external static pressure and be placed some distance away from the building and other obstacles. Place T-connectors on the end of the external tubes.

Nevertheless, it is not always possible to find a location for which the external static pressure is not influenced by obstacles, in this case it is better to place multiple pressure taps averaged together.

4.3 Regression model and method

The quadratic law has been discussed as an alternative to the commonly used power law (equation (1)) for the equation linking the flow rate and the differential pressure [53] [54] and Okuyama and Onishi recently estimated that the quadratic law would reduce regression uncertainties for airtightness tests [55]. The debate is not yet concluded but to our knowledge there is no indication in the literature if one law is better at minimizing the wind impact on the airtightness test results.

The standard requires to use the least square method to derive the C and n coefficients from the experimental measurements, without further precisions. The ordinary least square (OLS method) is usually used but there are some concerns about the validity of this method.

The Canadian standard (CAN CGSB-149.10-2019) and the German national annex DIN EN ISO 9972:2018-12 points out that measured values at low pressure have a higher uncertainty and a stronger influence on the result than values at high pressure due to the non-linearity of the pressure-flow relationship. To counteract this and to obtain the smallest quadratic deviation for the actual measured values, the measured data must be weighted with the square of the volume flow in the regression. This is the weighted least squares (WLS) method.

Delmotte noted that the OLS method is applicable when:

1) all the y (ln(q)) values are equally uncertain.
2) the uncertainties on x ln(Δp) are negligible [56].

He advises to use weighted method of least-squares (WLS) when condition 1) is not met and condition 2) is met. He mentions the possibility to use the effective variance method (solved by iteration) when neither condition 1) nor condition 2) are met. In a later publication [3], he mentions that in practice both 1) and 2) are not met and suggests the weighted line of organic correlation (WLOC) method as an alternative to the others. He applied both the OLS and WLOC methods to a sample of 6 measurements and observed a significant reduction of standard deviation with the WLOC methods for pressure differences under 40 Pa (about 30% at 10 Pa) and above 90 Pa.

A recent analysis [57] of almost 7500 blower door tests have found that WLOC (using the standard deviation of pressure and flow at each pressure station as an indicator of uncertainty) reduced uncertainties in C and n by about 20-30%.

Okuyama and Onishi have suggested two methods of weighting for the regression: weighting by residuals and weighting by measurement uncertainties. Weighting by residual (IWLS) is helpful to reduce the impact of sudden disturbances as wind gusts and seems to be in general the most appropriate method [55]. They also derived a method for estimating the reliability of the C and n coefficients, with both the calculation of more precise confidence intervals and the definition of a discrepancy ratio(β), indicating when measurements and regression are not valid. This method was tested on 5 actual buildings and β became larger than 1 in cases of strong wind or stack effects.

Finally, Prignon et al. [58] have compared the OLS, IWLS and WLOC methods on a series of 30 tests on an apartment. They found that:

– similar air flow rates at multiple pressure differences when averaging the 30 tests results
– standard deviations of the air flow rates for the 30 tests lower for WLOC and IWLS than OLS for low and high pressures, but similar for the 3 methods around 50 – 70 Pa (Figure 4), which is consistent with [3].

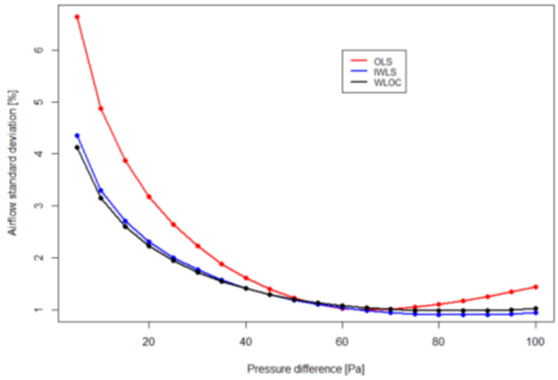

Figure 4 : Standard deviation (in %) of the airflow rates computed for the 30 tests as a function of the pressure difference for the OLS, the IWLS and the WLOC regression methods [58]

4.4 Number of pressure points

One can note from Figure 4 that the standard deviation is significant for low pressure differences even with optimized regression methods (about 4% for IWLS and WLOC and 7% for OLS at 4 Pa). On the other hand, at 50 Pa the 3 methods seem to give the same deviation of just over 1%. The stronger and the more unsteady the wind, the higher the standard deviation is expected for low pressure differences.

