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Error Estimation of Blower Door Measurements by Computer Simulation

Achim Geissler, University of Kassel, Germany

Abstract

Computer simulation of building airtightness measurements shows the effect of changes in pressure distribution across the building envelope due to wind force and temperature difference on measurement accuracy. The wide range of leakage distributions, wind directions and velocities considered give information on the boundaries of these uncertainties. For wind velocities on site of $v_{\mathrm{site}} \approx$ 3 m/s the additional uncertainty in the flow rate at 50 Pa (Q50) found is comparable to the uncertainty due to standard pressure gauges or operator (about 3%). The additional uncertainty for on site wind velocities of no more than $v_{\mathrm{site}} \approx$ 4,7 m/s is in the range of 7%. This is comparable to overall uncertainty in calm conditions. Unfavorable building location, leakage distribution and unlucky choice of external pressure taps can lead to significantly larger uncertainties in the measured flow rates of 10% for on site wind velocities of 3 m/s up to 40% for on site wind velocities of approx. 4.7 m/s, though.

1 Introduction

An increasing number of building airtightness measurements with the blower door method are being done. Lately, the measurement results are used as exhibit in court in more and more cases. Possible questions that can arise here are e.g. which one, if any, of two results that do not agree and are often gained by two different measurement teams, is the 'correct' one? When can two results be considered as beeing basically the same, i.e. what is the measurement accuracy?

The accuracy of building airtightness measurements with the blower door method depends on many parameters. Some of these, e.g. wind velocity or temperature, cannot be influenced by the blower door user. It is also not always possible to reschedule a measurement when unfavorable conditions are met in the field.

Little information can be found regarding the measurement uncertainty due to changes in the pressure distribution across the building envelope as a result of fluctuating wind forces or large temperature differences (not to be confused with the temperature correction of flow rate measurement). This is due mostly to the fact that the influence of leakage distribution, wind direction and wind velocity on measurement accuracy cannot be measured with an acceptable expense.

In [1] the accuracy of flow rates from blower door measurements are given for different cases of data spacing and reference pressure differentials. Sparse information of a qualitative nature on the effect of wind is given. Persily [2] gives more detailed results of a series of measurements made on one single building. Uncertainties in Q50 found for measurements at wind velocities of up to 2.5 m/s are less than 2%. Measurements at velocities of up to 6 m/s show uncertainties which reach 15%.

Murphy et. al [3] present results from round-robin tests. The aim of the study was to get information on the overall accuracy of standard equipment, including the operator. The influence of wind force is avoided by measuring on calm days only.

The authors of [4] give the results of a study directed at the influence of wind forces on blower door measurement accuracy. Repeated measurements of one building under a limited range of meteorological boundary conditions and with slightly varied vertical leakage distributions (and total leakage rates) give an uncertainty in equivalent leakage area of less than ± 11% for wind velocities not exceeding 5 m/s and of up to ± 20% for wind velocities under 8 m/s.

More knowledge of the possible magnitude of uncertainties due to wind and/or temperature differences is, however, necessary. Computer simulations of blower door measurements make it possible to study a wide range of parameters and their influence on (calculated) measurement uncertainties without costly measurement programs. Results of such simulated measurements are given in this paper [5].

2 Simulation model

2.1 General

Simulation of building airtightness measurements with the blower door method requires the modelling of leakage distributions of buildings. The multizone infiltration calculation program 'COMVEN' [6] is used for the calculations described in this paper. COMVEN is modified to feature floating control of a fan, the 'blower door'. Control parameter is the pressure difference across the building envelope. It is possible to use an average value of two or more pressures.

Results of computer simulations of infiltration and air exchange heavily depend on the choice of wind pressure coefficients. "Correct" wind pressure coefficients are difficult to determine [7, 8, 9]. Furthermore, detailed actual leakage distributions are difficult if not impossible to measure accurately.

