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Reducing Wind Sensitivity for Blower Door Testing

Benedikt Kölsch

Iain S. Walker, PhD
Fellow ASHRAE

ABSTRACT

The fan pressurization method is a common practice in many countries for measuring the air leakage of houses. The test results are sensitive to uncertainties in the measured pressures and airflows. In particular, changing wind conditions during a test result in some pressure stations having more or less uncertainty than others.

Usually, it is necessary to fit the measured data to the power-law equation. Using the ordinary least square (OLS) fitting method, the pressure exponent and flow coefficient can be determined, and the reported data at high pressures can be extrapolated to small pressures where natural infiltration occurs. However, this fitting method neglects the existing of the uncertainty of these measurements, which may lead to errors in the prediction of flows at low pressures and therefore to unreliable input data for energy simulations. The weighted line of organic correlation (WLOC) takes the uncertainty at each pressure station into account and minimizes the fitting residuals for both pressure and flow.

This paper shows the results of a statistical analysis of an extensive data set of over 7.400 fan pressurization test of six houses in 109 different leakage configurations. It was found that in over 90 % of the analyzed cases, WLOC enables a more reliable prediction of pressure exponent and flow coefficient at low pressure compared to OLS and appears to be a better fitting technique.

INTRODUCTION

Air leakage in building envelopes can be responsible for a significant part of the total heat load and affects significantly thermal comfort in residential as well as commercial buildings. Typically, the fan pressurization method, also known as blower-door test, is applied in buildings to quantify the airtightness of buildings and serves to assess the air infiltration rate. A fan applies a pressure difference across the building envelope and the respective airflow rate through the fan is recorded. This measurement method is described in various standards like ASTM E779 (ASTM 2019), DIN EN ISO 9972 (DIN 2018) or CAN/CGSB 149.10 (CAN/CGSB 2019). Using the blower-door test, the measured pressure range dramatically exceeds the pressure to which leaks in buildings are typically exposed. Measuring higher pressures has the advantage that impacts due to ambient conditions (e.g., wind), as well as the relative error of the measurement devices, are usually lower. However, a subsequent extrapolation to lower pressures where natural infiltration occurs is responsible for a significant error in the prediction of these values. Hence, the most precise measurements at high pressures are the least accurate ones (Walker et al. 2013; Carrié and Leprince 2016). The knowledge of the infiltration at low pressures may not be necessary for the comparison of buildings among each other or to meet specific energy code regulations, but it is a crucial quantity for energy calculations and assessments of indoor air quality. However, current standard test procedures do not require the measurement of uncertainties of the measured values, even though the uncertainties may significantly influence the prediction of the airflow rates at low pressures.

Benedikt Kölsch is a PhD candidate at German Aerospace Center (DLR), Institute of Solar Research, Jülich, Germany. **Iain S. Walker** is a scientist at Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA.

In this paper, the ability of the conventionally used Ordinary Least Square (OLS) regression method is compared with the Weighted Lines of Organic Correlation (WLOC) for their ability to predict envelope leakage parameters such as leakage area and air flow at the low pressures typical of low-rise buildings. WLOC was already introduced by Delmotte (Delmotte 2017) and takes the uncertainty of the measurement into account. In this study, a dataset of over 7.400 blower-door measurements was used to quantify and compare the repeatability of both extrapolation methods.

METHODOLOGY

Measurement Data Set

The data set of fan pressurization measurements used in this paper was recorded at the Alberta Home Heating Research Facility (AHHRF), which is located south of Edmonton, Alberta in Canada (Walker, 1993). Six different unoccupied test houses have been investigated at this research facility, each constructed differently. The initial objective was to test different heating and ventilation strategies for various construction types.

At each of these six test houses, repeated fan pressurization measurements have been conducted with different leak configurations. Repeated measurements with the same leak configuration enable the variability of the measurement results to be calculated. In order to prevent additional uncertainty due to the handling of an operator, all tests were automated, which increases the repeatability. Additionally, automated tests enable the record of a large set of data. Here, 7.500 sets of measurements have been recorded, where each of the tests contains typically around 20 measurements of the pressure difference across the building envelope which lie in a range from approximately less than 1 to around 100 Pa.

