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Airtightness of Buildings—Evaluation of Leakage-Infiltration Ratio and Systematic Measurement Error due to Steady Wind and Stack Effect

Christophe Y. M. Delmotte, Ir.

ABSTRACT

The fan pressurization method that is widely used to measure the airtightness of buildings is known to have quite large measurement error. It is made up of random measurement error (precision) and systematic measurement error (bias).

The first part of the present article explains, with analytical evidence, why steady wind and stack effect generate systematic measurement error and it assesses this error through Monte Carlo simulations. Tables with practical results are provided for common zero-flow pressure difference intervals. For example, they show that with a typical zero-flow pressure difference of 5 Pa (0,104 lb/ft²), the systematic measurement error at a reference pressure difference of 4 Pa (0,084 lb/ft²) is in the order of - 1,1% to -2,2%. Possible improvement of the test method is also suggested and assessed.

The second part of this article calls on the Monte Carlo simulations to assess the variability of the leakage-infiltration ratio. A simplified analytical formula has been developed to allow comparison and it shows very good correlation. Tables with practical results are also provided. For example, they show that the well-known value of 20 can be associated with a natural pressure field of [-3 Pa; +3Pa] ([-0,063 lb/ft²; +0,063 lb/ft²]).

INTRODUCTION

Leaks and cracks in the building envelope can be very numerous and are all different. They can be characterized by different properties like opening size, length, shape or roughness but there is no single physical value representing them all at the same time. It is however possible *"to measure the combined effect of all of the cracks in a section of the envelope; this might be done by measuring the flow through this section in response to a constant pressure across it"* (Sherman 1980). Implicitly, it is supposed that (the section of) the building envelope is subjected to uniform pressure difference (e.g. 4 Pa, 10 Pa or 50 Pa) (0,084 lb/ft², 0,209 lb/ft², 1,044 lb/ft²). However, such uniformity never exists under natural conditions caused by wind and stack effect, which entails that both of them prevent all attempts to reach and maintain uniform pressure difference on site.

Many sources of error can affect the measurement of building airtightness. The main ones are the following:

- Flow measurements;
- Pressure measurements;

Christophe Y. M. Delmotte is a civil engineer at the Belgian Building Research Institute, Brussels, Belgium.

- Steady wind and stack effect (non-uniformity of pressure across the envelope);
- Wind fluctuation (variation of pression around the building envelope);
- Measurement model (modelization).

The first objective of the present article is to understand why steady wind and stack effect generate systematic measurement error and to assess it through Monte Carlo simulations. Inevitably this also includes error due to the measurement model.

In energy related calculations (e.g. energy performance of buildings or design heat load), it is needed to go one step further and consider not only the airtightness of the building but also the air infiltration. Often, it is done using the leakage-infiltration ratio which on its turn is subjected to variability. The second objective of this article is to use the above mentioned Monte Carlo simulations to assess the variability of the leakage-infiltration ratio. A simplified analytical formula is developed to allow comparison.

INFLUENCE OF STEADY WIND AND STACK EFFECT

Zero-flow pressure difference

In the framework of the buildings airtightness measurement, ISO 9972 assumes the relation between the air flow rate through leaks and the pressure difference is a power function (Formula 1) with an exponent n comprised between 0,5 and 1,0 (Walker 1998).

$$q = C\,\Delta p^n \tag{1}$$

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 a building. These natural pressure differences are called “zero-flow pressure differences”. The equilibrium internal pressure is such that the air flow rate that enters the building is equal to the air flow rate that leaves. The sum of the air flow rates through the leaks (j = 1 to L) of the building envelope is therefore equal to zero (formally we should talk about mass flow) (Formula 2). Accordingly, parts of the envelope must necessarily undergo underpressure while others are in overpressure.

$$\sum_{j=1}^{L} C_j\,\left|\Delta p_{0,j}\right|^{n_j}\,sign\left(\Delta p_{0,j}\right) = q_0 = 0 \tag{2}$$

“Zero-flow” refers to the situation where there is zero air flow rate through fans. 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.

