# Airtightness of Buildings – Considerations regarding the Zero-Flow Pressure and the Weighted Line of Organic Correlation


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## ABSTRACT

This paper discusses two particular points of the buildings airtightness measurement method (ISO 9972) in relation with the calculation of the combined standard uncertainty: (1) the zero-flow pressure difference and (2) the weighted line of organic correlation.

The zero-flow pressure difference is measured at the start and the end of the test in order to calculate the change of pressure caused by the fan or blower door. Actually the zero-flow pressure difference fluctuates during the test in function of the wind and the temperature difference between inside and outside the building. One should therefore take this fluctuation into account in the uncertainty of the induced pressure difference. Theoretical developments are translated into a practical formula which could be applied in daily practice.

The air flow coefficient and air flow exponent are generally determined using an ordinary least squares regression technique (OLS). This is however not the most appropriate technique because there are uncertainties in both the measured air flow rates and the pressure differences. The paper shows how the weighted line of organic correlation (WLOC) could be used in order to take these uncertainties into account.

Applying both the uncertainty on the zero-flow pressure difference and the WLOC on a sample of measurements made under repeatability conditions has shown encouraging results regarding the reliability of combined standard uncertainties.



## KEYWORDS

Airtightness of buildings, zero-flow pressure, uncertainty, least-squares, line of organic correlation


## 1 INTRODUCTION

In European countries, increasing importance has been given to airtightness of buildings since the first publication of the directive on the energy performance of buildings in 2002. In some countries there even are requirements or financial incentives linked with the airtightness level. It is therefore more and more important to pay attention to the uncertainty of airtightness measurements.

The issue of uncertainty of airtightness measurements has already been dealt with in various publications (Persily 1985, Sherman 1994, Delmotte 2013, Walker 2013, Carrié 2014) but is still incompletely solved in practice. This was also a point of discussion during the last revision of ISO 9972.

This paper discusses two particular points of the buildings airtightness measurement method (ISO 9972) in relation with the calculation of the combined standard uncertainty: (1) the zero-flow pressure difference and (2) the weighted line of organic correlation.

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into account in the uncertainty of the induced pressure difference. Theoretical developments are translated into a practical formula which could be applied in daily practice.
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## 2 ZERO-FLOW PRESSURE DIFFERENCE

### 2.1 Pressure difference induced by the fan

In given climatic conditions (wind and temperature) and in the absence of fan, pressure differences $\Delta p_{0,j}$ are naturally generated across the envelope of the building. The equilibrium internal pressure is such that the airflow that enters the building is equal to the flow that leaves. The sum of the airflows through the building envelope is therefore equal to zero (formally we should talk about mass flow). Accordingly, parts of the envelope must necessarily undergo underpressure while others are in overpressure.
In the absence of wind or temperature difference, the action of a fan located in the building envelope induces an identical pressure difference $\Delta p$ across all points of the envelope. However, this is not quite true because the internal partitioning of the building may generate pressure losses. ISO 9972 requires opening all interior doors in order to minimize this effect.
When adding the effect of a fan to that of the wind and of the temperature difference, each point (j) of the envelope is subjected to a pressure difference $\Delta p_{m,j}$ equal to the sum of those it would undergo for each of the two separate effects ($\Delta p$ and $\Delta p_{0,j}$) (Sherman 1990) (Figure 1 and Formula 1). Each point thus undergoes a similar change in pressure while keeping its relative difference compared to the other points. Note that this principle of addition is not true for air flow rates.

