On the estimate and reduction of the zero-flow pressure estimation uncertainty in fan pressurization measurement

Martin Prignon[1], Christophe Delmotte[1], Benedikt Kölsch[2]

[1] *Buildwise*
Kleine Kloosterstraat 23
1932 ZAVENTEM,
Belgium

[2] *German Aerospace Center (DLR),*
Institute of Solar Research,
Linder Höhe, 51147 Cologne,
Germany

**Corresponding author: martin.prignon@buildwise.be*

ABSTRACT
Building airtightness is of foremost importance because of its impact on global energy consumption, but also on occupant's comfort, dimensioning of ventilation systems, hygrothermal behaviour, fire safety, etc. This building characteristic is usually measured with the fan pressurization method, following ISO 9972:2015 standard. This method requires to assume that the pressure difference due to wind and stack effect, called the zero-flow pressure difference, is constant during the test and that its value is the average of pre- and post-test measurements. This bold hypothesis leads to some uncertainty, referred in the literature as $u(\Delta p_{0,a})$. In this paper, we use two different datasets in order to (1) assess the validity of the formula proposed in literature to quantify this uncertainty term, (2) investigate some variations in the measurement protocol to reduce this source of uncertainty, and (3) evaluate the impact of this uncertainty source on the final result of the fan pressurization test. Results show that, specifically for this data set, this estimation represents a large uncertainty of 1.27 Pa in pressure measurements that could be slightly reduced by increasing the number of measurement or using a multiple-estimator procedure. This uncertainty source could represent a 1% uncertainty in the airflow rate at 50 Pa (the final result of the fan pressurization test). Further research should focus on using other datasets to remove some limitations of this study, and on the development of alternative procedures in order to reduce this consequent source of uncertainty.

KEYWORDS
Fan pressurization measurement; zero-flow pressure difference; uncertainty calculation.

1 INTRODUCTION
In practice, during a fan pressurization test, the pressure difference between the indoor and outdoor probes at a time t is the combination of the fan-induced pressure difference ($\Delta p_{ind,t}$) and the zero-flow pressure difference ($\Delta p_{0,t}$), which is the pressure difference induced by climatic conditions (Eq. 1).

$$\Delta p_t = \Delta p_{ind,t} + \Delta p_{0,t} \tag{1}$$

The value of interest ($\Delta p_{ind,t}$) cannot be measured directly, while the zero-flow pressure difference can only be measured when the fan is not operating (i.e., $\Delta p_{ind,t} = 0$). Consequently, the value of $\Delta p_{0,t}$ when the fan is operating has to be assumed. The (ISO 9972, 2015) standard suggests that the zero-flow pressure should be considered as a constant value during the test, based on a series of measurements taken before ($\Delta p_{0,pre,j}$) and after ($\Delta p_{0,post,j}$) the test. In this study, we assume that the same number N_0 of measurements are taken for both periods, leading to Eq. 2:

$$\Delta p_{0,t} = \Delta p_0 = 0.5 * \left(\frac{\sum_{j=1}^{N_0} \Delta p_{0,pre,j}}{N_0} + \frac{\sum_{j=1}^{N_0} \Delta p_{0,post,j}}{N_0} \right) \tag{2}$$

When there is wind or temperature variations during the test, the zero-flow pressure difference varies, and the constant assumption is not valid anymore. Mathematically, this is considered by defining an additional uncertainty term in the calculation, $u(\Delta p_{0,a})$. In the literature, different approaches to quantify this uncertainty source have been suggested by (Delmotte, 2017) (Eq. 3) and (Prignon et al., 2021) (Eq. 4):

$$u(\Delta p_{0,a})|_1 = \frac{\max(|\Delta p_{0,max} - \Delta p_{0,av}|;|\Delta p_{0,min} - \Delta p_{0,av}|)}{\sqrt{6}} = \frac{\delta}{\sqrt{6}} \approx \frac{\delta}{2.45} \tag{3}$$

$$u(\Delta p_{0,a})|_2 = \frac{\left(0.11 + 0.98 * \sigma(\Delta p_{0,m})\right)}{1.35} \tag{4}$$

This paper is a continuation of previous work and aims to (1) assess the validity of the formula proposed in the literature, (2) investigate some variations in the measurement protocol to reduce this source of uncertainty, and (3) evaluate the impact of this uncertainty source on the final result of the fan pressurization test. This paper is structured as follows. In the methodology section, the different datasets are described, and the methods for data analysis are illustrated. The outcome of this analysis is provided in the result section, including the quantification of the uncertainty source, comparison with values suggested in the literature, potential improvements through adaptations of the procedure, and assessment of its impact on the final results. Finally, in the conclusion, we summarize the outcomes of this work, highlight the limitations of the study, and describe the further work needed in this field of research.

