AIRTIGHTNESS OF BUILDINGS - CALCULATION OF COMBINED STANDARD UNCERTAINTY

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ABSTRACT

The paper presents a calculation method for the combined standard uncertainty associated with the buildings airtightness measurement done in accordance with the ISO standard 9972:2006 (or EN 13829).

The method consists in an application of the law of propagation of uncertainty (JCGM 100:2008) combined with a linear regression (y = a x + b). It goes from the measured values to the air leakage rate and the air change rate.

The ordinary method of least-squares and these of weighted least-squares (with and without negligible uncertainties of the x values) are presented. For each of these methods, the standard uncertainties of the constant a and b of the regression line and their estimated correlation coefficient are given.

The pertinence of the different methods of least-squares for the buildings airtightness measurement is discussed. It seems that the conditions of application of the unweighted method of least-squares are generally not met in the framework of the buildings airtightness measurement; it is therefore advisable to use the weighted method of least-squares.

Real measurement's data show that the combined standard uncertainty of the pressure differences is not always negligible compared with these of the airflow rates. The consideration of these two uncertainties in the calculation of the weights seems therefore necessary even if it requires a resolution by iteration.

KEYWORDS

Airtightness, blower door, uncertainty, least-squares

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 considerable 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 (e.g. Sherman, 1994) but is still incompletely solved in practice. This is also a point of discussion in the current revision of the related ISO standard 9972:2006.

This document presents a calculation method for the combined standard uncertainty associated with the buildings airtightness measurement done in accordance with the ISO standard 9972:2006.

This method consists in an application of the law of propagation of uncertainty (JCGM 100:2008) combined with a linear regression. The ordinary method of least-squares and these of weighted least-squares are presented.
The calculation results of the combined standard uncertainty must be considered with circumspection given that various sources of uncertainty are not taken into account in the measurement method (Sherman, 1994) (Walker, 2013).

2 BUILDINGS AIRTIGHTNESS MEASUREMENT

The test is done according to the ISO standard 9972:2006 by measuring the pressure difference across the building envelope over a range of pressures applied by steps of approximately 10 Pa and the corresponding airflow rate. The range of measurement stretches from about 10 to 100 Pa.

The test is done in depressurization on the one hand and in pressurization on the other hand. The air leakage rate is equal to the mean of the air leakage rate for depressurization and these for pressurization.

3 INPUT DATA

3.1 Zero-flow pressure difference

Before and after each test, the zero-flow pressure difference ($\Delta p_{0,1}$ and $\Delta p_{0,2}$) is determined from respectively K and L measurements of the pressure difference while there is no flow through the fan (covered fan).

3.2 Temperature

Before and after each test, the temperature inside the building (T_{int}) and outside (T_e) is measured. These measurements are done punctually (single point measurement).

3.3 Pressure-airflow couples

For each of the N pressure stations, the pressure-airflow couple is determined from J measurements of the pressure difference and the corresponding airflow rate.

The measurement points are noted $\Delta p_{m,i,j}$; $q_{r,i,j}$
The pressure-airflow couples are noted ($\Delta p_{m,i}$; $q_{r,i}$).

The airflow rates are calculated from a pressure difference measurement at the fan and the calibration factors provided by the manufacturer of the fan.

These two pressure measurement are done with two different manometers or two different channels of the same manometer.

3.4 Internal volume

The internal volume of the building (V) is generally calculated on the basis of the building plans.

4 ESTIMATION OF UNCERTAINTY OF MEASUREMENT

4.1 Type A evaluation of standard uncertainty

According to JCGM 100:2008, in most cases, the best available estimate of the expectation μ_q of a quantity q that varies randomly and for which J independent observations q_j have been obtained under the same conditions of measurement, is the **arithmetic mean** of the J observations:

$$\bar{q} = \frac{1}{J}\sum_{j=1}^{J} q_j \tag{1}$$

The experimental standard deviation of the mean $s(\bar{q})$ may be used as a measure of the uncertainty of $\bar{q}$:

$$s(\bar{q}) = \sqrt{\frac{1}{J(J-1)}\sum_{j=1}^{J}(q_j - \bar{q})^2} \tag{2}$$

This type of evaluation could be applied to the zero-flow pressure difference measurement and to the pressure-airflow couples.

