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# High-Rise Buildings Airtightness Measurements: Practical Advices and Error Estimation

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## ABSTRACT

*For an ideal building airtightness test, the pressure difference between inside and outside would be constant over time and uniform along the entire building envelope, so that each leakage is equally considered and that the test result does not depend on the test conditions. This is particularly challenging for high-rise buildings as they are more subject to strong stack effects: the temperature difference between inside and outside induces a pressure difference along the envelope directly proportional to its height. In addition, high-rise buildings can have a significant pressure loss through stairwells. These specificities of high-rise buildings conflict with several points of the standard ISO 9972 for the determination of buildings air permeability with the fan method. In particular, two requirements can be difficult to achieve:*

- *A zero-flow pressure at the ground floor* $|\Delta P_{0,ground}| < 5$ *Pa*
- *A first pressure point at the ground floor* $> 5^*|\Delta P_{0,ground}|$

*This paper suggests new criteria to replace these two requirements when they cannot be met:*

- *A standard deviation on the zero-flow pressure measurements of less than 5 Pa*
- *Averaging results of pressurization and depressurization tests*
- *The entire building is pressurized/depressurized with a margin of 10 Pa*
- $H^*\Delta T < 2000$ *m.K*

*The estimation of the error induced by the stack effect is discussed for these two sets of criteria. A parameter study is presented on the maximum error (encountered at the first pressure point) for a wide range of buildings heights (H), temperature difference (*$\Delta T$*) and leakage distributions. For configurations with* $H^*\Delta T < 2000$ *m.K, the new criteria allow:*

- *Increased possibilities of tests: a test is possible for every leakage distribution whereas the standard criteria (*$|\Delta P_{ground,0}| < 5Pa$ *) allow a test for less than 20% of simulated configurations when* $H^*\Delta T > 1000$ *m.K.*
- *A reduced theoretical maximum error: remains below 10% and for a given repartition is always smaller than for a test according to the standard criteria.*

*Additional detailed practical advices are given on how to perform airtightness tests on high-rise buildings.*

## INTRODUCTION

For an ideal building airtightness pressurization test, the pressure difference between inside and outside would be constant over time and uniform along the entire building envelope, so that each leakage is equally considered and that the test results do not depend on the test conditions.

Because of the stack effect and possibly also the pressure loss through stairwells, in high-rise buildings it is usually not possible to have a uniform pressure difference along the building's envelope (Lee et al., 2017) (Khoukhi and Al-Maqbali, 2011) (Lim et al., 2020) (Carrié et al., 2021) (Delmotte, 2021).

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The wind is also a major obstacle to this since it is usually unsteady and it creates over-pressure on the external windward façades, and under-pressure on the external leeward façades (Hurel and Leprince, 2021) (Carrié and Mélois, 2020) (Prignon et al., 2019). This is why it is recommended to test the air permeability of a building in calm wind conditions. Wind velocities are usually increasing with the height from the ground, so this issue may be more pronounced for high-rise buildings but is not specific to it, and is therefore not addressed in this paper.

One can note that there is no strict definition of what the minimum height of an "high-rise" building is. In the context of airtightness test, the height for which issues will arise depends on the temperature difference between inside and outside the building. The standard ISO 9972 (ISO, 2015) estimates that for H*ΔT above 250 m.K "it is unlikely that a satisfactory zero-flow pressure difference can be obtained".