This is questioning the relevance of having low pressure points. Another method would be to have only one single point measure (for example at 50 Pa), the zero-flow pressure and then the flowrate (at 50 Pa) would be measured at least 5 times to obtain 5 independent measurements (each pressure station subtracting its zero-flow pressure measurement).

Having only one high measure point have the following benefits regarding the reduction of the impact of wind on the airtightness measurement:

- The high-pressure point allows good precision on the measurement, especially in windy conditions (low standard deviation)
- The calculated air leakage would not be influenced by the low-pressure points affected by the wind and in general by the regression error
- It would be easier to implement than complex regression and/or the calculation of a discrepancy ratio to minimize the impact of wind
- The test would be quicker which limits the chance of strong changes in wind direction and intensity (compared to the zero-flow pressure measurement). This gain in time could encourage conducting both pressurization and depressurization tests as well as allowing longer durations of pressure measurements. According to the Van des Hoven spectrum the duration should be between 10 min and 1 h, which corresponds to the “spectral gap” allowing to be independent of the macro and micro-meteorological effects (see Figure 3).

On the other hand, if this alternative method is appropriate for airtightness measurements with good reproducibility, it may be less relevant for infiltration rates estimations under natural conditions. This is not only due to the fact that the artificially induced high pressure during the test may slightly deform the airtightness defects but also and mostly because having only one point measured supposes to use a theoretical fixed n value to extrapolate the flow rate at lower pressure. As discussed by Walker et al., if the average value of n is known to be in the vicinity of 0.65, the variation from home to home is significant with a standard deviation of 0.057 from about 7000 measurements [45]. They noted that a change of 0.1 in this exponent could induce an error of 29% in the extrapolation from 50 to 4 Pa and 48% in the extrapolation from 50 to 1 Pa. As a result, a single high-pressure measurement is not appropriate for detailed infiltration calculations with known leakages distribution. One should note however that this error may not be as significant as the one induced by strong modelling assumptions on the leakage distribution.

4.5 Better estimating the impact of wind

ISO 9972: 2015 provides an uncertainty calculation procedure, however this procedures as multiple limits that could be improved:

- It does not include the zero-flow pressure uncertainty on the total uncertainty
- It uses the OLS and, as seen in §4.3, which assumes that the uncertainty on the pressure measurement is negligible does not properly takes into account the uncertainty on the flowrate measurement

- It does not provide a method to calculate the coverage interval.

The French standard FD 50-784 (add-in to the ISO 9972) states that if the uncertainty is above 10% then the test is not valid. This requirement can prevent performing test in windy condition, while, in some cases the result of a test with an uncertainty above 10% can be enough to decide whether the building has met or not a target value.

To this end, the standard could first improve the uncertainty calculation (using a WLOC regression and including the zero-flow pressure uncertainty) and secondly include the calculation of a coverage interval (for example at 95%) as defined in JCGM 102:2011. If the confidence interval is below the target value then the building has passed even if the measurement uncertainty is above 10%.

Wind has an impact on both the random measurement error (precision) and systematic measurement error (bias). Uncertainty propagation can however only estimate the random measurement error. Estimation of systematic measurement error has to be done by other techniques.

5 Conclusion

This paper presented a state of the art of the numerical, laboratory and on-site studies on the characterization of the wind impact on the airtightness tests results. As detailed below, it allowed to point out further research needed for this purpose and to give possible guidance to minimize the wind impact and improve test standards.

5.1 Further research needed

For numerical simulations there is a need for:

- Including the stack effect and multizone buildings in the numerical models (at least for steady winds)
- Defining relevant-for-infiltration indicators for characterizing dynamic winds and wind gusts
- Applying models on pressurized buildings for dynamic winds
- Increasing knowledge on buildings' leakages behaviour according to wind variations.