4.2 Type B evaluation of standard uncertainty

According to JCGM 100 :2008, for an estimate of an input quantity q that has not been obtained from repeated observations, the standard uncertainty u(q) is evaluated by scientific judgment based on all of the available information on the possible variability of q.

The pool of information may include:

- previous measurement data;
- experience with or general knowledge of the behaviour and properties of relevant materials and instruments;
- manufacturer's specifications;
- data provided in calibration and other certificates;
- uncertainties assigned to reference data taken from handbooks.

This type of evaluation could be applied to the temperature measurement and the calculation of the internal volume.

When the pressure-airflow couples are determined from a single measurement of the pressure difference and the airflow rate for each pressure station or when each couple is considered as independent, it is advisable to estimate their Type B standard uncertainty.

4.3 Combined standard uncertainty

The standard uncertainty of the result (y) of a measurement, when that result is obtained from the values of a number (N) of other quantities (x_i) through a functional relationship (f), is termed combined standard uncertainty and denoted by u_c. It is the estimated standard deviation associated with the result and is equal to the positive square root of the combined variance obtained from all variance and covariance components, however evaluated, using the law of propagation of uncertainty (JCGM 100 :2008)

For uncorrelated input quantities:

$$u_c^2(y) = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) \tag{3}$$

For correlated input quantities:

$$u_c^2(y) = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}\,u(x_i)\,u(x_j)\,r(x_i,x_j) \tag{4}$$

where $r(x_i, x_j)$ is the estimated correlation coefficient of the quantities x_i and x_j.

In the framework of the buildings airtightness measurement, corrections made to the different quantities differ in case of depressurization and pressurization; it is therefore advisable to develop the combined standard uncertainties for these two modes separately.

Table 1: Development of the combined standard uncertainty for the depressurization test

Function	**Combined standard uncertainty**
$T_{int} = \dfrac{T_{int,1} + T_{int,2}}{2}$	$u_c(T_{int}) = \sqrt{\dfrac{u^2(T_{int,1})}{4} + \dfrac{u^2(T_{int,2})}{4}}$
$T_e = \dfrac{T_{e,1} + T_{e,2}}{2}$	$u_c(T_e) = \sqrt{\dfrac{u^2(T_{e,1})}{4} + \dfrac{u^2(T_{e,2})}{4}}$
$\Delta p_i = \Delta p_{m,i} - \dfrac{\Delta p_{0,1} + \Delta p_{0,2}}{2}$	$u_c(\Delta p_i) = \sqrt{u^2(\Delta p_{m,i}) + \dfrac{u^2(\Delta p_{0,1})}{4} + \dfrac{u^2(\Delta p_{0,2})}{4}}$
$q_{m,i} = q_{r,i}\sqrt{\dfrac{T_{int}}{T_0}}$	$u_c(q_{m,i}) = \sqrt{\left(\sqrt{\dfrac{T_{int}}{T_0}}\, u(q_{r,i})\right)^2 + \left(\dfrac{q_{r,i}}{2\,T_{int}}\sqrt{\dfrac{T_{int}}{T_0}}\, u_c(T_{int})\right)^2}$
$q_{env,i} = q_{m,i}\left(\dfrac{T_e}{T_{int}}\right)$	$u_c(q_{env,i}) = \sqrt{\left(\dfrac{T_e}{T_{int}} u_c(q_{m,i})\right)^2 + \left(\dfrac{q_{m,i}}{T_{int}} u_c(T_e)\right)^2 + \left(\dfrac{q_{m,i}\,T_e}{T_{int}^{\;2}} u_c(T_{int})\right)^2}$
$x_i = \ln(\Delta p_i)$	$u_c(x_i) = \sqrt{\left(\dfrac{u_c(\Delta p_i)}{\Delta p_i}\right)^2}$
$y_i = \ln(q_{env,i})$	$u_c(y_i) = \sqrt{\left(\dfrac{u_c(q_{env,i})}{q_{env,i}}\right)^2}$
Calculation of a and b by linear regression $y = ax + b$	$u_c(a)$, $u_c(b)$ and $r(a,b)$ depending on the regression method (see hereafter)
$n = a$	$u_c(n) = u_c(a)$
$C_{env} = e^b$	$u_c(C_{env}) = e^b\, u_c(b)$
$C_L = e^b\left(\dfrac{T_0}{T_e}\right)^{1-a}$	$u_c(C_L) = \sqrt{\left(e^b\left(\dfrac{T_0}{T_e}\right)^{1-a}\ln\left(\dfrac{T_e}{T_0}\right)u_c(a)\right)^2 + \left(e^b\left(\dfrac{T_0}{T_e}\right)^{1-a}u_c(b)\right)^2 + \left(\dfrac{e^b(a-1)}{T_e}\left(\dfrac{T_0}{T_e}\right)^{1-a}u_c(T_e)\right)^2 + 2\left(e^b\left(\dfrac{T_0}{T_e}\right)^{1-a}\right)^2\ln\left(\dfrac{T_e}{T_0}\right)u_c(a)\,u_c(b)\,r(a,b)}$