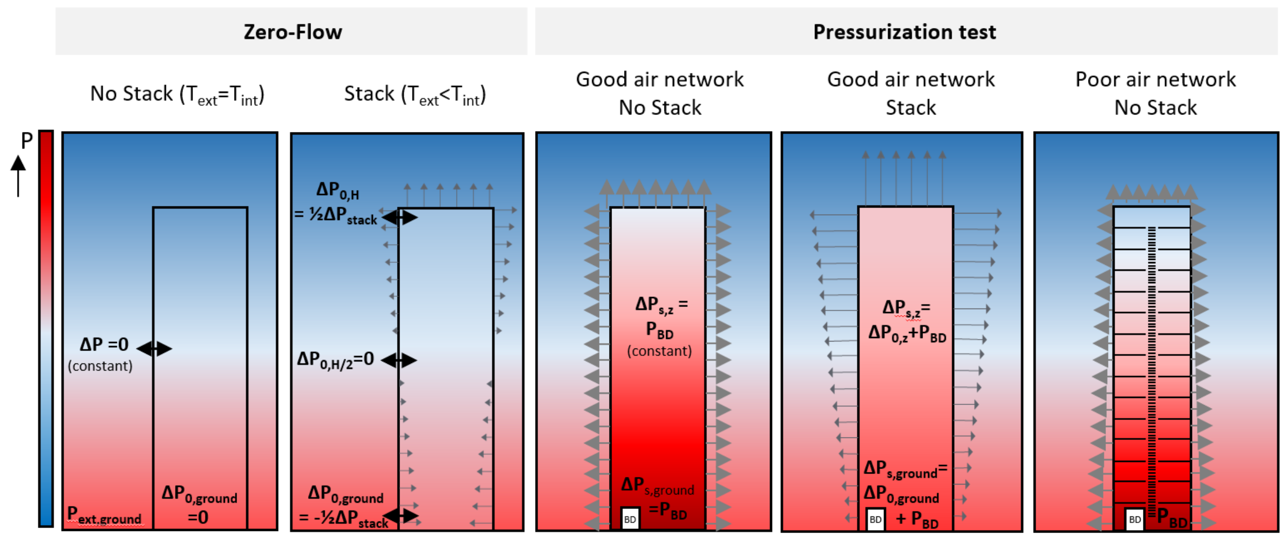


**Figure 1** Impact of stack effect and poor air network in the building on the pressure difference along the envelope.

## Stack effect

The stack effect describes the pressure difference due to a temperature (and therefore density) difference between inside and outside, that can induce air movements in buildings through openings or leakages. As shown in Figure 1, the pressure in the air decreases with height. If the air inside the building is at the same temperature than outside ($T_{ext}=T_{int}$), the pressure decreases equally inside and outside and therefore the pressure difference remains constant along the envelope. On the other hand, when the temperature is not the same, the pressure difference between inside and outside varies with the height. Taking the example of winter conditions ($T_{ext}<T_{int}$), the indoor air density is smaller than the outdoor air density, inducing that the heated air rises and exfiltrates by the top, creating over-pressure on the top floor and under-pressure on the ground floor where cold air infiltrates. Ideally the airtightness test would be performed with similar inside and outside temperatures conditions (mid-season, during the night to avoid sun radiation) but because of multiple constraints it is hardly possible to cancel this effect.

The variation of pressure difference between the top and the bottom of a building due to the stack effect ($\Delta P_{stack}$) is given as a function of the building's height (H) and the interior and exterior air densities (resp. $\varrho_{int}$ and $\varrho_{ext}$):

$$\Delta P_{stack} = -(\rho_{int} - \rho_{ext})gH \tag{1}$$

This equation is often approximated as follows (Taylor expansion):

$$\Delta P_{stack} \approx 0.044 \times H \times (T_{int} - T_{ext}) \tag{2}$$

### Pressure loss through stairwell and circulation

When a building is pressurized from the ground floor, the obstacles on the way to the upper floors prevent the pressure from homogenizing within the building. As a result, even without the stack effect, the pressure difference can decrease along the building's envelope (away from the pressure gauge) as shown in Figure 1. The leakier the building, the more significant the pressure loss since it varies with the square of the flowrate.

### Conflicts with standard ISO 9972

The first priority when testing the air permeability of a high-rise building is to comply with standard ISO 9972. Two requirements can however be difficult to achieve (Peper and Schnieders, 2019):

- On the zero-flow pressure (at the ground floor): $|\Delta P_{0,ground}| < 5$ Pa
- On the first pressure point (at the ground floor): $\Delta P_{s,ground} > 5^* |\Delta P_{0,ground}|$

## METHODOLOGY

In this paper an alternative is discussed to perform a test in high-rise buildings: replacing these 2 criteria when they cannot be achieved by the 4 following ones:

- A standard deviation on the zero-flow pressure measurements of less than 5 Pa
- Averaging results of pressurization and depressurization tests
- The entire building is pressurized/depressurized with a margin of 10 Pa which is ensured by a first pressure point $\Delta P_{s,ground}$ such that: $|\Delta P_{s,ground}| > \max(|\Delta P_{0,ground}| ; |\Delta P_{0,top}|) + 10$ Pa.
- $H^*\Delta T < 2000 m.K$

One should note that the 10 Pa margin is an arbitrary value that aims at compensating for the pressure measurement uncertainty and the pressure fluctuation both in time and in space around the building's envelope. In case of winds stronger than 3 on the Beaufort scale, this safety margin may not be sufficient, but as mentioned above, it is recommended to perform the tests in calm wind conditions.