As for laboratory measurements, the need for the following was pointed out:

- Additional studies to clearly define how the unsteady wind should be modeled in wind tunnels for the study of its impact on airtightness pressurization tests: what parameters are most significant, what corrections could be applied to offset modeling assumptions and in which conditions
- Research on the impact of the interaction between wind and stack effects on the result of the test
- Studies the behavior of real leakage with various frequency of wind gust to characterize their response and evaluate from which frequency wind gusts impact the air flow rate.

Finally, concerning on-site measurements, there is a need for a much more significant number of studies measuring the impact of natural wind on airtightness tests: in various locations, with a large range of wind characteristics and on various types of buildings geometry, leakages and leakage distributions. There is also a need to test various duration and frequency of each pressure station measurement (including zero-flow pressure). And, it would be interesting to compare the result and the uncertainty of one-point and multi-points measurement method (with different kind of linear regression).

5.2 Recommendations to minimize the wind impact on the airtightness test results

In addition to existing recommendations in standards, possible ways to reduce the wind impact on the airtightness tests results were pointed out:

- Improve pressure measurement
    - Use a T-connector or equivalent to ensure that only the static pressure is measured
    - Place the external pressure gauge some distance away from the building and other obstacles, if it is not possible measure the outside pressure at different sides of the building and average the results
        - In addition, the zero-flow pressure across the building envelope can be

measured at different place to determine the value of the first measurement point
    - The location of the pressure gauge shall remain the same during all the test
- Improve zero-flow and measurement-point pressure characterization
    - Increase the recorded period for each pressure measurement from 30 s to 60 s on medium-wind days.
    - Have an acquisition of 1 data per second
    - Each data is the average of at least 10 points within a second (to flat the noise due to high frequency wind on outdoor pressure)
- Adapt the pressure difference sequence
    - Average the results of pressurization and depressurization tests
    - To estimate a flowrate at 50 Pa, perform a single-point test
    - To estimate a flowrate at 4 Pa, with a wind up to 5 m/s perform a multi pressure-point test and extrapolate with a calculated flow exponent, and above 5 m/s perform a single-point test at 50 Pa and extrapolate with a default flow exponent (for example n=2/3).
    - Carry out similar pressure measurements during the airtightness test than during the zero-flow pressure measurement and use an average of the same number of values over the same time interval
- Improve the calculation method
    - Use a WLS or WLOC method for the regression
    - Include the zero-flow pressure uncertainty in the calculation of the total uncertainty
    - Provide a method to calculate the coverage interval of the result together with a decision rule.

By those means, one can reduce the wind impact and obtain a more accurate a test result. The improved calculation method allows a better estimation of the measurement uncertainty in order to take advantage of more accurate results when comparing two test results or checking the compliance with a limit value.

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7 Annex: Equilibrium internal pressure meaning (Zero-flow pressure)

The wind has an impact on the airtightness test result despite the zero-flow pressure subtraction. To understand this, we need to examine what the zero-flow pressure is exactly, and what is the error on the air leakage estimation induced by wind when using the standard calculation method.

For this purpose, we will take the example of a single-zone building with only two leaks: one windward and one leeward that are assumed to represent the leakages of respectively the windward (experiencing positive pressure) and all leeward façades (experiencing negative pressure). This simple case allows to model wind induced ventilation rates as mentioned by Etheridge et al. [59] and implemented by Carrié et al. [6].

Of course as stated by Carrié and Mélois [8], this is a crude representation of the complexity of real airflow paths. Nevertheless, it has the advantage of remaining relatively simple while allowing us to calculate the airflow rates in leaks subjected to different pressures during a pressurization test, which is the key problem in presence of wind.