2 METHODOLOGY

In this paper, two different datasets are used and manipulated in order to draw conclusions about the studied uncertainty source: 30 zero-flow pressure profiles and a dataset of 127 repeatability studies. Those datasets and how the analysis is performed is outlined in this section of the paper.

2.1 Zero-flow pressure profiles

The zero-flow pressure dataset includes 30 zero-flow pressure profiles obtained from measurements made on the same apartment in Brussels, without changing the location of the pressure probes. More details about the building geometry and orientation are provided in (Prignon et al., 2019). A zero-flow pressure profile is the measurement of zero-flow pressure difference for 15 minutes, which corresponds approximately to the duration of a fan pressurization test. As depicted in Figure 1, those profiles are divided into two parts: the estimation parts (in orange) used for zero-flow pressure estimation, and the estimated part (in green) used for assessing the estimation “quality” by comparing it with the measured value. Note that during a real fan pressurization test, the data recorded in the central part is not available since the fan is operating.

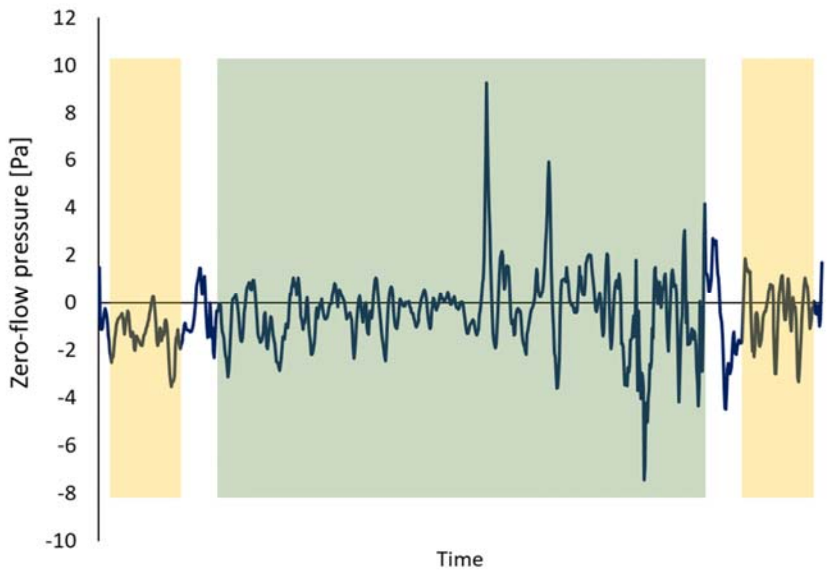

Figure 1. Typical zero-flow pressure profiles with the estimation (orange) and estimated (green) zones.

Those profiles are used to quantify $u\left(\Delta p_{0,a}\right)$ by comparing the estimated zero-flow pressure for a given estimation procedure ($\Delta p_{0,est}$) with 10 equally-spaced averages of N measurements made in the estimated zone (green) of the profiles ($\Delta p_{0,real,i}$, $i = 1, \ldots, 10$). The error is then defined for each average as the difference between the estimation and the average (Eq. 5).

$$e_i = \Delta p_{0,est} - \Delta p_{0,real,i} \tag{5}$$

We assume in this paper that the standard deviation of the 300 calculated values (10 for each test) provides a good approximation of the uncertainty source: $\sigma(e_i) \approx u\left(\Delta p_{0,a}\right)$. Indeed, (JCGM, 2008) states that if e_i is normally distributed, then the uncertainty on the standard deviation estimate (i.e., the risk that the standard deviation of the estimate is different from the standard deviation of the data) is 4.1%, which seems acceptable to us.

