Model error due to steady wind in building pressurization tests

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ABSTRACT

We have analysed the steady wind model error based on a simplified building model with one leak on the windward side and one on the leeward side of the building. Our model gives an analytical expression of this error that depends on the leakage distribution and pressure coefficients. Using a test pressure of 50 Pa in this model, standard measurement protocol constraints contain the steady wind model error within about 3% and 11% with wind speeds below 6 m s^{-1} and 10 m s^{-1}, respectively. At 10 Pa, the error is in the range of 35% and 60% at 6 m s^{-1} and 10 m s^{-1}, respectively. The results are very sensitive to the leakage distribution at the low pressure point. Averaging pressurization and depressurization test results may be more or less beneficial depending on the leakage distribution, pressure coefficients and test pressure.

KEYWORDS

Airtightness, pressurization test, infiltration, measurement

NOMENCLATURE

C	Air leakage coefficient (m^3 s^{-1} Pa^{-n})
C_p	Pressure coefficient (-)
n	Flow exponent (-)
p	Pressure relative to external pressure (Pa)
q	Volumetric airflow rate (m^3 s^{-1})
U	Wind speed at the building level (m s^{-1})
x	Dimensionless pressure (-)
y	Dimensionless pressure coefficient (-)
z	Dimensionless leakage distribution (-)
Greek symbols	
Δp	Pressure difference (Pa)
$\delta(x)$	Error of x (units of x)
ρ	Air density (kg m^{-3})

Subscripts and superscripts	
bd	Pertaining to blower door measurement device
down	Downstream (leeward façades)
est	Estimated value
H	High pressure point
i	Interior of building
j	Index of a variable
k	Integer
model	Pertaining to model errors
s	Pressure measurement station
up	Upstream (windward façades)
wind	Pertaining to wind errors
zp	Zero-flow pressure measurement

1 INTRODUCTION

The most common way to perform a building airtightness test is to measure the airflow rate leaking through the building envelope at a given pressure. The test protocol is detailed in several standards (e.g. ISO 9972). Sherman and Palmiter (1994) have analysed uncertainties in those tests due in particular to precision and bias errors of pressure and flow measurement devices, as well as the deviation of the flow exponent. Other authors have estimated the repeatability and reproducibility of those tests (see for example Delmotte and Laverge, 2011).

The error due to wind is known to be a major source of error in building pressurization tests. However, it has rarely been studied in depth. To our knowledge, only recently Walker and collaborators (2013) have investigated the impact of the wind on the uncertainties based on the analysis of large measurement datasets and give interesting practical guidelines to reduce the size of the uncertainties due to wind.

To further understand the impact of wind on the results of pressurization tests, this paper looks more specifically at the governing equations giving the airflow rate through the blower door as a function of wind speed. It proposes an analytical approach to characterize the error due to a steady wind in building pressurization tests with a one-zone model.

2 BUILDING IDEALIZATION AND DIMENSIONAL ANALYSIS

In our analysis, we assume that the building can be represented by a single zone separated from the outside by 2 types of walls: walls on the windward side of the building which are subject to the same upwind pressure; and walls on the leeward side which are subject to the same downwind pressure. We further assume that the airflow rate through the leaks of the envelope is given by a power-law with the same flow exponent. Therefore, the building can be represented by only 2 leaks, one upwind, and one downwind. In this simple case, the true leakage flow coefficient of the building is strictly equal to the sum of the leakage flow coefficients. The leakage airflow rate at p_i is:

$$q_{bd} = C_{up} \left(p_{up} - p_i\right)^n + C_{down} \left(p_{down} - p_i\right)^n \tag{1}$$

The zero-flow pressure may be derived analytically from the mass balance equation:

$$C_{up} \left(p_{up} - p_{zp,i}\right)^n + C_{down} \left(p_{down} - p_{zp,i}\right)^n = 0 \tag{2}$$

where:

$$p_{up} = C_{p,up} \frac{\rho U^2}{2} \qquad p_{down} = C_{p,down} \frac{\rho U^2}{2} \tag{3}$$