Zero-flow pressure

The zero-flow pressure (Δp0) is the difference in static pressure between inside and outside, in this annex the zero-flow pressure is considered to be the equilibrium internal pressure has defined in §2.

$$\Delta p_0 = p_i - p_{ext} \quad (2)$$

ISO 9972 (see §2) recommends to place the external pressure gauge some distance away from the building but not close to other obstacles, the objective is to ensure that this external pressure is not affected by wind. A T-connection may also be used make sure that it is the static and not the dynamic pressure that is measured. In practice, the external pressure probe/tubing may be influenced by surrounding obstacles, in which case the measured zero-flow pressure becomes:

$$\Delta p_0 = p_i - \left(p_{ext} + \frac{1}{2}\rho Cp_{gauge} U^2\right) \quad (3)$$

With Cp_{gauge} the Cp coefficient at the end of the pressure tube and U is the wind speed at the end of the pressure tube. This adds an additional uncertainty that is not taken into account here as the following assume that the external pressure sensor is not influenced by the wind (equation 2 apply). Generally, efforts are made to shelter the end of the pressure tube to minimize this uncertainty.

The zero-flow pressure is measured when the building is not pressurized by the measurement device, at exactly the same location as where the pressure difference between inside and outside will be measured during the whole test. The zero-flow pressure is due to the impact of the wind and stack effect. In case of stack-effect the pressure difference depends on the height of the measurement, for simplification purpose only wind is considered in this paragraph. One should note however that across each leak there is a pressure difference that differs from Δp_0:

$$\Delta p_{leak,j} = \Delta p_0 - p_j \quad (4)$$

With p_j the external pressure at the leakage j induced by the wind (Pa).

In our example, with the mass flow rate conservation, Δp_0 is such that:

$$C_{up}(\Delta p_0 - p_{up})^{n_{up}} + C_{down}(\Delta p_0 - p_{down})^{n_{down}} = 0 \quad (5)$$

With

C_{up}, C_{down} the flow coefficient of respectively the windward and leeward leakages

n_{up}, n_{down} the flow exponent of respectively the windward and leeward leakages, with a value between 0.5 (turbulent flow) and 1 (laminar flow)

p_{up}, p_{down} are the external pressure induced by wind respectively at the windward and leeward leakages (equal to 0 when there is no wind) and are given by:

$$p_j = \frac{1}{2}\rho C_{p,j} U^2 \quad (6)$$

With

U the wind velocity (m/s)

$C_{p,j}$ the wind pressure coefficient on the windward/leeward façade

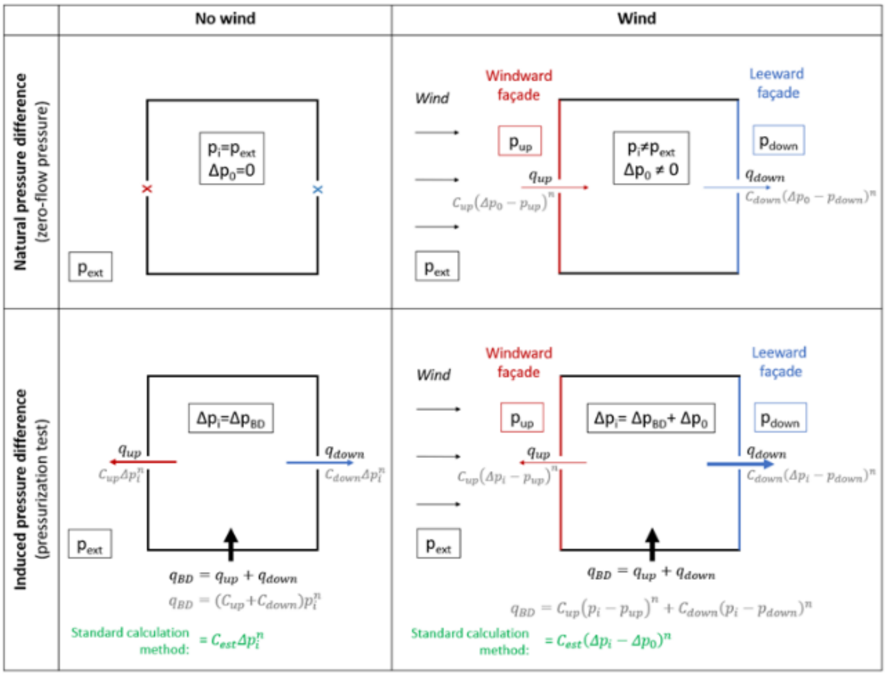

Figure 5 : Natural and induced pressure differences applied to a simplified two-leakage case, with and without wind