This section details the calculation of the error induced by the stack effect for a simplified 2-leak configuration, previously used in the literature (Carrié and Leprince, 2016) and illustrated in Figure 2: one leak at the bottom representative of all the leaks on the lower part of the building and one leak at the top representative of all the leaks on the upper part of the building.

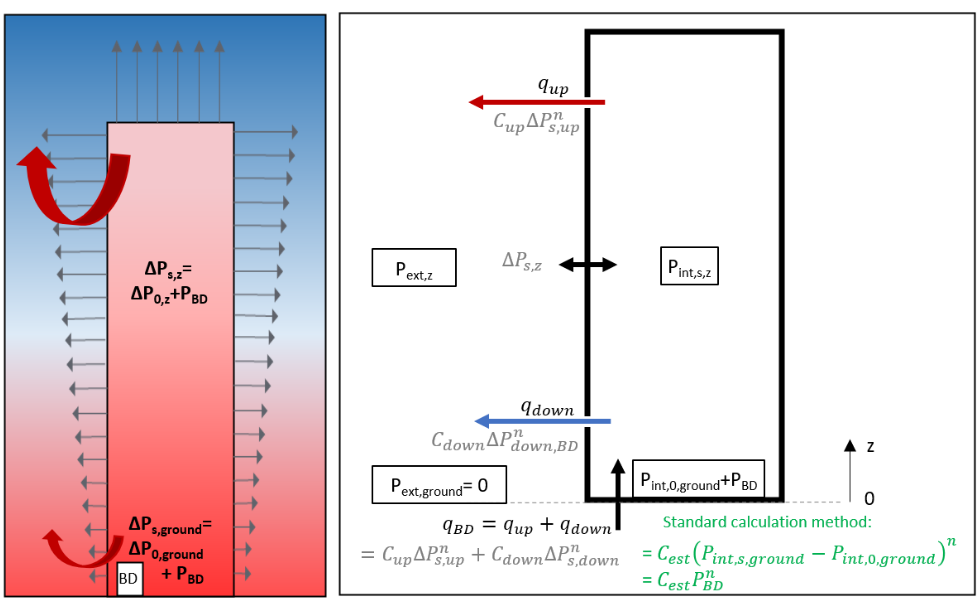


**Figure 2** Illustration of the simplified 2 leak configuration (pressurization test with stack effect)

## Calculation of the zero-flow pressure

Considering:

- The outdoor pressure at the gound level is equal to 0 ($P_{ext,ground}=0$), which is equivalent as considering that every other pressure is given as relative pressure compared to $P_{ext,ground}$.
- The indoor pressure at the ground floor ($P_{int,0,ground}$) is the natural zero-flow pressure before the test due to the stack effect
- j as the variable indexing the leaks (at a height $z_j$), j=up for the upper leak and j=down for the bottom leak :

The indoor pressure at leak "j" ($P_{int,0,j}$), and the external pressure at leak "j" ($P_{ext,j}$) are

$$P_{ext,j} = P_{ext,ground} - \rho_{ext} g z_j = -\rho_{ext} g z_j \tag{3}$$

$$P_{int,0,j} = P_{int,0,ground} - \rho_{int} g z_j \tag{4}$$

$$\begin{aligned}\Delta P_{0,j} = P_{int,0,j} - P_{ext,j} &= P_{int,0,ground} - \rho_{int} g z_j + \rho_{ext} g z_j \\ &= P_{int,0,ground} - (\rho_{int} - \rho_{ext}) g z_j\end{aligned} \tag{5}$$

The zero-flow pressure $P_{int,0,ground}$ is such that:

$$q_{up} + q_{down} = 0 \tag{6}$$

$$C_{up} \Delta P_{0,up}^{n_{up}} = -C_{down} \Delta P_{0,down}^{n_{down}} \tag{7}$$

$$\begin{aligned}&C_{up} \times sign(\Delta P_{0,up}) \times \left|\Delta P_{0,up}\right|^{n_{up}} \\ &\quad = -C_{down} \times sign(\Delta P_{0,down}) \times \left|\Delta P_{0,down}\right|^{n_{down}}\end{aligned} \tag{8}$$

$$C_{up}\left|\Delta P_{0,up}\right|^{n_{up}} = -C_{down}\left|\Delta P_{0,down}\right|^{n_{down}} \times sign\left(\frac{\Delta P_{0,up}}{\Delta P_{0,down}}\right) \tag{9}$$