Therefore, assuming C_{up} and $C_{p,up}$ are not null:

$$p_{zp,i} = \frac{1 + \left(\frac{C_{down}}{C_{up}}\right)^{1/n} \frac{C_{p,down}}{C_{p,up}}}{1 + \left(\frac{C_{down}}{C_{up}}\right)^{1/n}} C_{p,up} \frac{\rho U^2}{2} \tag{4}$$

It is useful to use dimensionless quantities to reduce the number of parameters.
Assuming $U \neq 0$, let:

$$x_j = \frac{p_{up}}{p_j}; y = -\frac{C_{p,down}}{C_{p,up}};\ z = \frac{C_{down}}{C_{up}} \tag{5}$$

Therefore, if $y\, z^{1/n} = 1$ then $p_{zp,i} = 0$; else:

$$x_{zp,i} = \frac{p_{up}}{p_{zp,i}} = \frac{1 + z^{1/n}}{1 - y\, z^{1/n}} \tag{6}$$

If the pressurization test is based on the leakage airflow rate measurement at a single pressure station $p_i = p_s$, the estimate of the leakage flow coefficient is:

$$C_{est} = \frac{C_{up}\left(p_{up} - p_s\right)^n + C_{down}\left(p_{down} - p_s\right)^n}{\left(p_{zp,i} - p_s\right)^n} \tag{7}$$

and the error on the estimated leakage airflow rate at any reference pressure is:

$$\frac{\delta q}{q}=\frac{q_{est}-q_{nowind}}{q_{nowind}}=\frac{C_{est}-\left(C_{up}+C_{down}\right)}{\left(C_{up}+C_{down}\right)}$$
$$=\frac{C_{up}\left(p_{up}-p_s\right)^n+C_{down}\left(p_{down}-p_s\right)^n-\left(C_{up}+C_{down}\right)\left(p_{zp,i}-p_s\right)^n}{\left(C_{up}+C_{down}\right)\left(p_{zp,i}-p_s\right)^n} \quad (8)$$

In dimensionless quantities, this gives:

$$\left(\frac{\delta q}{q}\right)_{model,wind}=\frac{1}{1+z}\frac{\left(1-x_s\right)^n+z\left(1+y\,x_s\right)^n}{\left(1-\frac{1-y\,z^{1/n}}{1+z^{1/n}}x_s\right)^n}-1 \quad (9)$$

Standard test protocols implicitly require the test pressure to be much greater than the upstream pressure. Therefore, x_s is small compared to 1 and assuming $y\,z^{1/n}\neq 1$, developing equation (9) in Taylor series truncated at order 2 near x_s gives to the following equation:

$$\left(\frac{\delta q}{q}\right)_{model,wind}=\frac{1}{1+z}\left(n\left(y\,z+\frac{1+z}{x_{zp,i}}-1\right)x_s\right.$$
$$\left.+\left(\frac{n\left(n-1\right)}{2}\left(1+y\,z^2\right)+\left(y\,z-1\right)\frac{n^2}{x_{zp,i}}+\left(1+z\right)\frac{n\left(n+1\right)}{2\,x_{zp,i}^2}\right)x_s^2\right)+O\left(x_s^3\right) \quad (10)$$

Note that the first order term is null only when $z = 0$ or $z = 1$. This expansion remains true with $x_{zp,i}\rightarrow\infty$ which is equivalent to $p_{zp,i}\rightarrow 0$ for $U\neq 0$.

3 PRESSURIZATION TEST CONDITIONS

3.1 Standard constraints for airtightness pressurization tests

For a test to be valid according to ISO 9972, the following constraints must be met:

- Constraint (a): $|p_L|\geq 10$ Pa
- Constraint (b): $|p_L|\geq 5\,|p_{zp,i}|$
- Constraint (c): $|p_H|\geq 50$ Pa
- Constraint (d): $|p_{zp,i}|\leq 5$ Pa

Since we are looking at the error at one specific pressure station, constraint (c) is not relevant for us, but we have applied the other constraints. Note that these constraints apply to measured pressure differences, not to the induced pressure difference.