The question of interest, however, is not an absolute value for infiltration over a specific period of time but a comparison of results for different boundary conditions in itself. Therefor, it is not necessary for the chosen leakage distributions and wind pressure coefficients to correspond to any single realistic case. They are chosen in such a way as to cover a wide range of realistic values [10, 11].

2.2 Simulation parameters and value ranges

The building model used is based on a simple geometry. It has a height to width to length ratio h:w:l of approximately 1:1:2. The clear ceiling height is 2.5 m. The slope of the roof is 45^o. The collar beam height is 6.5 m above grade. The thermal and airtightness boundary is in the collar beam ceiling. The jamb walls are 1 m high and are the thermal and the airtightness boundary of the building envelope as well [12]. The building has a total air volume of approx. 425 m^3.

Vertical (cellar, ground and first floors) and horizontal (north, west, south and east facades) leakage distributions are varied. Leaks in the cellar and in the garret are modeled with serial leakage paths. The pressure differential between the two adjacent zones of the building are set to the median from over 40 measurements of parts of buildings in single family dwellings done by the author [12].

Where appropriate, the location of the fan in respect to the horizontal leakage distribution is varied.

As mentioned above, the results of infiltration calculations depend heavily on wind pressure coefficients used. To get an overview of uncertainty boundaries three cases of wind pressure distributions are considered.

- very small values, as found for very sheltered buildings (case I),
- very large values, as found for exposed buildings (case II) and
- very irregular values, e.g. found for buildings exposed to one side only (case III).

Wind pressure coefficient values are taken from various authors. The complete list of values used can be found in [5]. Wind velocities given are meteorological velocities, i.e. refer to velocities 10 m above grade in flat terrain. Table 1 gives an overview of the parameters and their ranges.

Table 1: Overview of parameters and ranges.

Parameter	No.	Case 1	Case 2	Case 3
vertical leakage distribution	4	30 % 60 % 10 %	60 % 30 % 10 %	60 % 10 % 30 %
horizontal leckage distribution	3	25 % 25 % 25 % 25 %	50 % 0 % 50 % 0 %	100 % 0 % 0 % 0 %
leackage characteristics	2	0,5	1,0	–
orientation of the fan	3	'same'	'90°'	'opposite'
temperature difference $\Delta\vartheta$	5	-10 - 30 K, 10 K-steps		
wind direction	9	0-360°, 45°-steps		
wind velocity $v_{\rm met}$	5	0, 3, 6, 9, and 12 m/s		

2.3 Measurement strategies

A variety of measurement strategies are given in standards for building airtightness measurements, e.g. [13, 14, 15]. All standards require the measurement of a series of pressure differences (usually 10 to 60 Pa). Some require both pressurization and depressurization measurements. In addition, the measurement of leakage rate for one pressure differential only (50 Pa) will be discussed. In [13] the measurement of an offset is required only befor, in [14] and [15] befor and after the actual measurement. Two offset models are considered. With $\phi_{\rm Offset}$ being the current (mean) wind direction 'Offset' is

$$\text{Offset} = \text{Offset}(\phi_{\rm Offset}) \qquad (1)$$

and '$\overline{\text{Offset}}$' is

$$\overline{\text{Offset}} = \frac{1}{3}\,(\text{Offset}(\phi_{\rm Offset} - 45^o) + \text{Offset}(\phi_{\rm Offset}) + \text{Offset}(\phi_{\rm Offset} + 45^o)). \qquad (2)$$

The number and location of external pressure taps required differs as well. Alternatives are one tap on the facade [16] and approx. 10 m away from the building [13] or the average of four taps on the building facades [15] and dampened in addition [14]. The advantage of more than one external pressure tap is the averaging of the external pressure (e.g. [4]). In some situations only one tap is possible, it is always slightly less burdensome.

The described variations in measurement strategy have an influence on how measurement accuracy depends on wind velocity and wind direction and their fluctuations during the measurement. The wide selection of parameters given above is treated for a simple 'one-point-measurement' only. This 'one-point-measurement' is simulated at a mean pressure difference across the building envelope of 50 Pa. The wind speed is kept constant, the wind direction is changed through $\pm 90°$ in 45°-steps. The offset is taken once, at the begining of the 'measurement' according to eqn. 2.