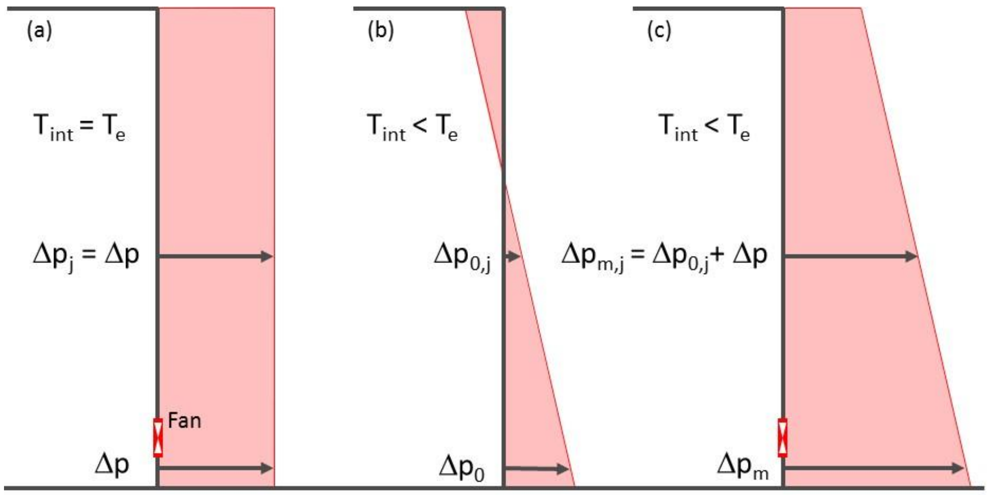


Figure 1: Example of pressure distribution over the height of a building (a) for a fan only, (b) for a temperature difference only and (c) for the combination of the fan and the temperature difference.

Additivity of pressure differences is used in ISO 9972 to indirectly measure the pressure difference induced by the fan:

1. Zero-flow pressure difference $\Delta p_0$ : Pressure difference is measured at one point of the envelope when the building is subject to natural conditions only (fan off and covered)

2. Measured pressure difference $\Delta p_m$ : Pressure difference is measured at the same point of the envelope when the fan is operating
3. Induced pressure difference $\Delta p$ : Pressure difference induced by the fan is calculated by subtracting the first value from the second (Formula 2)

$$\Delta p_{m,j} = \Delta p_{0,j} + \Delta p \quad (1)$$

$$\Delta p = \Delta p_m - \Delta p_0 \quad (2)$$

## 2.2 Complete building pressurization

The calculation model adopted by ISO 9972 assumes the entire building envelope is either pressurized or depressurized. It is therefore necessary that the pressure difference induced by the fan overcomes the pressure differences generated by climatic conditions. In this way for example, a natural depression of -3 Pa could be overcome by an induced pressure of 8 Pa.
The fact that ISO 9972 requires the zero-flow pressure difference to be less than 5 Pa in absolute value and the lowest measured pressure difference ($\Delta p_m$) to be at least 5 times the zero-flow pressure difference with a minimum of 10 Pa aims to respect the calculation model.
Although it is not specified in ISO 9972, this implies that the zero-flow pressure difference is measured at a point where the pressure difference generated by the climatic conditions is a priori the largest. In practice, the measuring point is usually located close to the blower door (itself often installed on the ground floor of the building) and there is no guarantee that this is the best location.

## 2.3 Average pressure difference on the envelope

The calculation model adopted by ISO 9972 also assumes that the pressure difference between inside and outside the building is identical at all points of the envelope. This is only possible in the absence of wind and temperature difference and is therefore virtually impossible to satisfy in practice.
To overcome this problem, ISO 9972 requires the pressure difference induced by the fan to be much greater than the absolute value of the pressure differences generated by climatic conditions. In this way, variations in the pressure difference remain relatively low and it is assumed that the hypothesis of the model are fulfilled. Under these conditions ISO 9972 assumes the average value of the pressure difference which is applied to the envelope to be equal to the pressure induced by the fan. This is an approximation because the average value of the zero-flow pressure difference is not necessarily equal to zero (even if the total airflow is equal to zero).
When the fan puts the whole building envelope in positive or negative pressure, the airflow through the fan is equal to the air flow rate through the envelope. Following the model of ISO 9972, this flow is associated with the pressure induced by the fan and eventually allows to characterize the air permeability of the envelope.

## 2.4 Measurement uncertainty

When measuring the airtightness of a building, it is not possible to measure the zero-flow pressure during the test and the climatic conditions most generally don’t remain constant (especially due to wind that can quickly change intensity and direction). So ISO 9972 requires the zero-flow pressure difference $\Delta p_0$ to be measured for at least 30 seconds both at the start ($\Delta p_{01}$) and the end ($\Delta p_{02}$) of the test. However, nothing prevents climatic conditions being different during the test. In addition to the uncertainty of the measures themselves, some variability in climatic conditions should also be taken into consideration.