Then, the same methodology is used in order to compare another estimation procedure called the multiple-estimators procedure. Instead of considering a constant zero-flow pressure during the whole test as suggested by ISO 9972:2015, the zero-flow pressure is measured before and after each pressure station, and an approximation is made for each. Figure 2 shows how the estimation and estimated zones from Figure 1 are adapted in that situation.

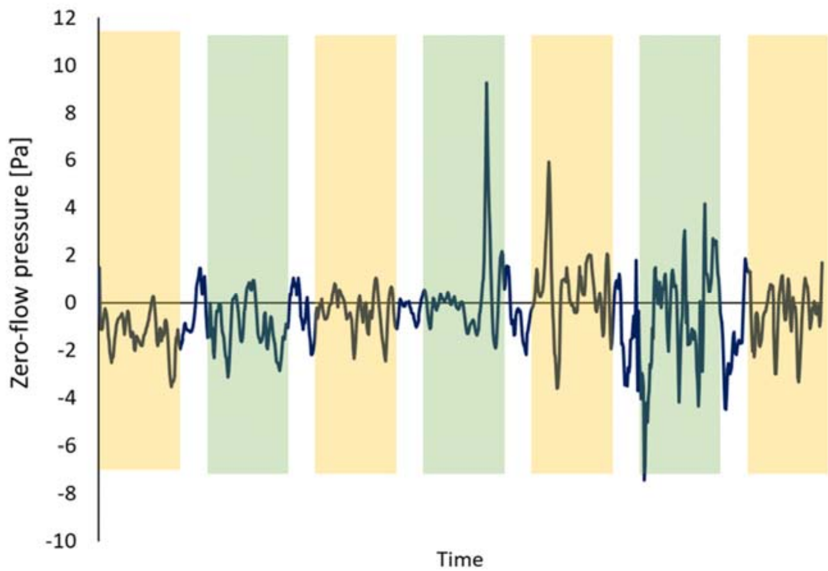

Figure 2. Typical zero-flow pressure profiles with the estimation (orange) and estimated (green) zones for the multiple-estimators procedure.

Under this estimation procedure, the zero-flow pressure estimate at pressure station i is the average of N_0 zero-flow pressure measurements made before and after that pressure station (Eq. 6). Except for the first and last, each estimation zone is used for two pressure stations. Note that the change of the estimation procedure also affects the total duration of the test, which is not an aspect further considered in this paper.

$$\Delta p_{0,i} = 0.5 * \left(\frac{\sum_{j=1}^{N_0} \Delta p_{0,i,pre,j}}{N_0} + \frac{\sum_{j=1}^{N_0} \Delta p_{0,i,post,j}}{N_0} \right) \tag{6}$$

The same dataset is also used to validate the uncertainty estimation suggested in the literature (Eq. 3 and Eq. 4). In that context, two criteria were observed:

1. The relevance of the variables used. This is done by calculating the Pearson's correlation coefficient between the absolute error, $|e_i|$, and the relevant variables: δ and $\sigma(\Delta p_{0,m})$.
2. The order of magnitude of the estimation. This is done by comparing the standard deviation of the observed error with the average of the calculated uncertainty of each dataset using one or another formula.

2.2 Semi-theoretical tests

Those zero-flow profiles were then combined with theoretical "perfect" fan-induced pressure profiles in order to estimate the impact of this uncertainty source on the uncertainty in the final results. These "perfect" profiles were obtained with 10 successive pressure stations of N measurements. For the ISO 9972 estimation procedure, 10 seconds were used for the transition from one station to another. For the multiple-estimators procedure, 20 seconds were needed to go from 0 to each station, while 10 seconds were needed to go from high-pressure measurements to 0. The combination is illustrated in Figure 3 for both estimation procedures.