For determination of the pressure differences, the outside pressures have been taken from a pressure averaging manifold which was connected with pressure taps on each of the four exterior walls of the buildings. This averaging of the wind pressure effect removes biases due to the strength of the wind and its blowing direction. Therefore, this pressure signal is less sensitive to wind pressure fluctuations. In reality, individual leaks are exposed to large wind fluctuations. Hence, the best solution would be a pressure difference measurement at each individual leak which is certainty unpractical or even impossible in field measurements. Hence, this four-point measurement is a sufficient approximation. In most field measurements, outside pressure data is recorded from only one point. In addition to the measurement of pressure difference across the building envelope, the standard deviation at each pressure station has been recorded as well, which is a fundamental value for this analysis.

In contrast to standards like ASTM E779 (ASTM 2019) or DIN EN ISO 9972 (DIN 2018), where offset pressures have to be recorded at the beginning and end of each measurement series, here, offset pressures have been recorded for each individual data point. A damper closed the fan opening for each offset pressure measurement because this opening can affect the pressure distribution throughout the building. Hence the envelope pressure differences in this analysis have been corrected for each data point with the offset pressure.

The associated flow rates through the building envelope were measured using a laminar flowmeter which was connected to the outside with a flexible duct. The flow rate was corrected for differences between inside and outside temperature according to the ASTM E779 standard (ASTM 2019). Pressure and flow measurements were taken over a period of 15 seconds, with a sampling rate of about ten samples per second. Additionally, the standard deviation of the pressure across the flowmeter ($\sigma_{\Delta P\ flowmeter}$) was recorded. Due to the linear behavior of the flowmeter, the standard deviation of the airflow rate (σ_Q) across the building envelope can be calculated using the following equation:

$$\sigma_Q = \sigma_{\Delta P\ flowmeter} \cdot \frac{Q}{\Delta P_{flowmeter}} \quad (1)$$

Additional recorded values are wind speed, wind direction and ambient temperatures, which were gathered from a weather station at the test site. All data with low and high wind pressures are included in this study.

Within this data set, 109 different configurations have been tested, e.g., pressurization and depressurization, open and closed flues, windows or passive vents. Prior to the actual analysis, the data set was filtered to remove erroneous data files, where no standard deviation or offset pressure was recorded. Finally, 7.402 from the original 7.500 sets of measurements are included in this study.

Regression Methods

Although there are historically several approaches to predict the relationship between the airflow rate (Q) and the pressure difference (ΔP) across the building envelope, the power-law form is nowadays the prevailing formulation in all measurement standards (Sherman and Chan 2006):

$$\mathrm{Q} = \mathrm{C} \cdot \Delta P^{n} \tag{2}$$

Where, C (in $m^3/(h\ Pa^n)$) is the flow coefficient and n represents the pressure exponent, which is limited to values between 0.5 and 1.0. Both n and C typically depend on the geometry and configuration of the cracks through which the infiltration occurs.

In order to determine flow coefficient and pressure exponent, a transformation of the power-law to a linear relationship is necessary by expressing both sides of Eq. (2) for each measured value as logarithms:

$$\ln(\mathrm{Q}) = \ln(\mathrm{C}) + \mathrm{n} \cdot \ln(\Delta\mathrm{P}) \tag{3}$$

A regression is applied to this linear form of the power law, where n is the slope and ln(C) is the intercept of this regression. In the following paragraphs, both regression techniques which are compared in this study are introduced.

Ordinary Least Square Method. The conventional approach for determining the pressure exponent n and pressure coefficient C is the Ordinary Least Square Method (OLS). Operators mainly use the OLS method in practice, and the calculation procedure of pressure exponent n and flow coefficient C is described, inter alia, in ASTM E779 (ASTM 2019). This method minimizes the sum of the squares in the differences of the measured values of a variable and predicts the values as a linear function. Pressure exponent and flow coefficient can directly be calculated using the following formulas:

$$n = \frac{\sum_{i=1}^{N}\left(x_i - \sum_{i=1}^{N}\frac{x_i}{N}\right)\left(y_i - \sum_{i=1}^{N}\frac{y_i}{N}\right)}{\sum_{i=1}^{N}\left(x_i - \sum_{i=1}^{N}\frac{x_i}{N}\right)^2} \tag{4}$$

$$C = \exp\left(\sum_{i=1}^{N}\frac{y_i}{N} - n \cdot \sum_{i=1}^{N}\frac{x_i}{N}\right) \tag{5}$$

The OLS regression method assumes that values of $y_i = \ln(Q_i)$ with i = 1…N are equally uncertain and in addition, the uncertainties of $x_i = \ln(\Delta P_i)$ are negligible (Delmotte 2013). However, these assumptions are generally not valid for measurements in real buildings and in particular in the presence of wind. Delmotte shows in his research that imperfect knowledge of the uncertainties leads to a shifting and rotation of the linear form of the power-law (Eq. (3)) and therefore increases the error of the prediction of pressure exponent and flow coefficient (Delmotte 2017).