A typical example of evolution of the zero-flow pressure difference at the start (30 seconds), during (10 minutes) and at the end (30 seconds) of a fictitious test is shown in Figure 2. In order to find the most probable value of this pressure during the test, ISO 9972 takes the mean of $\Delta p_{01}$ and $\Delta p_{02}$ (Formula 3).

The zero-flow pressure difference is no constant value. So one cannot calculate the Type A standard uncertainty (JCGM 2008) which would require to carry out several measurements of the same value. One should therefore calculate the Type B standard uncertainty (scientific judgement based on all of the available information on the possible variability). In order to take some variability in climatic conditions into account, one could consider a triangular distribution based on the average value of $\Delta p_{0,1}$ and $\Delta p_{0,2}$ and on the minimum and maximum values measured at the start and the end of the test. This should be added to the combined standard uncertainty of the induced pressure difference (Formula 4).

$$\Delta p = \Delta p_m - \frac{\Delta p_{0,1}+\Delta p_{0,2}}{2} \tag{3}$$

$$u_c(\Delta p) = \sqrt{u^2(\Delta p_m) + \frac{u^2(\Delta p_{0,1})}{4} + \frac{u^2(\Delta p_{0,2})}{4} + \left(\frac{max(|\Delta p_{0,max}-\Delta p_{0,av}|;|\Delta p_{0,min}-\Delta p_{0,av}|)}{\sqrt{6}}\right)^2} \tag{4}$$

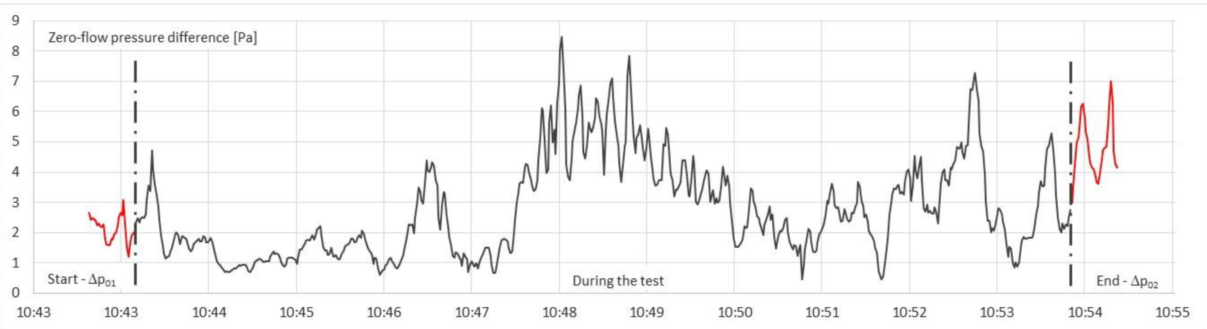


Figure 2: Example of evolution of the zero-flow pressure difference at the start (30seconds – max: 3,1 Pa – mean: 2,1 Pa – min: 1,2 Pa) , during (10 minutes – max: 8,5 Pa – mean: 2,7 Pa – min: 0,5 Pa) and at the end (30seconds – max: 7,0 Pa – mean: 4,8 Pa – min: 3,0 Pa) of a fictitious test.