$q_{50,d} = e^{b}\left(\frac{T_0}{T_e}\right)^{1-a} 50^{a}$	$u_c\left(q_{50,d}\right) = \sqrt{\left(e^{b}\,50^{a}\left(\frac{T_0}{T_e}\right)^{1-a}\ln\left(50\frac{T_e}{T_0}\right)u_c(a)\right)^2 + \left(e^{b}\left(\frac{T_0}{T_e}\right)^{1-a}50^{a}\,u_c(b)\right)^2 + \left(\frac{e^{b}(a-1)}{T_e}\,50^{a}\left(\frac{T_0}{T_e}\right)^{1-a}u_c(T_e)\right)^2 + 2\left(e^{b}\left(\frac{T_0}{T_e}\right)^{1-a}50^{a}\right)^2\ln\left(50\frac{T_e}{T_0}\right)u_c(a)\,u_c(b)\,r(a,b)}$

Table 2: Development of the combined standard uncertainty for the pressurization test

Function	**Combined standard uncertainty**
$T_{int} = \frac{T_{int,1} + T_{int,2}}{2}$	$u_c\left(T_{int}\right) = \sqrt{\frac{u^2\left(T_{int,1}\right)}{4} + \frac{u^2\left(T_{int,2}\right)}{4}}$
$T_e = \frac{T_{e,1} + T_{e,2}}{2}$	$u_c\left(T_e\right) = \sqrt{\frac{u^2\left(T_{e,1}\right)}{4} + \frac{u^2\left(T_{e,2}\right)}{4}}$
$\Delta p_i = \Delta p_{m,i} - \frac{\Delta p_{0,1} + \Delta p_{0,2}}{2}$	$u_c\left(\Delta p_i\right) = \sqrt{u^2\left(\Delta p_{m,i}\right) + \frac{u^2\left(\Delta p_{0,1}\right)}{4} + \frac{u^2\left(\Delta p_{0,2}\right)}{4}}$
$q_{m,i} = q_{r,i}\sqrt{\frac{T_e}{T_0}}$	$u_c\left(q_{m,i}\right) = \sqrt{\left(\sqrt{\frac{T_e}{T_0}}\,u\left(q_{r,i}\right)\right)^2 + \left(\frac{q_{r,i}}{2\,T_e}\sqrt{\frac{T_e}{T_0}}\,u_c\left(T_e\right)\right)^2}$
$q_{env,i} \cong q_{m,i}\frac{T_{int}}{T_e}$	$u_c\left(q_{env,i}\right) = \sqrt{\left(\frac{T_{int}}{T_e}u_c\left(q_{m,i}\right)\right)^2 + \left(\frac{q_{m,i}}{T_e}u_c\left(T_{int}\right)\right)^2 + \left(\frac{q_{m,i}\,T_{int}}{{T_e}^2}u_c\left(T_e\right)\right)^2}$
$x_i = \ln(\Delta p_i)$	$u_c\left(x_i\right) = \sqrt{\left(\frac{u_c\left(\Delta p_i\right)}{\Delta p_i}\right)^2}$
$y_i = \ln(q_{env,i})$	$u_c\left(y_i\right) = \sqrt{\left(\frac{u_c\left(q_{env,i}\right)}{q_{env,i}}\right)^2}$
Calculation of a and b by linear regression $y = ax + b$	$u_c(a)$, $u_c(b)$ and $r(a,b)$ depending on the regression method (see hereafter)
$n = a$	$u_c(n) = u_c(a)$
$C_{env} = e^{b}$	$u_c\left(C_{env}\right) = e^{b}\,u_c(b)$