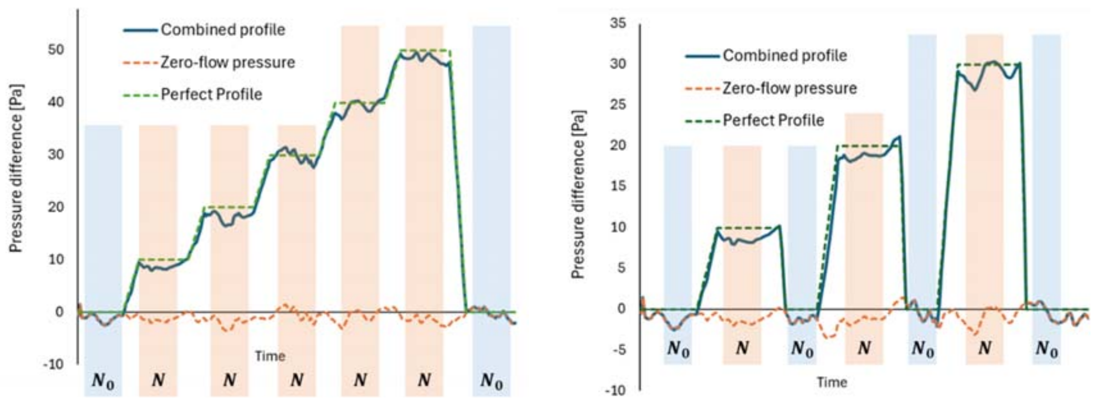

Figure 3. Example of semi-theoretical profiles obtained by combining zero-flow pressure profiles with "perfect" fan-induced pressure profiles created for the estimation procedure in line with ISO 9972:2015 (left) and the multiple-estimators procedure (right).

In parallel, the 30 "perfect" fan-induced pressure profiles were then used to create 30 "perfect" airflow profiles, by assuming a power-law relation with $C = 55$ and $n = 0.67$ (Eq. 7).

$$q_t = 55 * \left(\Delta p_{ind,t}\right)^{0.67} \tag{7}$$

Note that the total pressure is not "perfect" since it is the sum of the induced pressure and the zero-flow pressure. However, since the induced pressure is used to determine the airflow profile, this one is "perfect" (i.e., the airflow rate through the fan is constant at each station). Those profiles produce 30 semi-theoretical tests that are then used as a set of repeatability tests where only the zero-flow pressure varies. The rest of the ISO 9972:2015 procedure was applied without considering any other source of error than the zero-flow pressure estimation. In such conditions, the standard deviation of the 30 final air leakage rates is assumed being the uncertainty in the final result caused by the zero-flow pressure variation during a fan pressurization test.

2.3 Large dataset

A dataset of 127 repeatability studies, including more than 6.000 fan pressurization tests conducted on 6 different houses was also used in order to evaluate how different estimation procedures impact the variation in the final result. This dataset is described in detail in (Walker et al., 2013). In that dataset, the zero-flow pressure was measured before and after each pressure station, allowing the computation of the ISO 9972:2015 estimation procedure by considering only the first and the last zero-flow pressure measurements and the multiple-estimators procedure by considering all averages. Two important aspects are worth noticing when drawing conclusions based on this dataset:

1. The estimation procedure suggested in ISO 9972:2015 is expected to take less time than the multiple-estimator procedure. This is not investigated in this dataset because regardless of the measurements effectively used in the procedure, all were measured in practice.
2. All the pressure differences were determined by averaging measurements made on four different facades of the building, which does not follow the ISO 9972:2015 procedure. This has an important impact on the results and, consequently, conclusions drawn from this dataset should not be compared to the conclusion drawn from the other dataset and should be used in the context of 4-point averages only.

The comparison of both estimation procedures is made by averaging the 127 standards deviations observed.

3 RESULTS

3.1 Quantification of $u(\Delta p_{0,a})$

Figure 4 (left) shows the distribution profile of the errors due to zero-flow pressure difference estimation (e_i) using ISO 9972:2015 procedure, with $N_0 = N = 30$. The average is $\mu(e_i) = -0.06$ Pa and the standard deviation is $\sigma(e_i) = 1.27$ Pa. Figure 4 (right) shows the equivalent distribution when using the multiple-estimator procedure with $N_0 = N = 25$. For this second procedure, $\mu(e_i) = 0.09$ Pa and $\sigma(e_i) = 1.09$ Pa. Note that different N_0 and N were compared in both procedures because the dataset was not large enough to compare the second procedure with the same values for N and N_0.