However, both the American standard ASTM E 779-03 (§ 8.8) and Canadian standard CAN/CGSB-149.10-M86 (§ 6.2.2) are clear on the fact that it refers to the pressure difference across the building envelope.

In ISO 9972, one of the zero-flow pressure differences is measured and used as a reference value for the test. In the present article, it is termed “reference zero-flow pressure difference”. The interval between the minimum and maximum zero-flow pressure difference [$\Delta p_{0,min}$; $\Delta p_{0,max}$] is termed “zero-flow pressure difference interval”.

Effect of a fan

In the absence of wind and stack effect (generated by temperature difference between inside and outside), the action of a fan located in the building envelope induces an identical pressure difference Δp_{ind} across all points of the envelope (Formula 3). Under these conditions, the air flow rate through the fan ($q_{fan,model}$) is considered as the true leak air flow rate of the building.

$$\sum_{j=1}^{L} C_j\,\left|\Delta p_{ind}\right|^{n_j}\,sign\left(\Delta p_{ind}\right) = q_{fan,model} \tag{3}$$

Adding the effect of a fan to that of the wind and of the stack effect does not change the external pressure, rather it changes the equilibrium internal pressure (Sherman 1990). Each leak (j) of the envelope thus undergoes a similar change in pressure while keeping its relative difference compared to the other leaks (Figure 1).

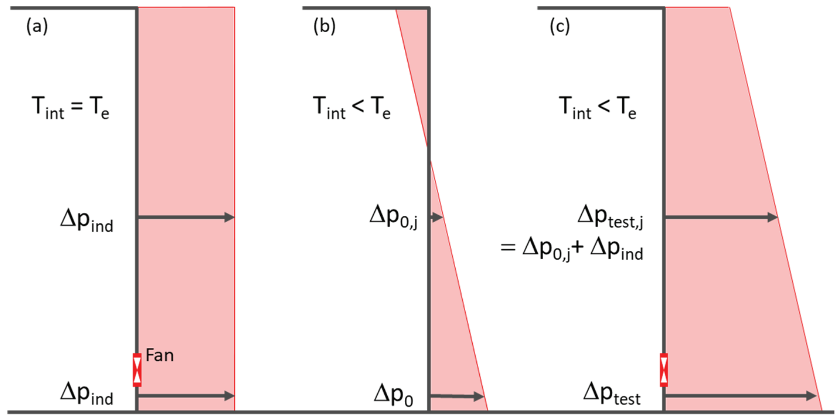

Figure 1 Example of pressure distribution over the height of a building (a) for a fan only, (b) for a temperature difference only and (c) for the combination of the fan and the temperature difference.

At this point, it is important to notice that as a consequence of Formula 2 some of the leaks feel a bit less pressure difference than the induced pressure difference while the other leaks feel a bit more pressure difference. This noticing is true whatever the leakage repartition or stack effect or wind.

Note that this principle of superposition of the pressure differences is not true for air flow rates. The reason is that Formula 1 is not linear. This means that each leak (j) does not undergo a similar change in air flow rate. The leaks do not even undergo a change in air flow rate that is equal to the one they would undergo in the absence of wind or stack effect with the fan inducing the same change in pressure.

In other words, the fan air flow rate necessary to cause a given increase of induced pressure difference Δp_{ind} in a building when there is no wind nor stack effect ($q_{fan,model}$ - Formula 3), is different from the fan air flow rate necessary to cause the same Δp_{ind} increase when there is wind or stack effect ($q_{fan,test}$ - Formula 4).

$$\sum_{j=1}^{L} C_j \left|\Delta p_{0,j} + \Delta p_{ind}\right|^{n_j} sign\left(\Delta p_{0,j} + \Delta p_{ind}\right) = q_{fan,test} \qquad (4)$$

However, since the sum of the natural air flow rates is null ($q_0 = 0$ – See Formula 2) and zero-flow pressure differences are kept low compared to that induced by the fan (commonly from about 10 Pa to 50 Pa, 75 Pa or 100 Pa) (about 0,209 lb/ft² to 1,044 lb/ft², 1,566 lb/ft² or 2,089 lb/ft²), ISO 9972 considers that there is no significant difference between both air flow rates ($q_{fan,model}$ and $q_{fan,test}$). Nonetheless this assumption generates a systematic measurement error ε_1 given by Formula 5.