With the assumption $n_{up}=n_{down}=n$:

$$\left(\frac{|\Delta P_{0,up}|}{|\Delta P_{0,down}|}\right)^n = -\frac{C_{down}}{\mathrm{C_{up}}} \times sign\left(\frac{\Delta P_{0,up}}{\Delta P_{0,down}}\right) \tag{10}$$

$$\frac{P_{int,0,ground} - \Delta\rho g z_{\mathrm{up}}}{P_{int,0,ground} - \Delta\rho g z_{\mathrm{down}}} = -\left(\frac{C_{down}}{\mathrm{C_{up}}}\right)^{\frac{1}{n}} \tag{11}$$

$$P_{int,0,ground} = \Delta\rho g\left(\frac{C_{up}^{\frac{1}{n}} z_{up} + C_{down}^{\frac{1}{n}} z_{down}}{C_{up}^{\frac{1}{n}} + C_{down}^{\frac{1}{n}}}\right) \tag{12}$$

For the specific case of uniform distribution ($C_{up}=C_{down}=C$):

$$P_{int,0,ground} = \Delta\rho g\left(\frac{z_{up} + z_{down}}{2}\right) \tag{13}$$

## Error on the flowrate estimation

During a pressurization test, with a blower door generating a pressure difference of $P_{BD}$ :

$$P_{ext,j} = -\rho_{ext} g z_j \tag{14}$$

$$P_{int,s,j} = P_{int,0,ground} - \rho_{int} g z_j + P_{BD} \tag{15}$$

$$\Delta P_{s,BD} = P_{BD} + P_{int,0,ground} - \Delta\rho g z_j \tag{16}$$

The global flowrate through the blower door is the addition of the flowrate at each leak j:

$$q_{BD} = \sum_j C_j \Delta P_{s,j}{}^n = C_{up} \Delta P_{s,up}{}^n + C_{down} \Delta P_{s,down}{}^n \tag{17}$$

The standard ISO9972 requires to use $P_{int,ground,0}$ as an averaged correction to estimate the flow coefficient:

$$C_{est} = \frac{q_{BD}}{\left(P_{int,s,ground} - P_{int,0,ground}\right)^n} = \frac{C_{up} \Delta P_{s,up}{}^n + C_{down} \Delta P_{s,down}{}^n}{P_{BD}^n} \tag{18}$$

The error at any pressure measurement reference $P_{ref}$ when estimating the flowrate with the standard method compared to the case without stack effect is therefore[1]:

$$E(q) = \frac{q_{est} - q_{nostack}}{q_{nostack}} = \frac{C_{est}.P_{ref}^n - C_t.P_{ref}^n}{C_t.P_{ref}^n} = \frac{C_{est} - C_t}{C_t}$$
$$= \frac{C_{up} \Delta P_{up,BD}{}^n + C_{down} \Delta P_{down,BD}{}^n - C_t P_{BD}^n}{C_t P_{BD}^n} \tag{19}$$
$$= \frac{C_{up}(P_{BD} + P_{int,ground,0} - \Delta\rho g z_{up})^n + C_{down}(P_{BD} + P_{int,ground,0} - \Delta\rho g z_{down})^n - (}{C_t P_{BD}^n}$$

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

If we consider that $z_{down} = 0$ and $z_{up} = H$, the error can be written as:

$$E(q) = \frac{\frac{C_{up}}{C_t}(P_{BD} + P_{int,0,ground} - \Delta\rho g H)^n + \frac{C_{down}}{C_t}(P_{BD} + P_{int,0,ground})^n}{P_{BD}^n} - 1 \tag{20}$$

Using the approximation given in equation 2:

$$E(q) = \frac{\frac{C_{up}}{C_t}(P_{BD} + P_{int,0,ground} - 0.044\Delta T H)^n + \left(1 - \frac{C_{up}}{C_t}\right)(P_{BD} + P_{int,0,ground})^n - P_{BD}^n}{P_{BD}^n} \tag{21}$$

When $C_{up} \neq C_{down}$ a Taylor development shows that the error decreases when the average is made between the test in pressurization and depressurization.