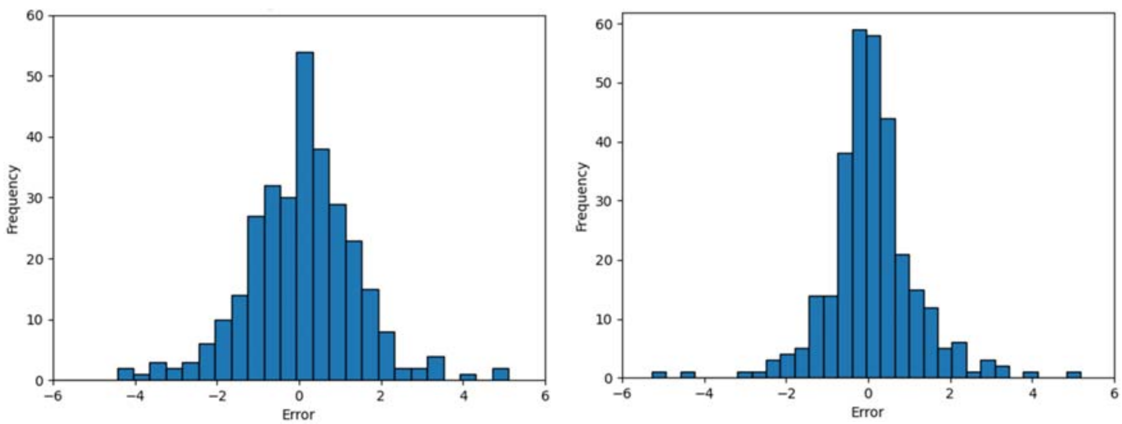

Figure 4. Distribution of the e_i values obtained with Eq. 5 when using the ISO 9972:2015 estimation procedure with $N_0 = N = 30$ measurements (left) and the multiple-estimators procedure with $N_0 = N = 25$.

The standard deviation of the error is influenced by the number of zero-flow pressure measurements used for the estimation (N_0) and the number of pressure measurements made at each pressure station (N). However, this influence is expected to vary depending on climatic conditions. The zero-flow pressure profile used in this study were obtained on a single-story apartment, which means that the stack effect is expected to be relatively small, and under wind conditions varying from 0.4 m/s to 4.0 m/s (15 min average during the tests).

Figure 5 shows how $u(\Delta p_{0,a})$ is impacted by a variation in N and N_0 values, where the ISO 9972:2015 estimation procedure is used. It shows that increasing the number of zero-flow pressure measurements (N_0) and the number of pressure measurements (N) provides a lower uncertainty. However, the large scattering of the results suggests that those observation should be considered with some caution and that a larger dataset should be used to generalize them, especially regarding the impact of N_0.

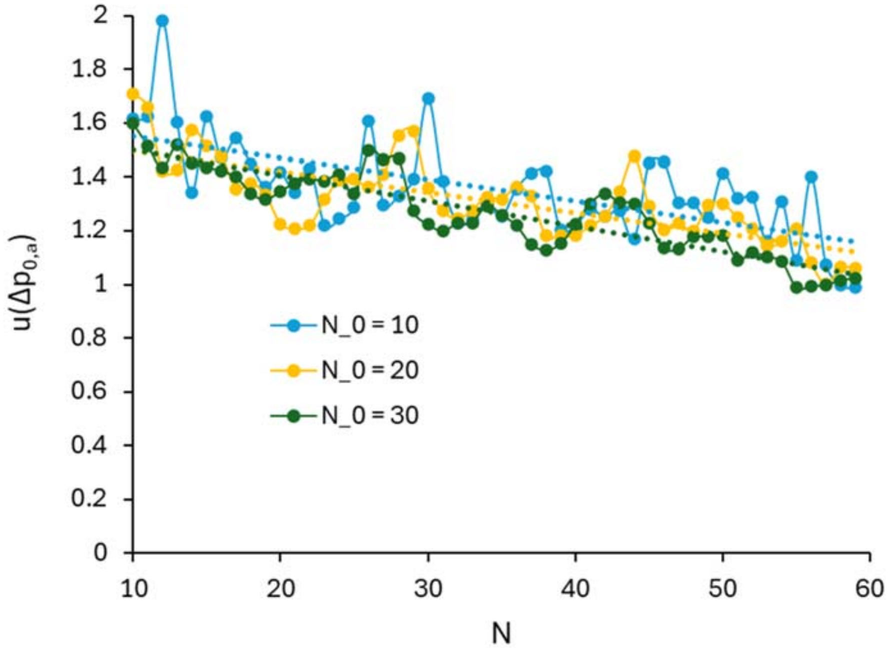

Figure 5. Impact of N_0 and N on the uncertainty estimation, calculated with Eq. 5, for the estimation procedure following ISO 9972:2015