$$q_{fan,test} = q_{fan,model} + \varepsilon_1 \qquad (5)$$

$$\varepsilon_1(\Delta p_{ind}) = \sum_{j=1}^{L} C_j \left|\Delta p_{0,j} + \Delta p_{ind}\right|^{n_j} sign\left(\Delta p_{0,j} + \Delta p_{ind}\right) - \sum_{j=1}^{L} C_j \left|\Delta p_{ind}\right|^{n_j} sign(\Delta p_{ind}) \qquad (6)$$

This steady wind and stack effect related error (ε_1) is the sum of the effects of variations around the pressure difference induced by the fan (Formula 6). Since it concerns power functions with an exponent between 0,5 and 1, a small downward variation of the pressure difference has more effect on the air flow rate than an equivalent upward variation. As a result, the value of the ε_1 error tends to be positive in underpressure and negative in overpressure. The test flow rate ($q_{fan,test}$) attributed to the effect of a uniform pressure difference is therefore generally underestimated (= smaller in absolute value). This tendency is more pronounced for low induced pressure differences (normally above 10 Pa) (0,209 lb/ft²) than for large induced pressure differences (commonly up to 50 Pa, 75 Pa or 100 Pa) (1,044 lb/ft², 1,566 lb/ft² or 2,089 lb/ft²). The only cases for which there is no error (ε_1 = 0) are those where there is no wind nor stack effect ($\Delta p_{0,j}$ =0) or where all leaks air flow exponents are equal to 1 (nj = 1) (the latter statement is a consequence of Formula 2).

Pressure difference sequence

The analysis of the steady wind and stack effect related error (ε_1) shows that it can be reduced by adequately selecting the lowest induced pressure difference ($\Delta p_{ind,1}$) in function of the zero-flow pressure difference interval.

Currently, ISO 9972 says that *"the lowest pressure difference shall be approximately 10 Pa or five times the value of the zero-flow pressure difference, whichever is the greatest"*.

An option to reduce the steady wind and stack effect related error (ε_1) would be to search for the largest zero-flow pressure difference in the building envelope and to use this value to directly fix the lowest induced pressure difference ($\Delta p_{ind,1}$) (not the test pressure difference). For example, it could be five times the largest zero-flow pressure difference with a minimum value of 10 Pa (0,209 lb/ft²).

Note that 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 zero-flow pressure differences (Delmotte 2019). This would require two manometers (one for the reference zero-flow pressure difference and another one for the internal equilibrium pressure) or at least two different exterior pressure taps with tubing.

Addition of power functions

Since the number and properties of leaks are unknown, ISO 9972 assumes they all have the same air flow exponent and therefore can be treated as a single leak. The airtightness of a building is then characterized by a power function with a single air flow coefficient C and a single air flow exponent n (Formula 1).

This assumption also generates a systematic measurement error (ε_2) because there is no single couple C and n that can be perfectly suitable for all pressure differences at the same time. This is due to the fact that the sum of two power functions is no power function except when the exponents of both summed power functions are the same (Delmotte 2021).

Systematic measurement error

Finally we are interested by the flow rate through the building envelope in response to a constant uniform reference pressure difference Δp_{ref} across it. The systematic measurement error ε on this flow rate is given by Formula 7. It is the difference between the calculated total air flow rate that would go through the leaks (uniform reference pressure difference, single air flow coefficient and single flow exponent) and the true leakage flow rate (uniform reference pressure difference, different air flow coefficients and different flow exponents).

$$\varepsilon(\Delta p_{ref}) = C\,|\Delta p_{ref}|^{n}\,sign(\Delta p_{ref}) - \sum_{j=1}^{L} C_j\,|\Delta p_{ref}|^{n_j}\,sign(\Delta p_{ref}) \qquad (7)$$

Note that the steady wind and stack effect related error (ε_1) and the power function related error (ε_2) are included in the systematic measurement error (ε) since they make part of the error on C and n. Unfortunately, since the number and properties of leaks are unknown, it is not possible to calculate this systematic measurement error in practice.