Weighted Line of Organic Correlation. The Weighted Line of Organic Correlation (WLOC) minimizes the sum of the product of the measured values and the weighted horizontal as well as vertical differences and the predicted line (Delmotte 2017). Accordingly, measurement points with higher uncertainty are less significant in the regression analysis. This characteristic is particularly more important in the estimation of airflow rates at low pressures. In comparison to other regression methods, pressure exponent and flow coefficient can be calculated without iteration:

$$n = \frac{\sqrt{\sum_{i=1}^{N} v_i w_i \sum_{i=1}^{N} v_i w_i y_i^2 - \left(\sum_{i=1}^{N} v_i w_i y_i\right)^2}}{\sqrt{\sum_{i=1}^{N} v_i w_i \sum_{i=1}^{N} v_i w_i x_i^2 - \left(\sum_{i=1}^{N} v_i w_i x_i\right)^2}} \tag{6}$$

$$C = \exp\left(\frac{\sum_{i=1}^{N} v_i w_i y_i - n \cdot \sum_{i=1}^{N} v_i w_i x_i}{\sum_{i=1}^{N} v_i w_i}\right) \tag{7}$$

Here, v_i and w_i are the weights of each measurement point x_i and y_i, which are defined as the reciprocal of the measured standard deviation at each pressure station. In this paper, the absolute and not the relative measurement error was taken into account. A relative error would give two points with the same absolute measurement uncertainty a higher weight at higher pressure stations compared to lower pressure station.

Figure 1 shows one example of a blower-door measurement with twelve different pressure stations and the corresponding measured airflow rates. At each pressure station the measurement standard deviations are plotted for each point as well. Both regression methods are applied to this measurement and the power-law functions of the OLS and WLOC fitting are plotted on a linear scale. The OLS fitting tries to find the most appropriate fit for all stations equally, whereas the WLOC has a considerably better fit for data points with low errors and weights data points less with larger errors. In particular, the fitting of WLOC is better for measurement data above 25 Pa, where in this specific case, the error is smaller.

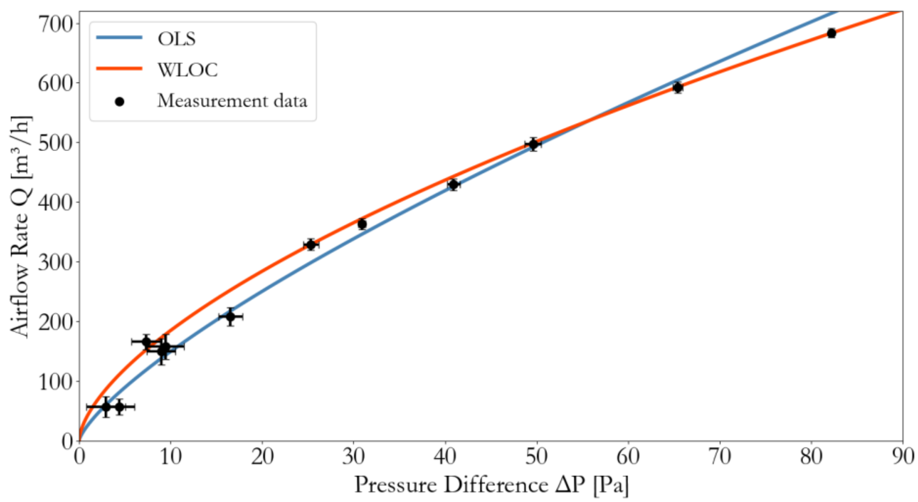


Figure 1: Comparison of fitting using OLS and WLOC in linear display for one blower-door measurement series.

RESULTS AND DISCUSSION

The two test methods were evaluated by determining the airfows and leakage areas calculated at 4 Pa and 10 Pa because these parameters are often used in reporting of air leakage measurements, are calculated in current standard test methods, and used in standardized energy and indoor air quality calculation proecurees. To evaluate the two approaches, we compared their results to those from a reference case for each configuration. The reference airflow rate and equivalent leakage area were determined by examining all the test results for each test configuration and using the results from the test with the lowest wind speed and best fit to the measured data (see Walker et al. 2013 for more details).