$C_L = e^b \left(\frac{T_0}{T_{int}}\right)^{1-a}$	$u_c(C_L) = \sqrt{\left(e^b \left(\frac{T_0}{T_{int}}\right)^{1-a} \ln\left(\frac{T_{int}}{T_0}\right) u_c(a)\right)^2 + \left(e^b \left(\frac{T_0}{T_{int}}\right)^{1-a} u_c(b)\right)^2 + \left(\frac{e^b (a-1)}{T_{int}} \left(\frac{T_0}{T_{int}}\right)^{1-a} u_c(T_{int})\right)^2 + 2\left(e^b \left(\frac{T_0}{T_{int}}\right)^{1-a}\right)^2 \ln\left(\frac{T_{int}}{T_0}\right) u_c(a)\, u_c(b)\, r(a,b)}$
$q_{50,p} = e^b \left(\frac{T_0}{T_{int}}\right)^{1-a} 50^a$	$u_c(q_{50,p}) = \sqrt{\left(e^b 50^a \left(\frac{T_0}{T_{int}}\right)^{1-a} \ln\left(50\frac{T_{int}}{T_0}\right) u_c(a)\right)^2 + \left(e^b \left(\frac{T_0}{T_{int}}\right)^{1-a} 50^a u_c(b)\right)^2 + \left(\frac{e^b (a-1)}{T_{int}} 50^a \left(\frac{T_0}{T_{int}}\right)^{1-a} u_c(T_{int})\right)^2 + 2\left(e^b \left(\frac{T_0}{T_{int}}\right)^{1-a} 50^a\right)^2 \ln\left(50\frac{T_{int}}{T_0}\right) u_c(a)\, u_c(b)\, r(a,b)}$

Table 3: Development of the combined standard uncertainty for the calculation of the air leakage rate and the air change rate

Function	**Combined standard uncertainty**
$q_{50} = \frac{q_{50,d} + q_{50,p}}{2}$	$u_c(q_{50}) = \sqrt{\frac{u_c^2(q_{50,d})}{4} + \frac{u_c^2(q_{50,p})}{4}}$
$n_{50} = \frac{q_{50}}{V}$	$u_c(n_{50}) = \sqrt{\left(\frac{1}{V} u_c(q_{50})\right)^2 + \left(\frac{q_{50}}{V^2} u(V)\right)^2}$

5 METHOD OF LEAST-SQUARES

In the framework of the buildings airtightness measurement, the relation between the airflow rate and the pressure difference has an exponential form.

$$q_{env} = C_{env}\,(\Delta p)^n \qquad (5)$$

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

$$\ln q_{env} = \ln C_{env} + n\,\ln \Delta p \qquad (6)$$

The ISO standard 9972:2006 requires the use of a least-squares technique for the calculation of the airflow coefficient C_{env} and the airflow exponent n. However it does not give more guidance.

5.1 Ordinary method of least-squares

The ordinary method of least-squares is applicable when all the y values ($y_i = \ln q_{env,i}$) are equally uncertain ($u_c(y_1) = u_c(y_2) = \cdots = u_c(y)$) and the uncertainties on x ($x_i = \ln \Delta p_i$) are negligible.