3.2 Range of input parameters

The sensitivity analysis performed further in this paper is restricted to the following ranges of the input parameters (note that constraints apply which may further restrict those ranges):

- The wind velocity U varies between 0 and 10 m s^{-1};
- The pressure measurement stations are initially set to 50 Pa and 10 Pa. Note however that constraint (b) may impose a pressure measurement station higher than those values.
- Table 1 gives 3 pairs of possible values of $C_{p,up}$ and $C_{p,down}$ inspired from Liddament (1996).

— The leakage distribution ratio ($z = \frac{C_{down}}{C_{up}}$) ranges from 0.1 to 160.

4 RESULTS

4.1 Impact of wind velocity and zero-flow pressure

Given that $p_{zp,i}$ is strictly decreasing with z from p_{up} down to p_{down}, limiting the zero-flow pressure to 5 Pa (Constraint (d)) for all possible input values implies $U \leq 3.45$ m s^{-1} for our range of C_p values. Our model confirms that Constraint (d) is unlikely to be met above 6 m s^{-1} as stated in ISO 9972. In fact, it is impossible for values of z greater than 1.5. However, this is not true for values of z smaller than approximately 1.5 (the zero-flow pressure may be much smaller than 5 Pa for wind velocities greater than 6 m s^{-1}). Figure 1 shows that the error (in absolute value) is below about 3% for wind speeds up to 6 m s^{-1} at building height and 11% up to 10 m s^{-1} for a test pressure at 50 Pa. The error is much greater at a test pressure of 10 Pa: it is in the region of 40% and 60% for wind speeds up to 6 m s^{-1} and 10 m s^{-1}, respectively (Figure 2).

4.2 Averaging pressurization and depressurization

Developing equation (9) in Taylor series (for $x_s << 1$) shows that averaging the results of two tests performed at opposite pressures p_s and $-p_s$ eliminates the first order term of the series and thereby yields a smaller error when the first order term is not null. This is confirmed in Figure 1-Figure 2 where the error of the average value is indeed smaller, but the benefit is relatively small.

4.3 Relaxing Constraint (d)

Constraint (d) ($|p_{zp,i}| \leq 5$ Pa) is directly related to the wind pressure (see equation (4)). Therefore, relaxing constraint (d) allows testing at higher wind velocities. We have not found a significant impact on the error range when relaxing constraint (d) (see Figure 1-Figure 2). It remains in the same range in either pressurization or depressurization mode (when averaging or not).

4.4 Restricted leakage distribution

With a restricted leakage distribution to $2 < z < 8$ which is meant to represent a deviation of a factor of 2 from an even distribution[1], we have found a significant effect on the error (Figure 3-Figure 4), in particular at 10 Pa, where the error drops below 3%.

5 CONCLUSIONS AND FUTURE WORK

One key result is that alone, the model error due to the wind on the estimated airflow rate is relatively small for the high pressure point, but it can become very significant with a low pressure point. While the error lies within 12% for wind speeds up to 10 m s^{-1} at 50 Pa, it can reach 60% at the low pressure point (10 Pa). However, these results are very sensitive to the leakage distribution for the low pressure point. Our analysis does not include other errors, in particular those due to precision and bias of the measurement devices used or the deviation of the flow exponent over the range of pressures. Because tests are usually performed at multiple pressure stations including relatively low pressures (close to 10 Pa), it would be useful to extend our model to include these additional source of errors.

[1] Evenly distributed leaks on the facades of a cube would give $z = 4$ (there are 3 facades on the leeward side plus the roof).