If it is assumed that n_{up}=n_{down}= n then **Error! Reference source not found.**) leads to:

$$\Delta p_0 = \frac{C_{up}^{\frac{1}{n}} p_{up} + C_{down}^{\frac{1}{n}} p_{down}}{C_{up}^{\frac{1}{n}} + C_{down}^{\frac{1}{n}}} \quad (7)$$

Error of the flow-rate estimation for steady wind

As illustrated in Figure 5, during the airtightness test the building is pressurized and the pressure difference Δp_i is measured between inside and outside. The global flowrate through the blower door is the addition of the flowrate at each leak j:

$$q_{BD} = \sum_j C_j(\Delta p_i - p_j)^n = C_{up}(\Delta p_i - p_{up})^n + C_{down}(\Delta p_i - p_{down})^n \quad (8)$$

As described by equation (1), since the external pressures p_j induced by the wind at each leakage are unknown, ISO9972 instead uses Δp_0 as an averaged subtraction to estimate the flow coefficient:

$$C_{est} = \frac{q_{BD}}{(\Delta p_i - \Delta p_0)^n} = \frac{C_{up}(\Delta p_i - p_{up})^n + C_{down}(\Delta p_i - p_{down})^n}{(\Delta p_i - \Delta p_0)^n} \quad (9)$$

The error at any difference pressure measurement reference Δp_{ref} when estimating the flowrate with (6) compared to the case without wind is therefore:

$$E(q) = \frac{q_{est} - q_{nowind}}{q_{nowind}} = \frac{C_{est}.\Delta p_{ref}^n - C_t.\Delta p_{ref}^n}{C_t.\Delta p_{ref}^n}$$
$$= \frac{C_{up}(\Delta p_i - p_{up})^n + C_{down}(\Delta p_i - p_{down})^n - C_t(\Delta p_i - \Delta p_0)^n}{C_t(\Delta p_i - \Delta p_0)^n}$$

(10)

With: C_t=C_{up}+ C_{down}

According to equation (10), the error tends to increase with p_{up} and p_{down}. To limit this error, there is a maximum value of Δp_0 allowed in ISO 9972, which is 5 Pa. Because of the relation between Δp_0 and p_{up} and p_{down} given in equation (7), for most buildings (with standard leakage repartition), this criteria will indeed indirectly limit the wind speed at building level at 5-6 m/s [6] and therefore limit the value of p_{up} and p_{down} to less than 10 Pa. However, for some specific building geometry (dwelling with only 2 external walls) it is possible that the leakage distribution is such that Δp_0 equals to zero whatever the wind speed (U).

One can note that for perfectly laminar leakages, the error due to wind with the standard calculation method is zero so long as the wind is invariant during the test. This is true for any leakage distribution and any external and internal pressures since according to equation (10) with n=1:

$$E(q) = 0 \leftrightarrow \Delta p_0(C_{up} + C_{down}) - C_{up}p_{up} - C_{down}p_{down} = 0$$

(11)

Which is the definition of Δp_0 given in equation (7) for this specific flow exponent.

Example calculation for a simplified two-leak case

To get a rough estimate of the errors that wind can introduce due to the ono-linearity of the pressure-flow relationship, the following calculations use Equation 10 applied to a two-leak case. For the example calculation, following values are assumed; $C_{p,up}$= 0.25, $C_{p,down}$ = -0.5, and a flow exponent of n= 0.65 (see table A2.5 of [60]). The error induced by the wind on the air flowrate when using the standard calculation method is given in Table 2 for a pressurization test (p+), depressurization test (p-) and the average of both tests (av.). It is calculated for three wind speeds (3, 5 and 10 m/s), 3 leakage distributions (C_{up}/C_t=0.25, 0.5 and 0.75) and four target pressure (10, 25, 50 and 100 Pa).

Table 2: Example of error induced by wind on the air flowrate with ISO 9972 for various wind velocities, leakage distributions and target pressures (n=0.65) with this simplified model.

