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Uncertainties in building pressurisation tests due to steady wind

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ABSTRACT

This paper deals with the quantification of the uncertainties due to wind in building pressurisation tests. The steady wind model error stems from the heterogeneous pressure distribution around the building. We have analysed this error based on a simplified one-zone 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 test and reference pressures at 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. This paper also includes an estimate of the combined uncertainty including other sources of errors which can be used to assess the relevance of measurement protocols. Under idealised conditions, using 50 Pa as reference pressure and a default flow exponent, it can be expected a combined expanded uncertainty of 6%–12% for wind speeds of 6–10 m s^{-1}, respectively.

1. Introduction

Several countries have developed or are developing plans to drastically reduce energy use in buildings to answer increasing concerns for climate change, outdoor air pollution, energy supply security, and fuel poverty. These plans often point out the potential benefits of building envelope improvements. The 2013 IEA Envelope Roadmap (IEA [5]) confirms the relevance of such improvements for better occupant comfort and quality of life as well as reduced health care costs and mortality. This roadmap stresses the significance of building air leakage. In particular, it recommends research and developments to tighten existing envelopes and to ease compliance tests.

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 9972:2006 [6], ASTM E779 [1]). Sherman and Palmiter [9] 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 [4]).

The error due to wind is known to be a major source of error in building pressurisation tests. However, it has rarely been studied in depth. To our knowledge, only recently Walker and collaborators [10] 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 pressurisation 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 characterise the error due to a steady wind with a one-zone model and to combine this error with bias and precision errors of the instruments.

2. Model error due to wind

2.1. Zero-flow pressure

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

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Nomenclature

C	Air leakage coefficient ($\mathrm{m^3\,s^{-1}\,Pa^{-n}}$)
C_p	Pressure coefficient (–)
n	Flow exponent (–)
p	Pressure relative to external pressure (Pa)
q	Volumetric airflow rate ($\mathrm{m^3\,s^{-1}}$)
U	Wind speed at the building level ($\mathrm{m\,s^{-1}}$)
$u(x)$	Standard uncertainty of quantity x (units of x)
$u_{exp}(x)$	Expanded uncertainty of quantity x (units of x)
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 ($\mathrm{kg\,m^{-3}}$)
$\sigma(x)$	Standard deviation (units of x)
$\sigma_{db}(n)$	Standard deviation of flow exponent from database (–)

Subscripts and superscripts

bd	Pertaining to blower door measurement device
bias	Pertaining to bias errors
c	Combined
down	Downstream (leeward façade)
est	Estimated value
H	High measurement pressure point
i	Interior of building
j	Index of a variable
k	Integer
L	Low measurement pressure point
model	Pertaining to model errors
nowind	No wind condition
precision	Pertaining to precision errors
ref	Reference pressure
s	Pressure measurement station
up	Upstream (windward façades)
wind	Pertaining to wind errors
zp	Zero-flow pressure measurement
+	Pertaining to pressurisation mode
−	Pertaining to depressurisation mode

Terms

Error (of a quantity) Difference between the estimate of a quantity and its true value

Uncertainty (of a quantity) Dispersion of values that could be reasonably attributed to the quantity of interest

isothermal conditions and that the airflow rate through the leaks of the envelope is given by a power-law with the same flow exponent:

$$q = C|\Delta p|^n sign(\Delta p) \tag{1}$$

(For brevity, we assume that $x^n = |x|^n sign(x)$ for negative values of x in the rest of this paper.) With these assumptions, all leaks on the windward side are subject to the same pressure difference and have the same flow exponent. The same applies to the leeward side. Therefore, the building can be represented by only 2 leaks, one upwind, and one downwind (Fig. 1). In this simple model, 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:

$$q_{bd} = C_{up}(p_{up} - p_i)^n + C_{down}(p_{down} - p_i)^n \tag{2}$$

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

$$C_{up}(p_{up} - p_{zp,i})^n + C_{down}(p_{down} - p_{zp,i})^n = 0 \tag{3}$$

where:

$$p_{up} = C_{p,up}\frac{\rho U^2}{2} \qquad p_{down} = C_{p,down}\frac{\rho U^2}{2} \tag{4}$$

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

$$p_{zp,i} = \frac{1 + \left(\frac{C_{down}}{C_{up}}\right)^{1/n}\frac{C_{p,down}}{C_{p,up}}}{1 + \left(\frac{C_{down}}{C_{up}}\right)^{1/n}} C_{p,up}\frac{\rho U^2}{2} \tag{5}$$

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

$$x_j = \frac{p_{up}}{p_j}; \qquad y = -\frac{C_{p,down}}{C_{p,up}}; \qquad z = \frac{C_{down}}{C_{up}} \tag{6}$$

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

$$x_{zp,i} = \frac{p_{up}}{p_{zp,i}} = \frac{1 + z^{1/n}}{1 - yz^{1/n}} \tag{7}$$

2.2. One-point pressurisation test

If the pressurisation 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 as per ISO 9972:2006 [6] is the airflow rate divided by the pressure corrected by the zero-flow pressure:

$$C_{est} = \frac{q_{est}}{(p_{zp,i} - p_s)^n} = \frac{C_{up}(p_{up} - p_s)^n + C_{down}(p_{down} - p_s)^n}{(p_{zp,i} - p_s)^n} \tag{8}$$

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

$$\frac{\delta q}{q} = \frac{q_{est} - q_{nowind}}{q_{nowind}} \tag{9}$$

where q_{est} and q_{nowind} are estimated at the same reference pressure. This leads to:

$$\begin{aligned}\frac{\delta q}{q} &= \frac{C_{up}(p_{up} - p_s)^n + C_{down}(p_{down} - p_s)^n - (C_{up} + C_{down})(p_{zp,i} - p_s)^n}{(C_{up} + C_{down})(p_{zp,i} - p_s)^n} \\ &= \frac{C_{est} - (C_{up} + C_{down})}{(C_{up} + C_{down})}\end{aligned} \tag{10}$$

In dimensionless quantities, this gives:

$$\left(\frac{\delta q}{q}\right)_{model,wind} = \frac{1}{1+z}\frac{(1 - x_s)^n + z(1 + yx_s)^n}{\left(1 - \frac{1 - yz^{1/n}}{1 + z^{1/n}}x_s\right)^n} - 1 \tag{11}$$

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 $yz^{1/n} \neq 1$, developing Eq. (11) in Taylor series truncated at order 2 near x_s gives to the following equation:

$$\begin{aligned}\left(\frac{\delta q}{q}\right)_{model,wind} &= \frac{1}{1+z}\left(n\left(yz + \frac{1+z}{x_{zp,i}} - 1\right)x_s\right. \\ &\quad + \left(\frac{n(n-1)}{2}(1 + yz^2) + (yz - 1)\frac{n^2}{x_{zp,i}} + (1 + z)\frac{n(n+1)}{2x_{zp,i}^2}\right)x_s^2 \\ &\quad + O(x_s^3)\end{aligned} \tag{12}$$