MONTE CARLO SIMULATIONS

Principle

Supposing the number and properties of leaks and also the zero-flow pressure difference they are subjected to due to wind and stack effect are known, it is then possible to calculate the systematic error for each particular case (Table 1). By repeating such calculation many times (e.g. 10 000 times) with random properties and pressure differences, it is possible to obtain statistics of the systematic measurement errors ε_1 and ε. Such calculation method is known as "Monte Carlo method".

Table 1 : Possible errors in function of the combination of wind and stack effect with flow exponents of the leaks (n_j)

Wind or stack effect	All n_j values the same $n_j = 1,0$	All n_j values the same $n_j = 0,5 \dots 0,9999$	n_j values different $n_j = 0,5 \dots 1,0$
No	$\varepsilon_1=0$ $\varepsilon_2=0$ $\varepsilon=0$	$\varepsilon_1=0$ $\varepsilon_2=0$ $\varepsilon=0$	$\varepsilon_1=0$ ε_2 ε
Yes	$\varepsilon_1= 0$ $\varepsilon_2=0$ $\varepsilon= 0$	ε_1 $\varepsilon_2=0$ ε	ε_1 ε_2 ε

Random variables generation

In order to make such simulations, the following parameters have to be randomized:

- air flow coefficient of each leak C_j
- air flow exponent of each leak n_j
- zero-flow pressure difference across each leak $\Delta p_{0,j}$

It is difficult to evaluate the number of leaks in a building. For the purposes of the simulations, a number of 50 leaks has been chosen (L=50 and j = 1 to 50).

The air flow coefficient represents globally the opening size of the leaks. It is a positive value. Random choice of the parameters is constrained by Formula 2. Therefore the airflow coefficient of the very last leak is not randomly chosen but calculated to force $q_0 = 0$.

The air flow exponent represents globally the type of air flow within the leaks. Theoretically, it is comprised between 0,5 and 1,0. Analysis of residential databases by Walker et al. (2013) showed a mean value around 0,65 with a standard deviation of about 0,06 to 0,07.

The zero-flow pressure difference across the leaks depends on their location in the building envelope, the wind speed and direction and the stack effect (depending itself on the building's height and the temperature difference between inside and outside the building). One could choose random location, fix the other parameters and calculate the equilibrium internal pressure. However, it comes to the same thing to fix the minimum and maximum pressure differences (zero-flow pressure difference interval) and choose the pressure difference randomly.

An important step in these Monte-Carlo simulations is therefore to fix the zero-flow pressure difference interval. This is the interval of zero-flow pressure differences that apply on the building envelope.

For example, if we take a building of 10 m height and a temperature difference of 25 K between inside and outside (the product of both is 250 mK), it generates a hydrostatic pressure difference of about 10 Pa (0,209 lb/ft²). If the leaks are equally spread on the height of the building envelope, the minimum zero-flow pressure difference is -5 Pa (-0,104 lb/ft²) and the maximum is +5 Pa (+0,104 lb/ft²).

To make sure that the simulations are really representative of this interval and not of a smaller one (what could happen when the random function does not reach the minimum or maximum value), the pressure difference of the first two leaks is respectively equal to the minimum and maximum value of the zero-flow pressure difference interval.

Note that this procedure virtually generates 10 000 different buildings or leak distributions. It is therefore a simulation of 10 000 systematic measurement errors for a given zero-flow pressure difference interval independently of the building.

According to ISO 9972, the lowest test pressure difference ($\Delta p_{test,1}$) depends on the reference zero-flow pressure difference $\Delta p_{0,ref}$ (see 1.3). It has to be 10 Pa (0,209 lb/ft²) or five times the value of this zero-flow pressure difference, whichever is the greatest. However, since there are no instructions for the place of measurement of this reference zero-flow pressure difference, it can take any value within the zero-flow pressure difference interval (Delmotte 2019).