For the specific case where $C_{up}=C_{down}$, the error can be written as:

$$E(q) = \frac{1}{2}\left(\left(1 - \frac{\Delta\rho g H}{2P_{BD}}\right)^n + \left(1 + \frac{\Delta\rho g H}{2P_{BD}}\right)^n\right) - 1 \tag{22}$$

In this specific case one can note that the error is the same in overpressure and underpressure. It also shows that if n was equal to 1 the error would be null.

## RESULTS AND DISCUSSION

[1] This error concerns the flowrate estimation at a given pressure point only, the effect of the linear regression is not considered.

## Estimation of the induced error for a given pressure point

The error induced by the stack effect on the air flowrate estimation when using the standard calculation method is given in Table 1 for a pressurization test (p+), depressurization test (p-) and the average of both tests (av.). It is calculated according to equation (20) for six values of $\Delta T*H$ (ranging from 50 to 2000 K.m), three leakage distributions ($C_{up}/C_t$=0.25, 0.5 and 0.75) and four generated pressures (10, 25, 50 and 100 Pa).

**Table 1- Error Induced by the Stack Effect on the Air Flowrate with ISO 9972 for Various ΔTxH Values, Leakage Distributions and Generated Pressures (n=0.65)**

| ΔT*H (K.m) | $C_{up}/C_t$ | $\Delta P_{0,ground}$ (Pa) | $P_{BD}$: Pressure generated by the blower door or an equivalent system (Pa) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 10 | | | 25 | | | 50 | | | 100 | | |
| | | | p+ | p- | av. | p+ | p- | av. | p+ | p- | av. | p+ | p- | av. |
| 50 | 0,25 | -0,3 | 1% | -1% | 0% | 1% | -1% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | 0,5 | -1,1 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | 0,75 | -1,9 | -1% | 1% | 0% | -1% | 1% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| 100 | 0,25 | -0,7 | 2% | -3% | 0% | 1% | -1% | 0% | 1% | -1% | 0% | 0% | 0% | 0% |
| | 0,5 | -2,2 | -1% | -1% | -1% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | 0,75 | -3,7 | -3% | 2% | 0% | -1% | 1% | 0% | -1% | 1% | 0% | 0% | 0% | 0% |
| 250 | 0,25 | -1,7 | 5% | -12% | -4% | 2% | -3% | 0% | 1% | -1% | 0% | 1% | -1% | 0% |
| | 0,5 | -5,5 | -4% | -4% | -4% | -1% | -1% | -1% | 0% | 0% | 0% | 0% | 0% | 0% |
| | 0,75 | -9,3 | -12% | 5% | -4% | -3% | 2% | 0% | -1% | 1% | 0% | -1% | 1% | 0% |
| 500 | 0,25 | -3,4 | 7% | -32% | -13% | 4% | -8% | -2% | 2% | -3% | 0% | 1% | -1% | 0% |
| | 0,5 | -11,0 | -30% | -30% | -30% | -2% | -2% | -2% | -1% | -1% | -1% | 0% | 0% | 0% |
| | 0,75 | -18,6 | -32% | 7% | -13% | -8% | 4% | -2% | -3% | 2% | 0% | -1% | 1% | 0% |
| 1000 | 0,25 | -6,9 | 4% | -43% | -19% | 6% | -28% | -11% | 4% | -8% | -2% | 2% | -3% | 0% |
| | 0,5 | -22,0 | -50% | -50% | -50% | -12% | -12% | -12% | -2% | -2% | -2% | -1% | -1% | -1% |
| | 0,75 | -37,1 | -43% | 4% | -19% | -28% | 6% | -11% | -8% | 4% | -2% | -3% | 2% | 0% |
| 2000 | 0,25 | -13,7 | -39% | -52% | -46% | 6% | -39% | -17% | 6% | -28% | -11% | 4% | -8% | -2% |
| | 0,5 | -44,0 | -61% | -61% | -61% | -45% | -45% | -45% | -12% | -12% | -12% | -2% | -2% | -2% |
| | 0,75 | -74,3 | -52% | -39% | -46% | -39% | 6% | -17% | -28% | 6% | -11% | -8% | 4% | -2% |

The values in grey correspond to generated pressures for which the criteria on the generated pressure by the blower door is not respected ($|\Delta P_{s,ground}| > \max(|\Delta P_{0,ground}| ; |\Delta P_{0,top}|) + 10$ Pa), which invalidates the measurement point (with an allowance of +/- 3 Pa).