U (m/s)	External pressure (Pa)	C_{up}/C_t	Δp_0 (Pa)	Target pressure $\lvert\Delta p_i\rvert$											
				10 Pa			25 Pa			50 Pa			100 Pa		
				p+	p-	av.	p+	p-	av.	p+	p-	av.	p+	p-	av.
3	p_{up}=1,35 p_{down}=-2,7	0,25	-2	-2%	2%	0%	-1%	1%	0%	0%	0%	0%	0%	0%	0%
		0,5	-0,6	0%	-1%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		0,75	0,6	1%	2%	2%	1%	-1%	0%	0%	0%	0%	0%	0%	0%
5	p_{up}=3,75 p_{down}=-7,5	0,25	-4	*1%*	*-14%*	*-7%*	1%	-3%	-1%	1%	-1%	0%	0%	0%	0%
		0,5	-0,8	4%	-14%	-5%	2%	-4%	-1%	1%	-2%	0%	1%	-1%	0%
		0,75	0,6	-5%	-1%	-3%	-1%	0%	-1%	-1%	0%	0%	0%	0%	0%
10	p_{up}=15 p_{down}=-30	0,25	**-7,2**	*18%*	*-267%*	*-125%*	*18%*	*-91%*	*-37%*	*11%*	*-21%*	*-5%*	*6%*	*-9%*	*-2%*
		0,5	-0,9	-14%	-87%	-51%	8%	-48%	-20%	6%	-12%	-3%	4%	-5%	-1%
		0,75	0,6	-86%	-7%	-47%	-16%	-8%	-12%	-6%	2%	-2%	-2%	2%	0%

As expected, one can note that the error becomes significant for high wind speeds and/or low internal pressures. For this example, even a moderate wind of 5 m/s can induce an error up to 14% for Δp_i=10 Pa, with Δp_0 below the 5 Pa standard threshold value. These results show that wind speed alone is not sufficient to determine if errors become excessive, because the changes with leak distribution (C_{up}/C_t) have a very strong influence on the results. However, in general, leakage distribution is unknown and we must rely on wind speed to estimate errors. It should also be noted that high target pressures of 50 or 100 Pa have results that become insensitive to wind effects.

Averaging the pressurization and depressurization tests results can reduce significantly the error induced by wind, with a maximum of 7% found when $|\Delta p_j|<|\Delta p_i|$. However, when this is not the case (i.e. when some leaks flow in the opposite direction to the test condition), averaging both results is not enough to prevent from very significant errors, reaching 50% here.
While the specific numerical values of the results are reasonable examples of expected errors they cannot be generalized to all buildings. Rather, they serve as a guide to show that higher windspeeds introduce higher errors, errors depend strongly on leak distribution and above 50 Pa the target pressure dominates and wind effects are insignificant. In addition. Large errors can occur even if a test is limited to $\Delta p_0 < 5$ Pa.

Conclusion

The following conclusions can be drawn on the standard calculation method:

- If the wind is steady, it is accurate for a flow exponent n=1 for every leak (linear equations), whereas in reality is neither constant (it varies with the leakage geometry) nor equal to 1 (usually around 0.65 for buildings) and the wind is not steady.
- The first order of the error is cancelled by averaging pressurization and depressurization test results. The remaining error can however still be significant.
- The error increases with the pressure ratio $p_j/\Delta p_i$. If the wind pressure is greater than the internal pressure (in absolute value), some leaks will flow in the opposite direction to the test condition, which leads to very significant errors.
- The condition on the zero-flow pressure to limit systematic measurement error due to wind ($\Delta p_0 < 5$ Pa) does not always prevent from significant wind effect. Cases for which the building geometry and the leakage distribution are such that the addition of the $C_j p_j^{n_j}$ of each leakage is close to 0 will lead to a Δp0 value below 5 Pa, even with strong winds inducing high external pressure on the envelope. This is more likely to happen when testing apartments than detached houses with only two walls out of 5 exposed to wind.

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The Air Infiltration and Ventilation Centre provides technical support in air infiltration and ventilation research and application. The aim is to promote the understanding of the complex behaviour of the air flow in buildings and to advance the effective application of associated energy saving measures in the design of new buildings and the improvement of the existing building stock.