SIMULATION RESULTS

Simulations have been made for different zero-flow pressure difference intervals, respecting the ISO 9972 way of determining the lowest test pressure difference. The main results of the simulations are given in Table 3 and Table 4.

Analysis of steady wind and stack effect related errors ε_1 shows that inducing a pressure difference lower than the maximum zero-flow pressure difference (absolute value) generates large ε_1 errors (and this can happen with the current ISO 9972 rules). However, the combination of higher pressure measurements and linear regression finally reduces the systematic measurement error ε.

Analysis of the results shows that the systematic measurement error ε is mainly negative for low pressure differences (underestimation of the leak air flow rate). At 50 Pa (1,044 lb/ft²), the error is limited to about ±1%.

The wider the zero-flow pressure difference interval, the larger the systematic errors are. This is due to larger fluctuations around the induced pressure (see Formula 6).

These results also show that measurements in depressurization and pressurization have similar statistics for errors. However, these are different for each particular case; when the one reaches a maximum, the other does not. This is the reason why the spread of the errors for the average of both is lower than for each of them.

Other simulations have been made with another method of determining the lowest induced pressure difference (five times the largest zero-flow pressure difference with a minimum value of 10 Pa (0,209 lb/ft²)). The main results are given in Table 5.

Analysis of the results show that searching for the largest zero-flow pressure difference and fixing the first induced pressure difference on that basis avoids using too low induced pressure and therefore reduces the systematic measurement error. This may be important for measurements in unfavourable conditions (e.g. for high rise buildings).

LEAKAGE-INFILTRATION RATIO

Besides the study of measurement uncertainty, the simulations offer the possibility to examine the leakage-infiltration ratio (LIR). According to Jones et al. (2016), the leakage-infiltration ratio is *"a simple linear relationship between the air*

Table 3 : Systematic measurement error ε for depressurization from simulations (Percentiles 2,5%, 50% and 97,5%) (10 test pressures up to 100 Pa (2,089 lb/ft²) – Lowest test pressure according to ISO 9972)

Zero-flow pressure difference interval Pa	ε(-4 Pa) %			ε(-10 Pa) %			ε(-50 Pa) %		
	$Q_{0,025}$	$Q_{0,5}$	$Q_{0,975}$	$Q_{0,025}$	$Q_{0,5}$	$Q_{0,975}$	$Q_{0,025}$	$Q_{0,5}$	$Q_{0,975}$
[-0 ; 0]	-1,0	-0,7	-0,4	-0,2	-0,1	-0,1	0,0	0,1	0,1
[-1 ; 1]	-1,3	-0,7	-0,2	-0,5	-0,2	0,1	0,0	0,1	0,2
[-2 ; 2]	-1,7	-0,8	-0,1	-0,9	-0,3	0,3	-0,2	0,0	0,3
[-3 ; 3]	-2 ,2	-1,0	0,0	-1,2	-0,4	0,3	-0,3	0,0	0,3
[-4 ; 4]	-2,8	-1,3	-0,1	-1,6	-0,6	0,3	-0,4	0,0	0,4
[-5 ; 5]	-3,3	-1,6	-0,2	-2,0	-0,8	0,3	-0,5	0,0	0,4
[-7,5 ; 7,5]	-5,5	-2,3	-0,4	-3,5	-1,3	0,2	-0,8	-0,2	0,4
[-10 ; 10]	-10,4	-2,8	-0,5	-6,9	-1,6	0,1	-1,2	-0,3	0,4

Table 4 : Systematic measurement error ε for the average of depressurization and pressurization from simulations (Percentiles 2,5%, 50% and 97,5%) (10 test pressures up to 100 Pa (2,089 lb/ft²) – Lowest test pressure according to ISO 9972)