One can note that for uniform leakage distribution ($C_{up}/C_t$=0.5), underpressure and overpressure tests will give the same results (see equation 21). On the other hand, for non-uniform leakage distributions, the error can vary significantly between the underpressure and overpressure tests. The two non-uniform leakage distributions presented are however symmetrical, which explains why their averaged errors are equal.

## Estimation of the maximum error (1st pressure point)

When testing a building, the error induced by the stack effect on the flowrate estimation is maximum for the first pressure point, that is to say when $P_{BD}$ is in same order of magnitude as $P_{int,0,ground}$.

As a result, in order to calculate the maximum error induced by the new criteria listed in the methodology section, the error is calculated at the 1st pressure point for:

- $H*\Delta T$ ranging from 50 to 2000 m.K (with a step of 50 m.K)
- Leakage distributions $C_{up}/C_t$ ranging from 0 to 1 (with a step of 0.01)
- Both for a pressurization/depressurization test and for the averaged result
- Both for the standard ($|\Delta P_{0,ground}|<5$ Pa and $|\Delta P_{s,ground}| > 5*(|\Delta P_{0,ground}|)$ and the new criteria ($|\Delta P_{s,ground}| > \max(|\Delta P_{0,ground}| ; |\Delta P_{0,top}|) + 10$ Pa)

The results are presented in Figure 3.

One can note that for $H*\Delta T < 2000$ m.K with the new criteria:

- A test is possible for every leakage distribution whereas the standard criteria allow a test for less than 20% of configurations when $H*\Delta T > 1000$ m.K. These 20% correspond to configurations with unequal leakage distributions which are not commonly found. The new criteria seem therefore particularly useful for very high buildings and/or temperature differences.
- The averaged results (advised here) always induce a smaller maximum error than a single test according to the standard criteria and remain below 10%. By comparison, in (Carrié et al., 2021) the error due to the stack effect is discussed without averaging pressurization and depressurization results. They found out that setting a pressure induced by the blower door $P_{BD}$ at the first pressure station twice greater than the stack pressure $\Delta P_{stack}$ allow to contain the error below 5%. This implies higher $|P_{BD}|$ values than for averaged results, which can be hard to achieve for strong effect.
- The maximum averaged results are higher than the maximum averaged results obtained with the standard criteria for $H*\Delta T > 800$ m.K, which is explained by the fact that all leakage distributions are tested, while sthe standard allow only most favourable ones.