This method consists of finding the **regression line y = a x + b** that minimalize the sum of the squares of the difference between the measurement points and the line; which comes to minimalizing the following sum:

$$\sum_{i=1}^{N} \left(\left(a\, x_i + b \right) - y_i \right)^2 \tag{7}$$

The constants a and b of this regression line are calculated as follows (Cantrell, 2008) (Taylor, 2000) :

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

$$a = \frac{N \sum x_i y_i - \sum x_i \sum y_i}{N \sum x_i^2 - \left(\sum x_i \right)^2} \tag{8}$$

$$b = \frac{\sum x_i^2 \sum y_i - \sum x_i \sum x_i y_i}{N \sum x_i^2 - \left(\sum x_i \right)^2} \tag{9}$$

The standard uncertainties of the constant a and b are given by :

$$u_c(a) = \sqrt{\frac{N\, s^2}{N \sum x_i^2 - \left(\sum x_i \right)^2}} \tag{10}$$

$$u_c(b) = \sqrt{\frac{s^2 \sum x_i^2}{N \sum x_i^2 - \left(\sum x_i \right)^2}} \tag{11}$$

where

$$s^2 = u_c^2(y) \tag{12}$$

When $u_c^2(y)$ is unknown, s^2 can be evaluated based on the scattering of the y_i values around the regression line [12].

$$s^2 = s^2(y) = \frac{\sum \left(y_i - y_{i,est} \right)^2}{N-2} = \frac{\sum \left(y_i - a\, x_i - b \right)^2}{N-2} \tag{13}$$

The estimated correlation coefficient of the constants a and b is given by :

$$r(a, b) = -\frac{\sum x_i}{\sqrt{N \sum x_i^2}} \tag{14}$$

The coefficient of determination (r^2), which measures the quality of the adjustment of the measurement points by the method of least-squares, is given by (Cantrell, 2008) (Spiegel, 1996) :

$$r^2 = \frac{\left(N \sum x_i y_i - \sum x_i \sum y_i \right)^2}{\left(N \sum x_i^2 - \left(\sum x_i \right)^2 \right)\left(N \sum y_i^2 - \left(\sum y_i \right)^2 \right)} \tag{15}$$

The combined standard uncertainty associated with any estimate y, obtained through the relation $y = a\, x + b$, can be deduced trough the law of propagation of uncertainty :

$$u_c(y) = s \sqrt{\frac{1}{N} + \frac{\left(x - \bar{x} \right)^2}{\sum \left(x_i - \bar{x} \right)^2}} \tag{16}$$

An interest of this formula is to show that the uncertainty on the estimated values through the regression line increases as one goes away from the mean value of x.

5.2 Weighted method of least-squares

Negligible uncertainties of x

When the uncertainties of the y values are not equal (and the uncertainties of the x values are negligible), it is advisable to use the weighted method of least-squares.

This method consists of finding the **regression line y = a x + b** that minimalize the sum of the squares of the weighted difference between the measurement points and the line; which comes to minimalizing the following sum:

$$\sum_{i=1}^{N} w_i \left(\left(a\,x_i + b \right) - y_i \right)^2 \quad (17)$$

The weight w_i applied to each measurement point i is equal to :

$$w_i = \frac{1}{s^2(y_i)} = \frac{1}{u_c^2(y_i)} \quad (18)$$

The constants a and b of this regression line are calculated as follows (Cantrell, 2008) (Taylor, 2000):

$$a = \frac{\sum w_i \sum w_i x_i y_i - \sum w_i x_i \sum w_i y_i}{\sum w_i \sum w_i x_i^2 - \left(\sum w_i x_i\right)^2} \quad (19)$$

$$b = \frac{\sum w_i\, x_i^2 \sum w_i\, y_i - \sum w_i\, x_i \sum w_i\, x_i\, y_i}{\sum w_i \sum w_i x_i^2 - \left(\sum w_i x_i\right)^2} \quad (20)$$