Zero-flow pressure difference interval Pa	ε(-4 Pa) %			ε(-10 Pa) %			ε(-50 Pa) %		
	$Q_{0,025}$	$Q_{0,5}$	$Q_{0,975}$	$Q_{0,025}$	$Q_{0,5}$	$Q_{0,975}$	$Q_{0,025}$	$Q_{0,5}$	$Q_{0,975}$
[-0 ; 0]	-1,0	-0,7	-0,4	-0,2	-0,1	-0,1	0,0	0,1	0,1
[-1 ; 1]	-1,1	-0,7	-0,4	-0,3	-0,2	-0 ,1	0,0	0,1	0,1
[-2 ; 2]	-1,2	-0,8	-0,6	-0,4	-0,3	-0,2	0,0	0,0	0,1
[-3 ; 3]	-1,5	-1,1	-0,8	-0,5	-0,4	-0,3	0,0	0,0	0,1
[-4 ; 4]	-1,8	-1,3	-0,9	-0,8	-0,6	-0,4	0,0	0,0	0,0
[-5 ; 5]	-2,2	-1,6	-1,1	-1,1	-0,8	-0,5	-0,1	0,0	0,0
[-7,5 ; 7,5]	-4,1	-2,2	-1,4	-2,5	-1,2	-0,7	-0,3	-0,1	-0,1
[-10 ; 10]	-8,2	-2,6	-1,6	-5,3	-1,4	-0,9	-0,7	-0,2	-0,1

leakage rate and the infiltration rate". It can be considered over a period of time (e.g. the heating or cooling season) or, as it is the case in this article, under given steady state conditions.

From the simulations it is possible to calculate the infiltration air flow rate due to the zero-flow pressure differences and compare it to the true leakage flow rate at uniform pressure difference. The leakage-infiltration ratio obtained this way (Formula 8) is shown in Table 6. It is a variable value that strongly depends on the zero-flow pressure difference interval.

$$LIR(\Delta p) = C\Delta p^n / q_{inf} \qquad (8)$$

Leakage-infiltration ratio can also be estimated analytically by making assumptions on the leaks and zero-flow pressure difference repartition on the building envelope. Supposing uniform repartition of the leaks over the height of a building and linear evolution of the zero-flow pressure difference between $-\Delta p_{max}$ and Δp_{max}, the leakage-infiltration ratio can be calculated by Formula 9 (Delmotte 2021).

$$LIR(\Delta p) = 2(n+1)(\Delta p / \Delta p_{max})^n \qquad (9)$$

Application of this formula gives results (see Table 7) in line with the simulations and sheds new light on the well-known value of 20 (Jones et al. 2016).

Table 5 : Systematic measurement error ε for the average of depressurization and pressurization from simulations (Percentiles 2,5%, 50% and 97,5%)(10 induced pressures up to 100 Pa (2,089 lb/ft²) – Lowest induced pressure according to new method)

Zero-flow pressure difference interval Pa	ε(-4 Pa) %			ε(-10 Pa) %			ε(-50 Pa) %		
	$Q_{0,025}$	$Q_{0,500}$	$Q_{0,975}$	$Q_{0,025}$	$Q_{0,500}$	$Q_{0,975}$	$Q_{0,025}$	$Q_{0,500}$	$Q_{0,975}$
[-0 ; 0]	-1,1	-0,7	-0,4	-0,2	-0,1	-0,1	0,0	0,1	0,1
[-1 ; 1]	-1,1	-0,7	-0,4	-0,3	-0,2	-0,1	0,0	0,1	0,1
[-2 ; 2]	-1,2	-0,8	-0,6	-0,4	-0,3	-0,2	0,0	0,1	0,1
[-3 ; 3]	-1,5	-1,1	-0,7	-0,6	-0,4	-0,3	0,0	0,0	0,1
[-4 ; 4]	-1,8	-1,2	-0,8	-0,7	-0,5	-0,4	0 ,0	0,0	0,0
[-5 ; 5]	-2,0	-1,4	-1,0	-0,9	-0,6	-0,5	0 ,0	0,0	0,0
[-7,5 ; 7,5]	-2,4	-1,7	-1,2	-1,2	-0,9	-0,6	-0,1	-0,1	-0,1
[-10 ; 10]	-2,8	-2,0	-1,4	-1,5	-1,1	-0,8	-0,2	-0,2	-0,1