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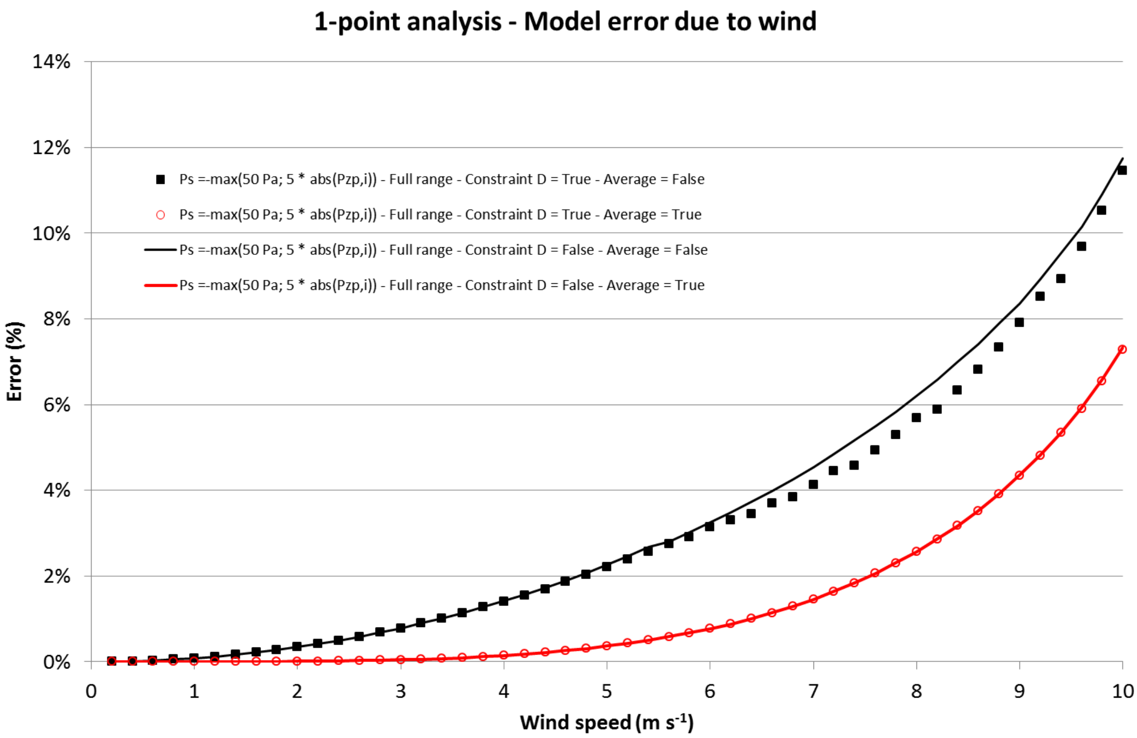

Figure 1 : Error due to wind as a function of wind speed and leakage distribution.