Computer simulation of measurements which consist of a sequence of pressure differentials is done for uniform horizontal leakage distribution only. The wind direction and velocity are constant for each pressure step but may change inbetween. Four measurement strategies are considered ('S1' through 'S4', see figure 1). The offset is taken according to eqn. 1.

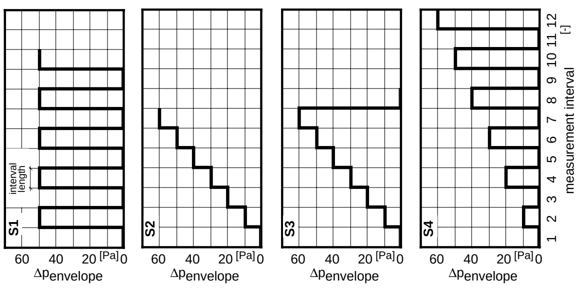

Figure 1: Pressure differential sequences for the measurement strategies S1 through S4.

3 Results

All results presented in this paper refer to calculated measurement uncertainties for depressurization tests of small low rise buildings. If not stated otherwise, external pressure was taken as the mean value of four taps, one on each facade. Comparison of simulation results, the "uncertainty" given, is based on the relative change of flow rate

$$\delta_{\dot{m}} = \frac{\dot{m} - \dot{m}_{\mathrm{ref}}}{\dot{m}_{\mathrm{ref}}} \cdot 100\%$$

where the reference value is the flow rate in calm conditions at temperature equilibrium

$$\dot{m}_{\mathrm{ref}} = \dot{m}(\Delta\vartheta = 0, v = 0).$$

In discussing results, 'lowest' refers to the largest negativ number.

Temperature difference
The effects of temperature difference can be neglected. In combination with wind a temperature difference of 20 K lead to an increase in calculated measurement uncertainty in the range of 6 to 18 % of the uncertainty. The larger increase was found for cases with small uncertainty.

Constant wind direction
If the wind direction is the same during the whole measurement, including the offset measurement, the calculated measurement uncertainty does not depend on the number and positioning of external pressure taps. Wind velocity has a negligible influence.

Offset
Figure 2 gives calculated measurement uncertainty vs. offset. It can be seen that a small offset is not a guarantee for a small uncertainty due to wind influence. Uniformly large wind pressure coefficients (case II, not shown) give similar results. Calculations with small wind pressure coefficients (case I, not given) show an offset larger than 3 Pa for wind velocities of 6 m/s, large wind pressure coefficients lead to offsets larger than 3 Pa for wind velocities of 3 m/s.

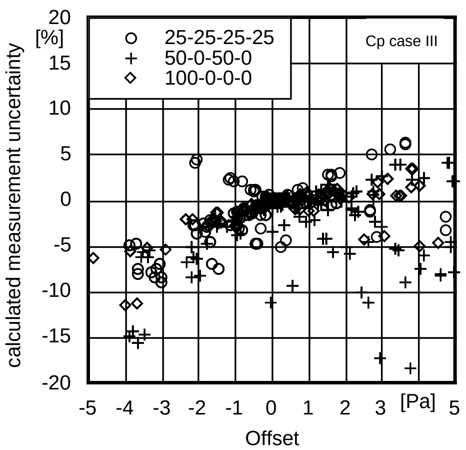

Figure 2: Calculated measurement uncertainty vs. offset (cut to ± 5 Pa). Results for all three horizontal leakage distributions considered. Wind pressure coefficients according to case III.

Vertical leakage distribution
The results obtained show that calculated measurement uncertainties and by inference actual measurement uncertainties do not depend on the vertical leakage distribution for all practical purposes. The vertical leakage distributions considered lead to a standard deviation of 4.5 – 10 % of the calculated measurement uncertainty at 6 m/s.