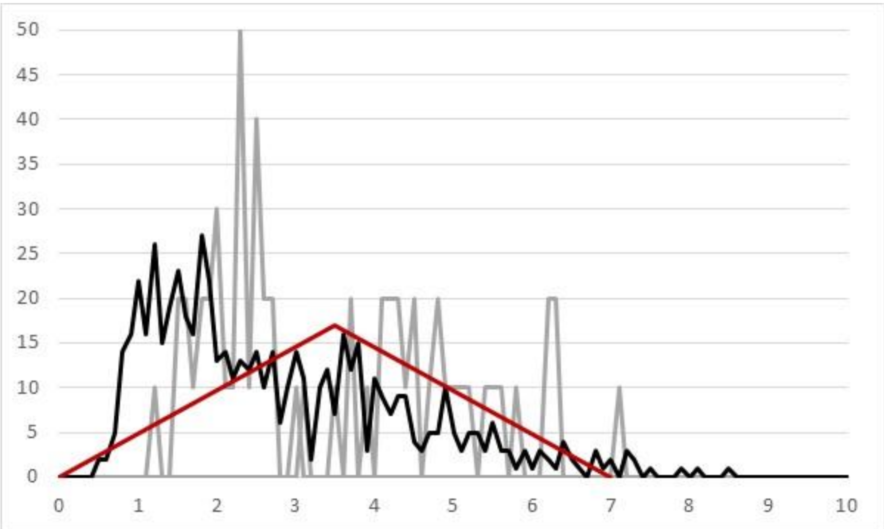


Figure 3: Example of triangular distribution for the estimation of the zero-flow pressure difference (red line) and its actual frequency distribution during a fictitious test (black curve). The grey curves are those of the zero-flow pressure difference at the start and at the end of the test.

In order to reduce the uncertainty related to the modelling, it could be worth measuring the pressure difference at several points of the envelope. This would give more chances to catch the greatest zero-flow pressure difference and determine the lowest measurement stage accordingly. In this sense, looking for the location of the measurement point that provides the lowest zero-flow pressure difference in order to comply with the criteria of ISO 9972 is not recommended.

### 2.5 Impact of measurement uncertainty

In the framework of the buildings airtightness measurement, ISO 9972 assumes the relation between the airflow rate and the pressure difference has an exponential form (Formula 5).

$$q_{env} = C_{env} \cdot \Delta p^n \tag{5}$$

This exponential relation can be transformed into a linear relation as follows:

$$\ln q_{env} = \ln C_{env} + \mathrm{n} \cdot \ln \Delta p \tag{6}$$

Introducing some estimation error E on the induced pressure difference in formula (6) leads to the following:

$$\ln q_{env} = \ln C_{env} + \mathrm{n} \cdot \ln(\Delta p \pm E) \tag{7}$$

$$\ln q_{env} = \ln C_{env} + \mathrm{n} \cdot \ln\left(\Delta p \left(1 \pm \frac{E}{\Delta p}\right)\right) \tag{8}$$

$$\ln q_{env} = \ln C_{env} + \mathrm{n} \cdot \ln \Delta p + \mathrm{n} \cdot \ln\left(1 \pm \frac{E}{\Delta p}\right) \tag{9}$$

The last formula shows that imperfect knowledge of the induced pressure difference can lead to shifting and rotating the linear relation (and thus modifying the $C_{env}$ and n values). This is due to the fact that ln (1 ± E/Δp) strongly depends on E/Δp and that Δp typically varies from 10 Pa to 100 Pa. Lower pressure points are thus further shifted than higher pressure points (Figure 4).

In order to take this effect into account in the calculation of the combined standard uncertainty, it is important to select an appropriate least square regression method (see clause 3) (Delmotte 2103) (ISO/TS 28037).

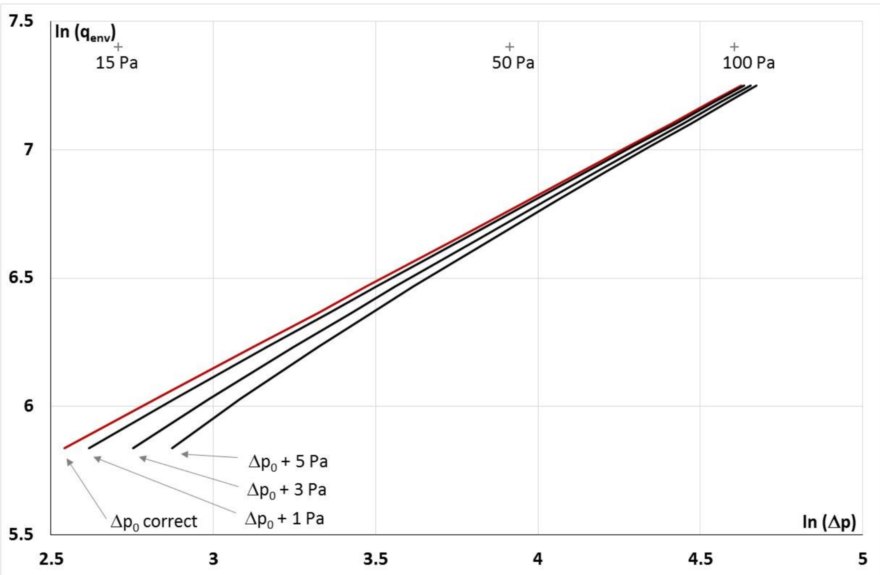


Figure 4: Imperfect knowledge of induced pressure difference leads to shifting and rotating the regression line