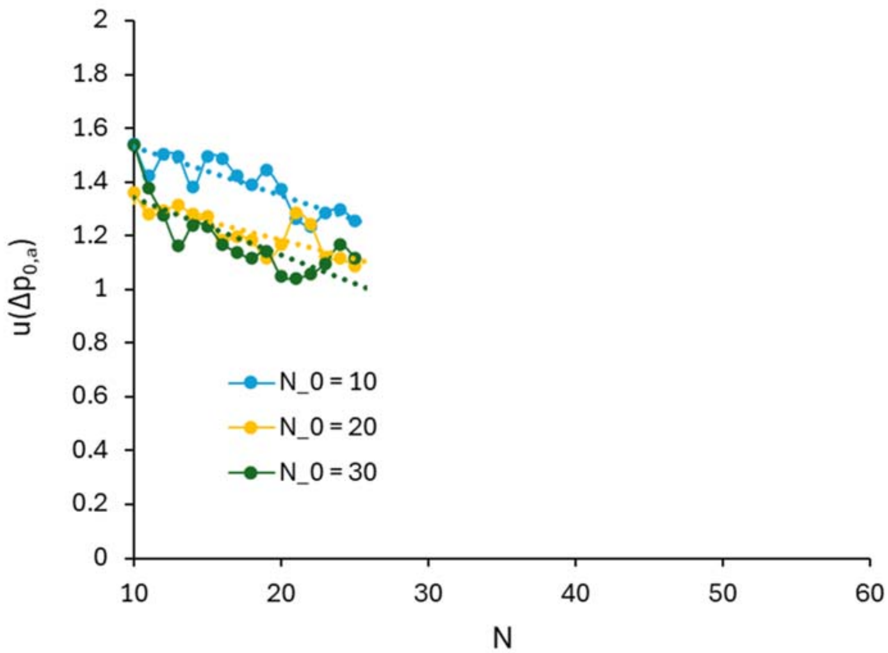

Figure 6Figure 6 shows a similar graph for the multiple-estimator procedure. In this case, the impact of having $N_0 > 10$ is more pronounced, while $N_0 = 20$ and $N_0 = 30$ seems to perform similarly. Whatever the N_0 value, increasing the number of pressure measurements at pressure station (N) also reduces the uncertainty. Note that due to the longer duration of this second procedure, it was not possible to check cases with $N > 30$ with the dataset.

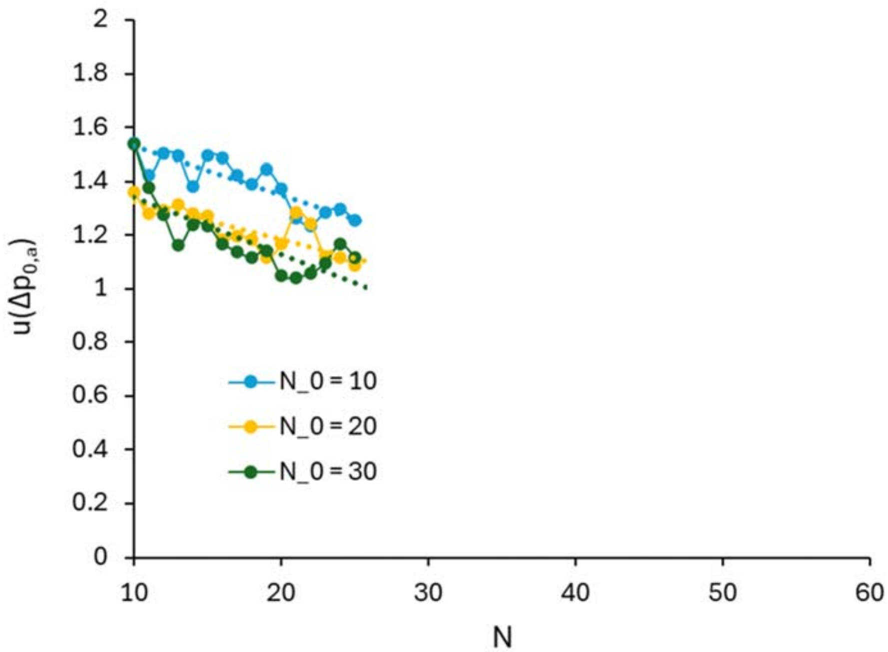

Figure 6. Impact of N_0 and N on the uncertainty estimation, calculated with Eq. 5, for the multiple estimator procedure.