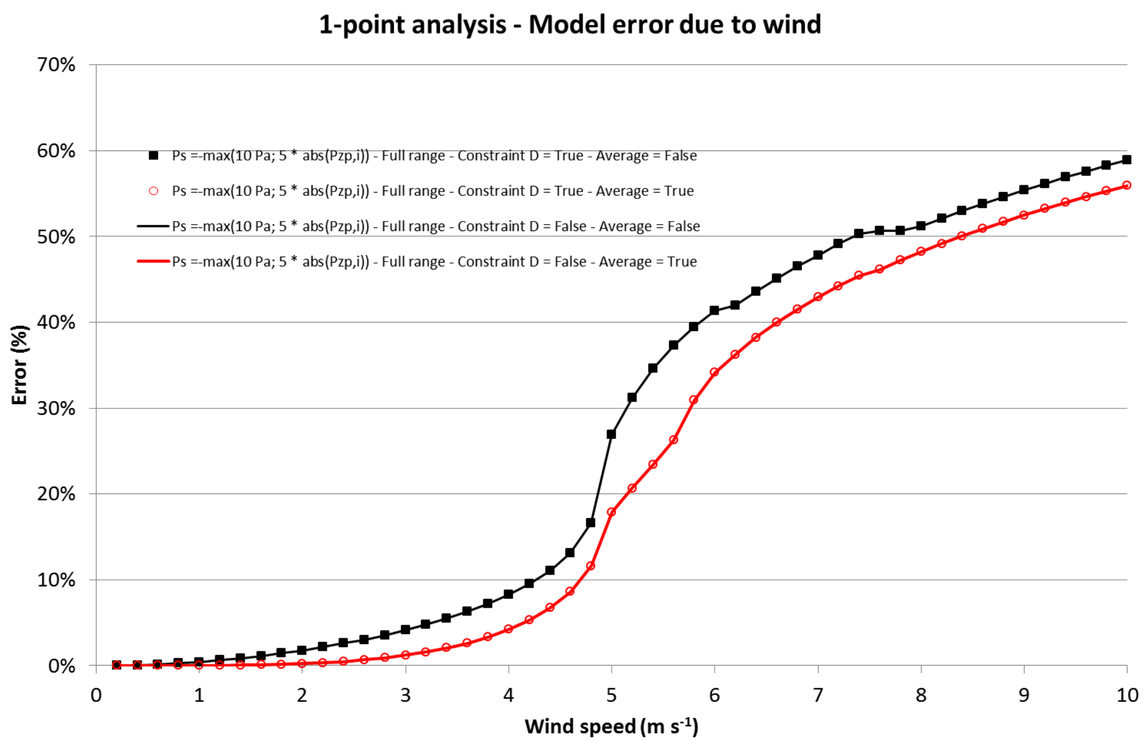

Figure 2 : Error due to wind as a function of wind speed and leakage distribution.