Horizontal leakage distribution
Results of the calculations show that variations

of the horizontal leakage distribution lead to significant changes in calculated measurement uncertainty. The standard deviation of the calculated measurement uncertainties at 6 m/s is found to be between approx. 40 and 90%. The span between lowest and highest calculated measurement uncertainties found increases with the concentration of leaks on fewer facades. However, the difference between the calculated uncertainties for the horizontal distributions 50-0-50-0 and 100-0-0-0 is negligible. Orientation of the fan relativ to facades with/without leaks has no influence for four external pressure taps, a significant influence for one external pressure tap.

Leakage characteristics
The calculated measurement uncertainties increase with increasing leakage pressure exponent. Calculations for pressurization measurements show that pressurization and depressurization uncertainties cancel each other for a leakage pressure exponent of unity.

Wind pressure coefficients
Naturally, the calculated measurement uncertainties increase with increasing wind pressure coefficients (increasing building exposure to wind forces). But, the calculations with uniform horizontal leakage distribution show the largest uncertainties for wind pressure coefficients according to case III.

Figure 3 gives an example for the calculated uncertainty vs. wind velocity for the horizontal leakage distribution 100-0-0-0.

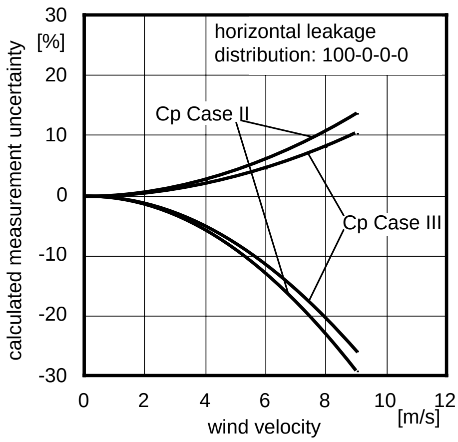

Figure 3: Calculated uncertainty vs. wind velocity.

One external pressure tap
For uniform horizontal leakage distribution and wind pressure coefficients according to case II the reduction of external pressure taps on the facades from four to one leads to an increase in calculated measurement uncertainty of 400 to 500%.

External pressure tap according to [13]
The pressure tap is modelled by a tap on one facade with a small wind pressure coefficient which is constant for all wind directions. The calculations lead to following results:

- In the range of Cp=0.05 to Cp=0.2 the wind pressure coefficient does not change the calculated measurement uncertainty.
- The tap according to [13] as modelled leads to significantly lower measurement uncertainties as compared to the single tap on the facade described above.
- For the horizontal leakage distributions 25-25-25-25 and 100-0-0-0 the span of calculated measurement uncertainties is larger, for the horizontal leakage distribution 50-0-50-0 slightly smaller than that for four external pressure taps ([4] gives measurement results which show an uncertainty of ± 6,5% for the single tap and ± 3% for four taps at site wind velocities of approx. 2 m/s).
- Offset values are slightly larger than for calculated measurements with one pressure tap on the facade.

Measurement strategies
Calculation of uncertainties for measurements according to the strategies 'S1' to 'S4' are based on actual wind data. Figure 4 shows the measured wind velocity and wind direction data used. The data is from two 10 minute scans at a scan rate of 1 Hz. The total duration of the simulated measure-

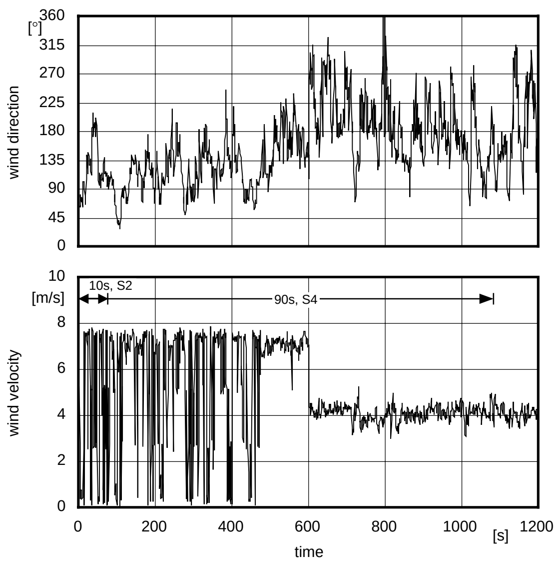

Figure 4: Wind direction and wind velocity over two ten-minute intevals (scan rate 1 Hz).