3.2 Comparison with the uncertainty terms suggested in literature

When applying ISO 9972:2015, medium correlations (Pearson's correlation coefficient $0.5 > r > 0.3$; (Ellis, 2010)) were found between the absolute error and the variables used in the literature for quantification of the approximation uncertainty. Additionally, the averages of the calculated uncertainties are in the same order of magnitude as the standard deviation of error ($u(\Delta p_{0,a}) \approx \sigma(e_i) = 1.27$ Pa, for $N_0 = N = 30$):

- $\overline{u(\Delta p_{0,a})}|_1 = 1.53$ Pa ; and $r(\delta\,;|e|) = 0.35$
- $\overline{u(\Delta p_{0,a})}|_2 = 0.94$ Pa ; and $r(\sigma(\Delta p_0)\,;|e|) = 0.35$

Those results suggest that the choices made in the literature were relevant, but they do not perfectly grasp the real error caused by this approximation. However, based on the dataset used in this study, Eq. 4 could be adapted to provide a better estimate of the uncertainty:

$$u(\Delta p_{0,a})|_{2,new} = 1.1 * \sigma(\Delta p_{0,m})$$
$$\rightarrow \overline{u(\Delta p_{0,a})}|_{2,new} = 1.28 \text{ Pa} \tag{9}$$

Note that although Eq. 3 seems to overestimate the uncertainty, it is based on a mathematical background (triangular distribution) and adapting the proposed equation would not be relevant since it would have no physical meaning. This is not the case for Eq. 4, which is empirically derived. Note that regardless of the equation used, it should always be zero in case of constant wind and constant temperature differences, which is the case for both suggestions here.

3.3 Impact on final result uncertainty

Table 1 shows the evolution of $\sigma(q_{50})$ and $\sigma(q_4)$ (in % of measured airflow) using both estimation procedures and for both datasets. The post-processing of the data uses WLOC regression method and Eq. 4 for $u(\Delta p_{0,a})$. Note, however, that using another regression method or another equation for $u(\Delta p_{0,a})$ is not expected to provide much different results for those observed variables.

Table 1. Standard deviation of the repeatability studies using the semi-theoretical profiles and the large dataset, for the ISO 9972:2015 estimation procedure and the multiple-estimator procedure, at 4 and 50 Pa of pressure difference.

	Semi-theoretical profiles (1 repeatability study)		**Large dataset (109 repeatability studies)**	
	$\sigma(q_4)$	$\sigma(q_{50})$	$\overline{\sigma(q_4)}$	$\overline{\sigma(q_{50})}$
ISO 9972:2015 procedure	4.35	1.06	8.35	4.27
Multiple-estimator procedure	3.23	0.42	7.94	4.21

For the semi-theoretical profiles (i.e., constant airflows and induced pressure at each pressure station), the results from the 30 tests are not normally distributed (checked with Shapiro-Wilk test for both procedures at 4 and 50 Pa). Consequently, non-parametric tools should be used to check the statistical significance of the differences observed between the procedures (Wilcoxon signed-rank test for the mean comparison, and Fligner-Killeen Test for the variance comparison):

- At q_{50}, using different estimation procedures shows no significant differences in averages but a significant difference in their variances. This suggests that using a multiple-estimator procedure reduces the uncertainty without creating any bias compared to the ISO 9972:2015 procedure.
- At q_4, however, there is neither a significant difference in averages nor in their variances. This suggests that the multiple-estimator procedure has no added value.