## 3 WEIGHTED LINE OF ORGANIC CORRELATION

### 3.1 Applicability of least squares

ISO 9972 requires the use of a least squares technique for the calculation of the airflow coefficient $C_{env}$ and the airflow exponent n based on a series of measurement points ($\Delta p_i$ , $q_{env,i}$) (i = 1 … N). However it does not give further guidance.

The Ordinary method of Least Squares (OLS) is applicable when all $y_i$ values ($y_i = \ln q_{env,i}$) are equally uncertain ($u_c(y_1)= u_c(y_2)=\cdots=u_c(y_n)$) and the uncertainties on $x_i$ values ($x_i = \ln \Delta p_i$) are negligible (Delmotte 2013). When uncertainties of $y_i$ values are not equal (and uncertainties of $x_i$ values are negligible), it is advisable to use the Weighted method of Least Squares (WLS). None of these two methods are theoretically applicable to the buildings airtightness measurement because both sets of $x_i$ and $y_i$ values have non negligible and unequal uncertainties. It is therefore proposed to examine the possibility of using the Weighted Line of Organic Correlation (WLOC) which takes both sets of uncertainties into account.

### 3.2 Description of the method

The WLOC consists of finding the regression line $y = a + b \cdot x$ that minimalizes the sum of the products of the weighted vertical and horizontal differences between the measurement points and the line (Figure 5); which comes to minimalizing the following sum:

$$\sum_{i=1}^{N}(v_i|x_i - x(y_i)| \cdot w_i|y_i - y(x_i)|) \tag{10}$$

$$\sum_{i=1}^{N}\left(v_i\left|x_i - \frac{y_i - a}{b}\right| \cdot w_i|y_i - (b\,x_i + a)|\right) \tag{11}$$

Weights $v_i$ and $w_i$ applied to each measurement point i are equal to the following, which means that points with higher uncertainty receive less importance than others:

$$v_i = \frac{1}{s(x_i)} = \frac{1}{u_c(x_i)} \tag{12}$$

$$w_i = \frac{1}{s(y_i)} = \frac{1}{u_c(y_i)} \tag{13}$$

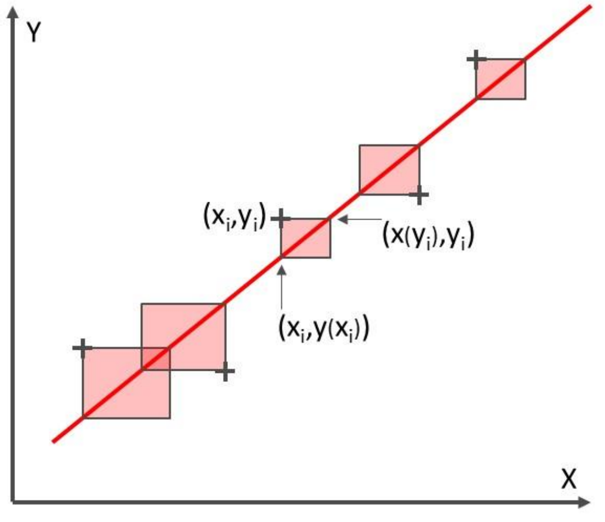


Figure 5: The (weighted) line of organic correlation minimalizes the sum of the products of the (weighted) vertical and horizontal differences between the measurement points and the line.