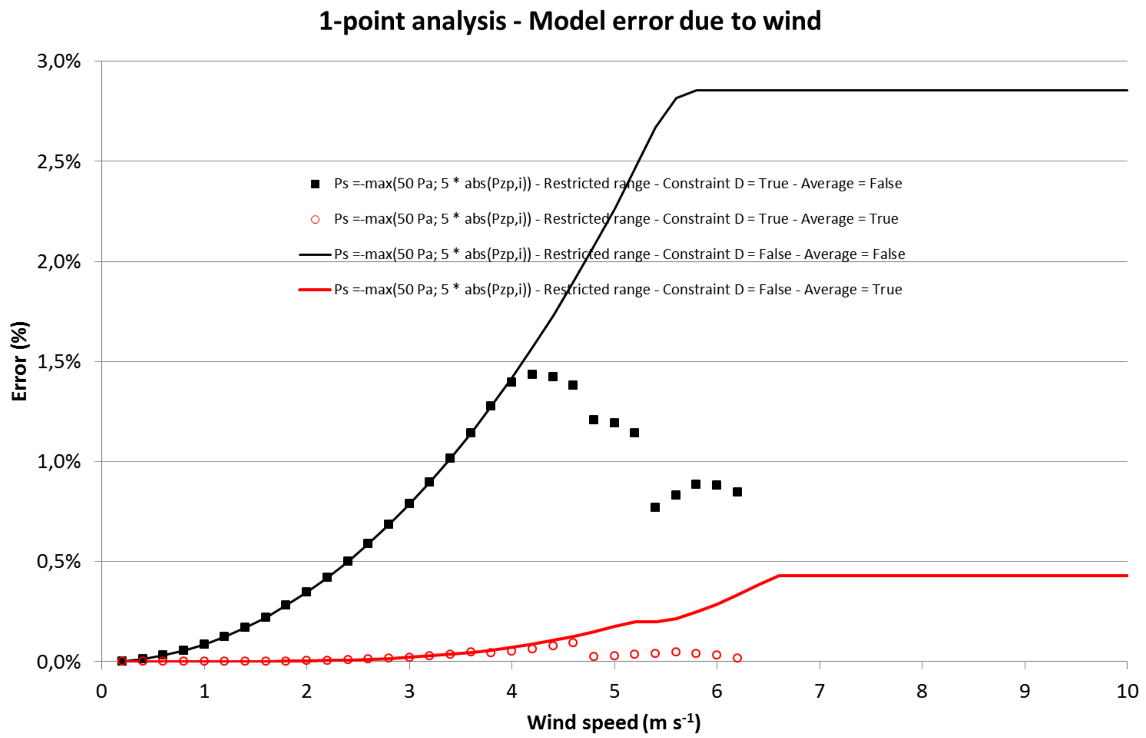

Figure 3 : Error due to wind as a function of wind speed and leakage distribution.

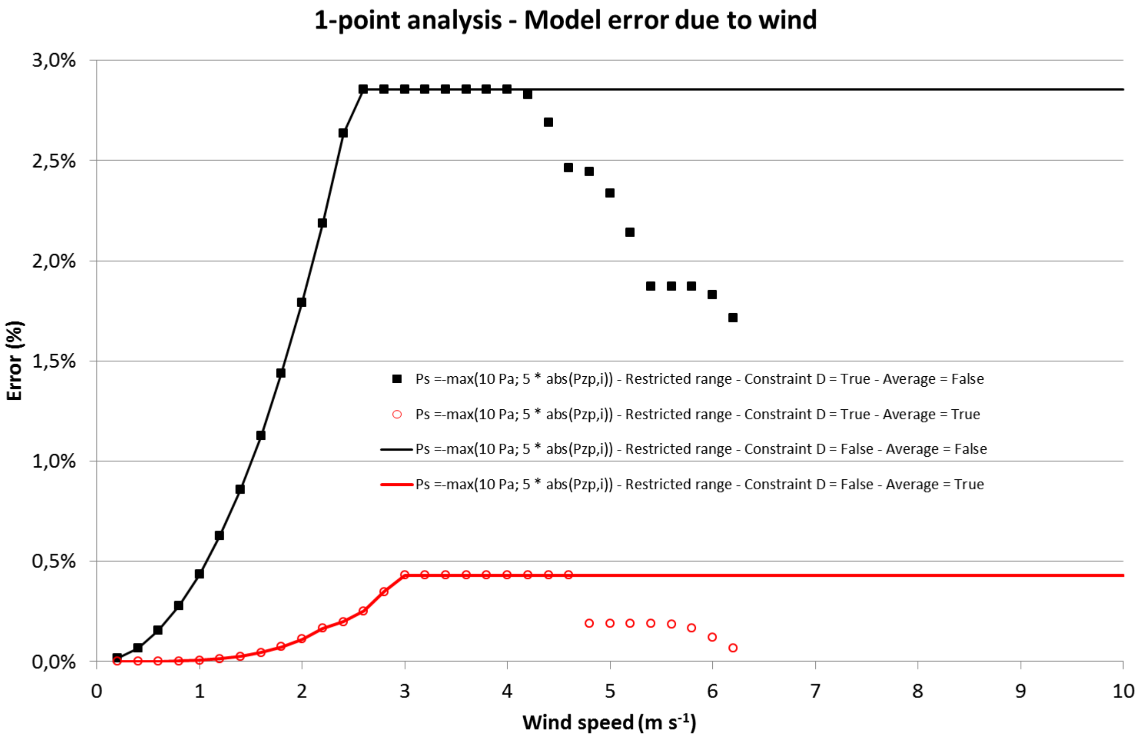

Figure 4 : Error due to wind of average result between pressurization and depressurization tests as a function of wind speed and leakage distribution.

Test case ID	$C_{p,up}$	$C_{p,down}$	$y = -\frac{C_{p,down}}{C_{p,up}}$
1	0.05	-0.30	6.0
2	0.25	-0.50	2.0
3	0.50	-0.70	1.4

Table 1: Values of wind pressure coefficients used in sensitivity analyses.