When examining the large dataset, the repeatability tests with $N < 10$ were removed, resulting in the analysis of 109 of the 127 repeatability tests. This arbitrary choice was made to avoid cases with strong risks of having a standard deviation that is not a good estimate of the uncertainty. Since most of the tests are not normally distributed, the same non-parametric tests were used to assess the statistical significance of the observed difference:

- At q_{50}, using different estimation procedures shows a significant difference in averages for 20 of the 109 repeatability studies, and a significance difference in the standard deviation for none of them.
- At q_4, results show a significant difference in averages for 45 of the 109 repeatability studies, while a significance difference in standard deviation is found for only one of them. Those results suggest that the multiple-estimator procedure has no added value in this context.

Note that because of the variations observed in the methodology for data acquisition (e.g., averaging the pressure difference using four different manometers placed on different facades, as mentioned in section 2.3), the results using semi-theoretical profiles and those using the large dataset cannot be directly compared.

An additional interesting observation is that the values found in Table 1 for applying the ISO 9972:2015 procedure on semi-theoretical profiles ($\sigma(q_{50}) = 1.06\%$) are close to the values found on other repeatability studies where $\sigma(q_{50})$ is in the range [1.1% ; 2.3%] (Bracke et al., 2016; Delmotte and Laverge, 2011; Kim and Shaw, 1986; Novak, 2015; Persily, 1982; Prignon et al., 2018). This suggests that this source of uncertainty could represent a large part of the final random error.

4 CONCLUSION

In this study, we analysed the impact of the zero-flow pressure estimation on the uncertainty of the fan pressurization test and investigated two ways to reduce this uncertainty source: increasing the number of measurements (N and N_0) or using another estimation procedure. This was done by analysing two different datasets: one is a dataset of zero-flow pressure profiles while the other is a dataset of 127 repeatability test. The main findings can be summarized as follows:

- There is a large uncertainty on the pressure measurements due to the zero-flow pressure estimation ($u(\Delta p_{0,a}) = 1.27$ Pa in this dataset). This uncertainty also affects the final result of the fan pressurization test (a random error of 1.06% of the measured airflow rate in this study).
- While using a multiple-estimators procedure to replace the ISO 9972:2015 seems to lower the final uncertainty (as shown in Table 1), those trends were not statistically confirmed except at 50 Pa for the zero-flow pressure dataset.
- This source of uncertainty can be reduced by increasing the number of measurements for the zero-flow pressure (N_0) and at each pressure station (N). No clear threshold value was found, and larger datasets should be used to draw relevant guidelines.

Those results provide a better knowledge of the uncertainty of the fan pressurization measurement, which is relevant in order to suggest improvement of the measurement protocol. Additionally, quantifying uncertainty terms is needed when applying weighted regression techniques, such as WLOC described by (Delmotte, 2017), which have been shown to provide a better estimate of the real uncertainty by (Delmotte, 2017; Prignon et al., 2020).

This work contains some limitations, including but not limited to the small size of the first dataset, which does not allow for a comprehensive analysis of the impact of N and N_0 on the uncertainty calculation. Additionally, the conclusion drawn from both datasets could not be compared to each other due to the variations in the measurement procedure.

Given that this important source of uncertainty seems to be responsible for a large part of the final uncertainty of the test, further research should investigate adaptations of the fan pressurization protocol that could reduce this source of uncertainty. Moreover, the results obtained in this study should be confirmed by applying the same methodology to other datasets of zero-flow pressure measurements, including different building typologies and different locations of pressure probes within the building.

5 ACKNOWLEDGEMENTS

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6 NOMENCLATURE

Variables

Δp	Total pressure difference
Δp_{ind}	Fan-induced pressure difference
Δp_0	Zero-flow pressure difference
$u(\Delta p_{0,a})$	Uncertainty due to the zero-flow pressure approximation
N	Number of measurements made for the pressure averages at each stations
N_0	Number of measurements made for the average of zero-flow pressure
δ	Term used to simplify Eq. 3, with no physical meaning

Subscripts

i, j	refer to an element in a series
t	refers to a moment in time
m	refers to a measured quantity
new	refers to a new version of the model
$pre, post$	refer to measurements period before and after the period with the fan operating
est	refers to an estimated value
$real$	refers to a real value
$1, 2$	refer to two different uncertainty estimation formula provided in the literature
$4, 50$	refer to two typical pressure difference used in standards

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