ments range from 90 sec. to 1080 sec., depending on the number of pressure steps and the length of averaging intervall chosen (10, 30, 60 and 90 s).

The vertical leakage distribution chosen is 30-60-10 (top to bottom). The horizontal leakage distribution is uniform. Wind pressure coefficients are according to case II. The pressure exponent for all leaks is 0.5. Calculated measurement uncertainties are compared for flow rates at 4 and 50 Pa. Results obtained are as follows.

- If the measurement result sought is the flow rate at 50 Pa pressure difference only, the strategie 'S1' shows the best results.
- Using an average from external pressure taps on all four facades leads to the smallest uncertainties. The largest uncertainty found is +4 (-1) % as opposed to +7 (-3) % for one external pressure tap according to [13] and +21 (-10) % for one simple external pressure tap.
- Agreement with calculation results from the 'one-point-measurement' used for the parameter variations described above is good.
- The span of calculated measurement uncertainties found for the measurement strategies considered is approx. the same as the span found for different intervall lengths within each of the strategies.
- If only one external pressure tap is used, it should be designed and positioned in such a way as to give a measurement signal which is independant of wind forces.
- A significant change in the wind characteristic during the measurement leads to a larger mean measurement uncertainty when measuring with strategies 'S2' or 'S3'.
- Extrapolation to 4 Pa leads to a significant increase in measurement uncertainty due to wind.
- A series of flow rate measurements at 50 Pa pressure difference interspaced with offset measurements shows the best results for 50 Pa flow rates for the wind conditions and measurement intervalls studied.
- Both the strategies according to [15] and [13] show an increase in calculated measurement uncertainties if the wind characteristics change significantly during the measurement
- The calculated measurement uncertainty due to wind forces can be approximated with a simple power function of the wind velocity.
- The total leakage rate has a negligible impact on calculated measurement uncertainty.

Comparison of calculated measurement uncertainties with uncertainties due to measurement apparatus and operator leads to following statements: The results given show an overall 95% confidence intervall of the flow rate at 50 Pa of ± 7.5%. The operator contributes approx. ± 2% hereof.

For wind velocities on site of $v_{\text{site}} \approx 3$ m/s the additional uncertainty in the measured flow rate is of the same order of magnitude as the uncertainty due to standard pressure gauges and the operator. The additional uncertainty for on site velocities of no more than $v_{\text{site}} \approx 4{,}7$ m/s can be compared to the overall uncertainty of typical measurement systems on calm days (wind velocity below 2.2 m/s [3]). Unfavorable conditions regarding horizontal leakage distribution and building exposition can lead to significantly larger uncertainties in the measured flow rates.

4 Discussion

Wind direction and wind velocity will usually fluctuate during a blower door measurement. Therefor, number and positioning of external pressure taps as well as measurement strategy will have an impact on measurement accuracy. Following statements can be made on the basis of computer simulations of blower door measurements. The statements are valid for the model used in this paper.

- Information gained from the offset measured in respect to wind induced uncertainty is limited.
- Measurement uncertainties due to wind forces increase with the concentration of leaks on less facades of the building.
- In general, four external pressure taps lead to the smallest measurement uncertainties.
- If only one external pressure tap (can be) is used, it should be designed and positioned in such a way as to measure total pressure.
- Averaging pressurization and depressurization measurements (under the same conditions) leads to a cancellation of uncertainties for leakage pressure exponents equal unity only. However, the average of pressure exponents for buildings is 0.65 – 0.67.

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