Constants a and b of this regression line are calculated as follows:

NOTE For the sake of simplification $\sum x_i$ is used for $\sum_{i=1}^{N} x_i$

$$a = \frac{\sum v_i\, w_i\, y_i - b \sum v_i\, w_i\, x_i}{\sum v_i\, w_i} = \bar{y} - \frac{S_y}{S_x}\, \bar{x} = \bar{y} - b\, \bar{x} \qquad (14)$$

$$b = \frac{\sqrt{\sum v_i\, w_i \sum v_i\, w_i\, y_i^2 - (\sum v_i\, w_i\, y_i)^2}}{\sqrt{\sum v_i\, w_i \sum v_i\, w_i\, x_i^2 - (\sum v_i\, w_i\, x_i)^2}} = \sqrt{\frac{\Delta y}{\Delta x}} = \frac{S_y}{S_x} \qquad (15)$$

a and b are eventually used for the calculation of n and $C_{env}$ :

$$n = b \qquad (16)$$

$$C_{env} = e^a \qquad (17)$$

Other important characteristics of the weighted line of organic correlation are the following:

Weighted mean

$$\bar{x} = \frac{\sum v_i\, w_i\, x_i}{\sum v_i\, w_i} \qquad (18)$$

$$\bar{y} = \frac{\sum v_i\, w_i\, y_i}{\sum v_i\, w_i} \qquad (19)$$

Variance

$$S_x^2 = \frac{\sum v_i\, w_i (x_i - \bar{x})^2}{\sum v_i\, w_i} \qquad (20)$$

$$S_y^2 = \frac{\sum v_i\, w_i (y_i - \bar{y})^2}{\sum v_i\, w_i} \qquad (21)$$

Covariance

$$S_{xy} = \frac{\sum v_i\, w_i (x_i - \bar{x})\,(y_i - \bar{y})}{\sum v_i\, w_i} \qquad (22)$$

Coefficient of determination

$$r^2 = \frac{S_{xy}^2}{S_x^2\, S_y^2} \qquad (23)$$

Advantages of WLOC is that it minimizes errors in both X and Y directions and that it provides a unique line identical regardless of which variable, X or Y, is used as the response variable (Helsel and Hirsch 2002) (Figure 4). Considering that the regression lines pass through the centroid of the data $(\bar{x}, \bar{y})$, this property becomes more important as one is interested in the estimate of the air leakage rate at low pressure difference (e.g. 4 or 10 Pa). Another advantage of WLOC is that it can be solved without iteration which is not the case of some other methods (e.g. ISO/TS 28037).

Experimental variances of a and b and their estimated correlation coefficient can be calculated as follows. These values are needed to calculate the combined standard uncertainty of the air leakage rate at reference pressure difference from the standard uncertainties of the input data (Delmotte 2013).

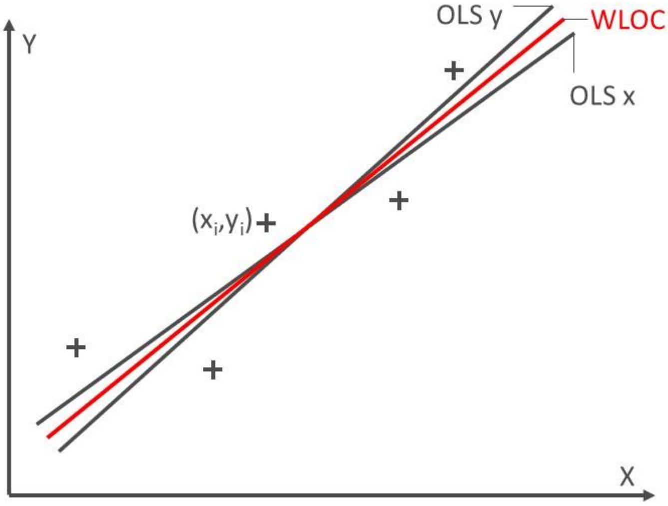


Figure 6: The weighted line of organic correlation provides a unique line identical regardless of which variable, X or Y, is used as the response variable.

Experimental variance

$$s^2(a) = \sum \left(\frac{\partial a}{\partial x_i}\right)^2 \frac{1}{v_i^2} + \left(\frac{\partial a}{\partial y_i}\right)^2 \frac{1}{w_i^2} \tag{24}$$

$$s^2(b) = \sum \left(\frac{\partial b}{\partial x_i}\right)^2 \frac{1}{v_i^2} + \left(\frac{\partial b}{\partial y_i}\right)^2 \frac{1}{w_i^2} \tag{25}$$