Table 6 : Leakage-Infiltration Ratio (LIR) from simulations (Percentiles 2,5%, 50% and 97,5%)

Zero-flow pressure difference interval Pa	LIR(4 Pa)			LIR(10 Pa)			LIR(50 Pa)		
	$Q_{0,025}$	$Q_{0,5}$	$Q_{0,975}$	$Q_{0,025}$	$Q_{0,5}$	$Q_{0,975}$	$Q_{0,025}$	$Q_{0,5}$	$Q_{0,975}$
[-0 ; 0]	-	-	-	-	-	-	-	-	-
[-1 ; 1]	6,9	7,8	9,1	12,5	14,3	16,8	35,8	41,4	49,2
[-2 ; 2]	4,4	5,0	5,8	8,0	9,1	10,7	22,9	26,4	31,2
[-3 ; 3]	3,4	3,8	4,5	6,2	7,0	8,2	17,6	**20,2**	24,0
[-4 ; 4]	2,8	3,2	3,7	5,1	5,8	6,7	14,7	16,8	19,7
[-5 ; 5]	2,4	2,7	3,2	4,4	5,0	5,9	12,7	14,5	17,1
[-7,5 ; 7,5]	1,9	2,1	2,4	3,4	3,8	4,5	9,7	11,2	13,0
[-10 ; 10]	1,5	1,7	2,0	2,8	3,2	3,7	8,1	9,2	10,8

Table 7 : Leakage-Infiltration Ratio (LIR) from calculation (air flow exponent n = 0,65)

Zero-flow pressure difference interval Pa	LIR(4 Pa)	LIR(10 Pa)	LIR(50 Pa)
[-1 ; 1]	8,1	14,7	42,0
[-2 ; 2]	5,2	9,4	26,7
[-3 ; 3]	4,0	7,2	**20,5**
[-4 ; 4]	3,3	6,0	17,0
[-5 ; 5]	2,9	5,2	14,7
[-7,5 ; 7,5]	2,2	4,0	11,3
[-10 ; 10]	1,8	3,3	9,4

CONCLUSION

Systematic measurement error is inseparable from the fan pressurization method that is widely used to measure the airtightness of buildings. This systematic error cannot be calculated in practice, but the simulations carried out make it possible to evaluate its extent in function of the zero-flow pressure difference interval (see Table 3 and Table 4) which can be estimated by measurements.

This article presents an option that allows the systematic error to be reduced. This is mainly useful when one wishes to express the measurement result at a quite low reference pressure difference like e.g. 4 Pa (0,084 lb/ft²) or 10 Pa (0,209 lb/ft²) (see Table 5).

The calculation technique used in this article could be used in future research to define new measurement conditions that would allow the scope of application of ISO 9972 to be extended, e.g. for high-rise buildings which most of the time exceed the zero-flow pressure difference interval of ±5 Pa (±0,104 lb/ft²).

Information on Leakage-infiltration ratio could be used in different ways. Starting from given steady state conditions to evaluate the possible extent of the LIR or starting from a given LIR to get a rough idea of the corresponding average pressure conditions.

NOMENCLATURE

LIR = Leakage-Infiltration Ratio

C = Air flow coefficient
L = Total number of leaks in the building envelope
n = Air flow exponent (also referred to as “pressure exponent”)
q = Air flow rate
q_{fan} = Air flow rate through the fan
q_{inf} = Sum of the natural air flow rates (inwards) [infiltration]
q_0 = Sum of the natural air flow rates (inwards and outwards)
T_{int} = Internal air temperature
T_e = External air temperature
Δp = Pressure difference
Δp_{ind} = Induced pressure difference
$\Delta p_{ind,1}$ = Induced pressure difference at 1st pressure station of the test
Δp_{ref} = Reference pressure difference
Δp_{test} = Test pressure difference
Δp_0 = Zero-flow pressure difference
$\Delta p_{0,ref}$ = Reference zero-flow pressure difference
ε = Measurement error
ε_1 = Steady wind and stack effect related error
ε_2 = Power function related error

Subscripts

i, j, k = Element of a series
model = Referring to the measurement model
test = Referring to the practical test

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