Their standard uncertainties are given by :

$$u_c(a) = \sqrt{\frac{\sum w_i}{\sum w_i \sum w_i x_i^2 - \left(\sum w_i x_i\right)^2}} \quad (21)$$

$$u_c(b) = \sqrt{\frac{\sum w_i x_i^2}{\sum w_i \sum w_i x_i^2 - \left(\sum w_i x_i\right)^2}} \quad (22)$$

Their estimated correlation coefficient is given by:

$$r(a,b) = -\frac{\sum w_i x_i}{\sqrt{\sum w_i \sum w_i x_i^2}} \quad (23)$$

The coefficient of determination (r^2) is given by :

$$r^2 = \frac{\left(\sum w_i \sum w_i\, x_i\, y_i - \sum w_i\, x_i \sum w_i\, y_i\right)^2}{\left(\sum w_i \sum w_i\, x_i^2 - \left(\sum w_i\, x_i\right)^2\right)\left(\sum w_i \sum w_i\, y_i^2 - \left(\sum w_i\, y_i\right)^2\right)} \quad (24)$$

The weighted method can be useful because the assumption that the uncertainties of all the y values are equal is not necessarily met in practice. It is for example the case when the measured values of the airflow rates have equal uncertainties. Indeed, the linear regression is applied to the logarithms of the measured values and not to the measured values themselves. In that case the law of propagation of uncertainty shows that:

$$if\ \ u_c\ \ q_{env,i}\ \ = C \qquad (constant)$$

$$y_i = \ln(q_{env,i})$$

$$then\ \ u_c\ \ y_i\ \ = \sqrt{\frac{u_c\ \ q_{env,i}}{q_{env,i}}^{2}} = \frac{u_c\ \ q_{env,i}}{q_{env,i}} = \frac{C}{q_{env,i}}$$

$u_c\ \ y_i$ is therefore all the greater as $q_{env,i}$ is small. The weight w_i applied to each measurement point should therefore be equal to

$$w_i = \frac{1}{u_c^2\ \ y_i} = \frac{q_{env,i}^2}{C^2}$$

Which could be simplified as follows and explains the weighting proposed by the CAN standard CGSB-149.10-M86:1986:

$$w_i = q_{env,i}^2$$

Note: The formulae for $u_c(a)$ and $u_c(b)$ presented above do not accept this simplification.

<u>*Non-negligible uncertainties of x*</u>

When both x and y values have non-negligible uncertainties, the weighting can be adapted as follows (Cantrell, 2008) (Taylor, 2000) :

$$w_i = \frac{1}{u_c^2\ \ y_i\ \ + a^2\, u_c^2\ \ x_i} \tag{25}$$

This method termed **effective variance** requires however a resolution by iteration given the presence of the constant a in the definition of the weighting.

Note: There are other methods in the literature that take the uncertainties of both x and y into account (Cantrell, 2008).

6 DISCUSSION

It seems that the conditions of application of the unweighted method of least-squares are generally not met in the framework of the buildings airtightness measurement; it is therefore advisable to use the weighted method of least-squares.

Real measurement's data show that the combined standard uncertainty of the pressure differences is not always negligible compared with these of the airflow rates. The consideration of these two uncertainties in the calculation of the weights seems therefore necessary even if it requires a resolution by iteration.

Taking into account the standard uncertainties of the input data of the weighted method of least-squares and not their scattering around the regression line is debatable (as would the opposite choice be). This problem could be limited by considering a large number of measurement points for each pressure station (e.g. at least 10). These points would bring information about other sources of uncertainty.

This application of the law of propagation of uncertainty is based on data's that are considered in the measurement method. However since various sources of uncertainty are not taken into account in the method (Sherman, 1994) (Walker, 2013), the combined standard uncertainty on the air leakage must be considered as a part of the total uncertainty.

7 ACKNOWLEDGEMENTS

This paper is based on a study done at the Belgian Building Research Institute in the framework of the "Etanch'Air" project with the financial support of the Walloon Region. A more extended paper is available from the author.

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