Estimated correlation coefficient

$$r(a,b) = \frac{s^2(a+b) - s^2(a) - s^2(b)}{2\, s(a)\, s(b)} \tag{26}$$

with

$$\frac{\partial a}{\partial x_i} = \frac{\sqrt{\Delta y}}{\sqrt{\Delta x}} \left(\frac{-v_i w_i}{\sum v_j\, w_j} - \frac{\left(\sum v_j w_j x_j\right)^2 v_i w_i}{\Delta x \sum v_j\, w_j} + \frac{\left(\sum v_j\, w_j\, x_j\right) v_i w_i x_i}{\Delta x}\right) \tag{27}$$

$$\frac{\partial a}{\partial y_i} = \frac{v_i w_i}{\sum v_j\, w_j} - \frac{\left(\sum v_j w_j x_j\right) v_i w_i y_i}{\sqrt{\Delta x}\sqrt{\Delta y}} + \frac{\left(\sum v_j w_j x_j\right)\left(\sum v_j w_j y_j\right) v_i w_i}{\sum v_j w_j \ \sqrt{\Delta x}\sqrt{\Delta y}} \tag{28}$$

$$\frac{\partial b}{\partial x_i} = \frac{\sqrt{\Delta y}}{\sqrt{\Delta x}} \frac{\left(\left(\sum v_j w_j x_j\right) v_i w_i - \left(\sum v_j w_j\right) v_i w_i x_i\right)}{\Delta x} \tag{29}$$

$$\frac{\partial b}{\partial y_i} = \frac{\sqrt{\Delta y}}{\sqrt{\Delta x}} \frac{\left(\left(\sum v_j w_j\right) v_i w_i y_i - \left(\sum v_j w_j y_j\right) v_i w_i\right)}{\Delta y} \tag{30}$$

$$s^2(a+b) = \sum \left(\frac{\partial a}{\partial x_i} + \frac{\partial b}{\partial x_i}\right)^2 \frac{1}{v_i^2} + \left(\frac{\partial a}{\partial y_i} + \frac{\partial b}{\partial y_i}\right)^2 \frac{1}{w_i^2} \tag{31}$$

NOTE Since it is needed to make additions including sums of values, we use i and j ( = 1 … N) in order to make a distinction between both addition levels.

# 4 EXPERIMENTAL RESULTS

Applying both the uncertainty on the zero-flow pressure difference and the WLOC on a sample of 6 measurements made under repeatability conditions has shown encouraging results regarding the reliability of combined standard uncertainties. Compared to OLS, it has considerably reduced the repeatability standard deviation for low pressure stations (Figure 7). Moreover, combined standard uncertainties of the air leakage rate at reference pressure difference based on WLOC better fit to the variation of real data than OLS which strongly underestimates them (Figures 8 and 9).

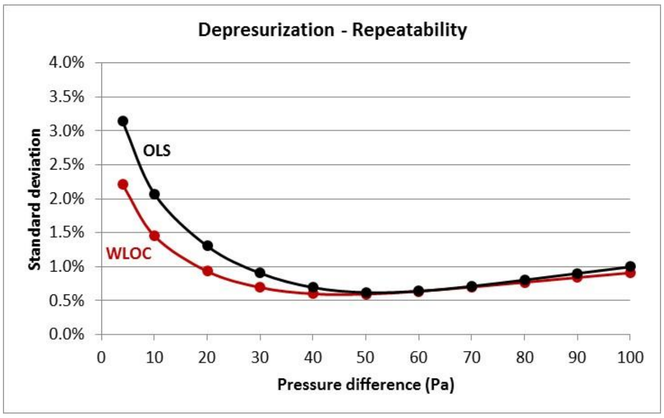


Figure 7: WLOC shows better repeatability than OLS (sample of 6 measurements under repeatability conditions)