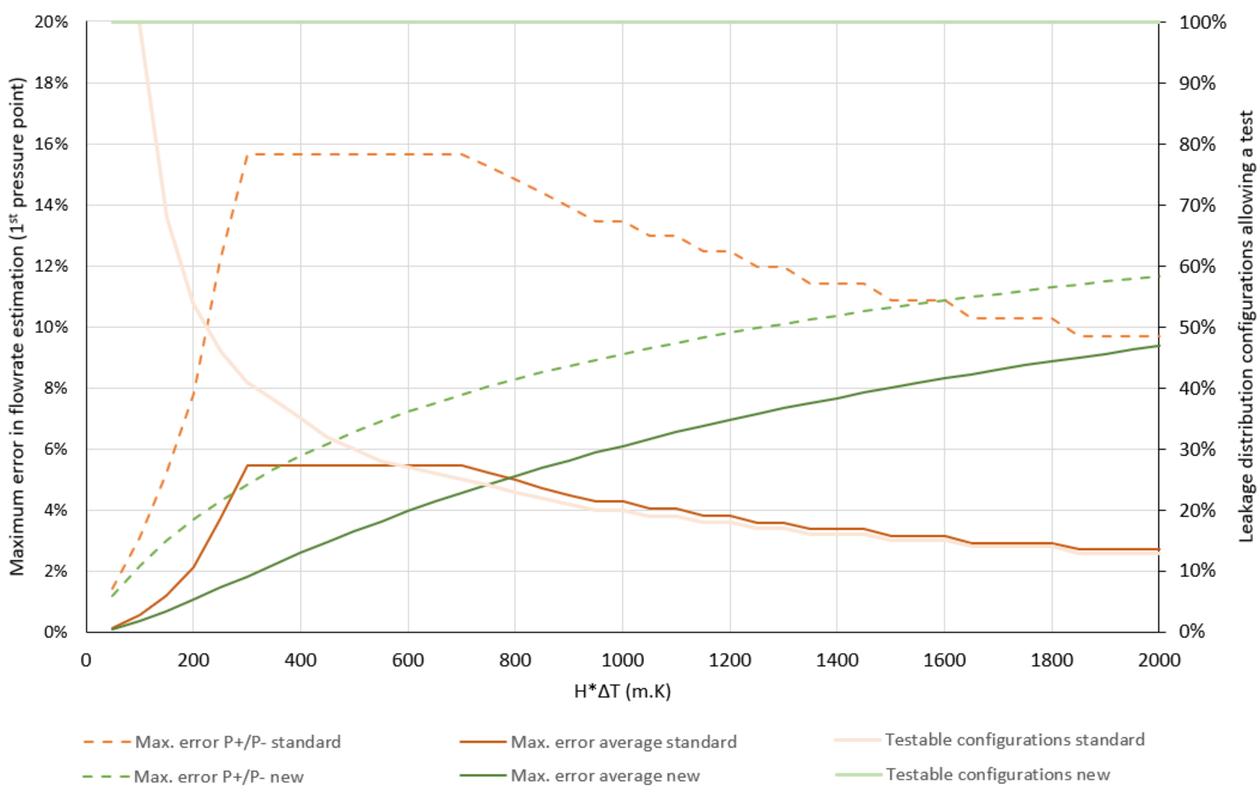


**Figure 3** Maximum error and percentage of testable configurations according to the product H*ΔT; both according to the standard and new criteria

## CONCLUSION

This paper has presented the issues regarding the pressurization tests for high-rise buildings and pointed out two criteria of ISO 9972 that can hardly be met, mainly due to the stack effect.

- A zero-flow pressure at the ground floor $|\Delta P_{0,ground}| < 5$ Pa
- A first pressure point at the ground floor $> 5*\Delta P_{0,ground}$

As an alternative when these criteria cannot be achieved, the authors have suggested to replace them by four new ones:

- A standard deviation on the zero-flow pressure measurements of less than 5 Pa

- Averaging results of pressurization and depressurization tests
- The entire building is pressurized/depressurized with a margin of 10 Pa
- $H^*\Delta T < 2000$m.K

A simplified 2-leak model was introduced to estimate the error induced by stack effect when testing buildings airtightness. With an application on both the standard ISO 9972 criteria and these new suggested criteria, the main conclusions are that the new criteria allow:

- To significantly increase the possibilities of tests: a test is possible for every leakage distribution whereas the standard criteria allow a test for less than 20% of simulated configurations when $H^*\Delta T > 1000$m.K.
- To reduce the theoretical maximum error: it remains below 10% and, for a given leakage repartition, the error is always smaller than for a test according to the standard criteria.

## ACKNOWLEDGMENTS

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## NOMENCLATURE

- C = air leakage coefficient ($m^3/s.Pa^n$)
- $\Delta P$ = pressure difference (Pa)
- $\Delta T$ = temperature difference ($T_i$-$T_{ext}$) (°C)
- E = error (-)
- g = gravitational acceleration ($m/s^2$)
- H = height of the building (m)
- n = flow exponent (-)
- P = pressure relative to external pressure (Pa)
- p+ = pressurization test (-)
- p- = depressurization test (-)
- q = volumetric airflow rate ($m^3/s$)
- ρ = Air density (-)
- T = Temperature (K)
- z = Height from the ground (m)

## Subscripts

- *av* = averaged (p+ and p- results)
- *BD* = induced by blower door measurement device
- *down* = lower leakage
- *est* = estimated value
- *ext* = exterior
- *ground* = ground floor level (z=0)
- *int* = interior of building
- *j* = index of leakage
- *nostack* = no stack effect ($T_i$=$T_{ext}$)
- *ref* = reference pressure
- *s* = At a given pressure measurement station (during a pressurization test)
- *stack* = stack effect
- *t* = total (up + down)
- *top* = top floor level
- *up* = upper leakage
- *0* = zero-flow pressure measurement (blowerdoor switched off)

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