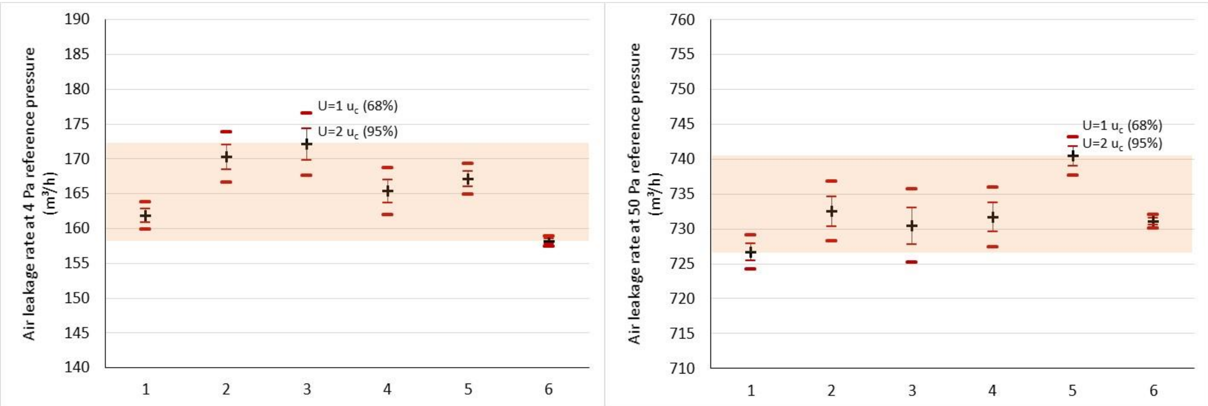


Figure 8: Combined standard uncertainties calculated with OLS strongly underestimate the variation of real data (sample of 6 measurements under repeatability conditions). Many results (+) are out of the 95% expanded uncertainty (U) of the other results.

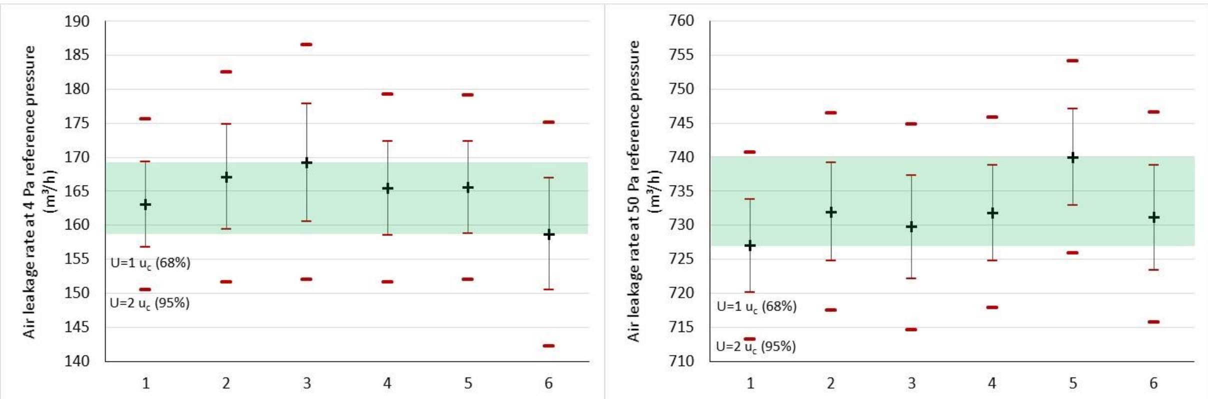


Figure 9: Combined standard uncertainties calculated with WLOC fit very well the variation of real data (sample of 6 measurements under repeatability conditions). All results (+) are within the 95% expanded uncertainty (U) of the other results.

## 5 NOMENCLATURE

$C_{env}$ = Air flow coefficient
E = Estimation error on the induced pressure difference
*i, j* = element of a series
n = Air flow exponent (also refered to as “pressure exponent”)
N = Total number of measurement points
$q_{env}$ = Air flow rate through the building envelope
s(x) = Experimental standard deviation of estimate x
$T_{int}$ = Internal air temperature
$T_e$ = External air temperature
$u_c(x)$ = Combined standard uncertainty of estimate x
$v_i$ = Weight attributed to estimate $x_i$
$w_i$ = Weight attributed to estimate $y_i$
$\Delta p$ = Induced pressure difference
$\Delta p_0$ = Zero-flow pressure difference
$\Delta p_{0,av}$ = Average value of $\Delta p_{0,1}$ et $\Delta p_{0,2}$
$\Delta p_{0,max}$ = Maximum value of all $\Delta p_0$ values measured at the start and at the end of the test
$\Delta p_{0,min}$ = Minimum value of all $\Delta p_0$ values measured at the start and at the end of the test
$\Delta p_m$ = Measured pressure difference

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