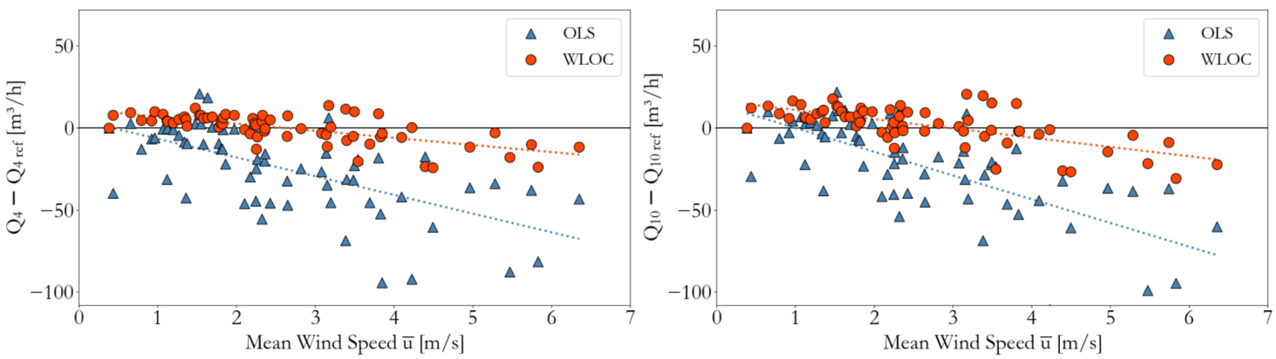
Although all 109 different leak configurations have been analyzed, we will present detailed results from a single configureation for illustrative purposes (showing the in-depth analysis of all configurations would far exceed the scope of this paper). We chose a configuration that clearly shows differences between the the OLS and WLOC approaches: a masonry structure with an open 150 mm diameter furnace flue in depressurization. Sixty-five tests were performed in this leakage configuration, with 20 different pressure stations at each measurement.

Airflow Rate. First, the estimations of airflow rates at lower pressures have been analyzed. For every measurement, the pressure exponent and flow coefficient were calculated using OLS and WLOC and the respective airflow rate was determined using the power-law (Eq. (2)). Airflow rates at 4 Pa have been chosen, because this is typically a relevant metric for energy simulation (Ng et al. 2013) or indoor air quality applications (Vornanen-Winqvist et al. 2018) and therefore relevant for users. In buildings, the envelope pressure under real conditions is usually in the range of 4 Pa or less.

In figure 2 (a), the difference between the airflow rate at 4 Pa and a reference value of the airflow rate at 4 Pa is plotted as a function of measured mean wind speed. The error of blower-door measurements is highly correlated with the wind speed at the time of the respective measurement. For this reason, DIN EN ISO 9972 (DIN 2018) recommends conducting blower-door measurements only if the wind speed does not exceed 6 m/s. As a reference value, the airflow rate with the lowest corresponding wind speed is chosen and can therefore be seen as a measurement close to the true value of the airflow rate at 4 Pa. This value functions as a benchmark to all other measurements at higher mean wind speeds. Consequently, a reasonable estimation of the airflow rate at low pressures and thus a good fitting technique is characterized by a small difference between the measured airflow rate and the reference value, even though the mean wind speed increases. Figure 2 (a) exhibits a clear difference between both considered fitting techniques. For the OLS fitting, the mean absolute difference between the measured airflow rate and the reference value increases significantly with increasing wind speed. The fact that the mean difference becomes negative indicates that the actual airflow rate at 4 Pa is more and more underestimated with increasing wind speed. The estimated airflows with WLOC fitting are on average much closer to the reference value, which indicates a far better estimation of airflow rates even at disturbing ambient conditions. There is still a trend of underestimating the airflow rate with increasing wind speed, but this error of underestimation is far lower compared to OLS.

Figure 2 (b) shows the same analysis but with the estimated airflow rate at 10 Pa. The results are similar to the results obtained from figure 2 (a). The higher the mean wind speed, the higher is still the underestimation of the airflow rate at 10 Pa for the OLS fitting. The predicted values calculated with WLOC fitting are still far closer to the reference value.

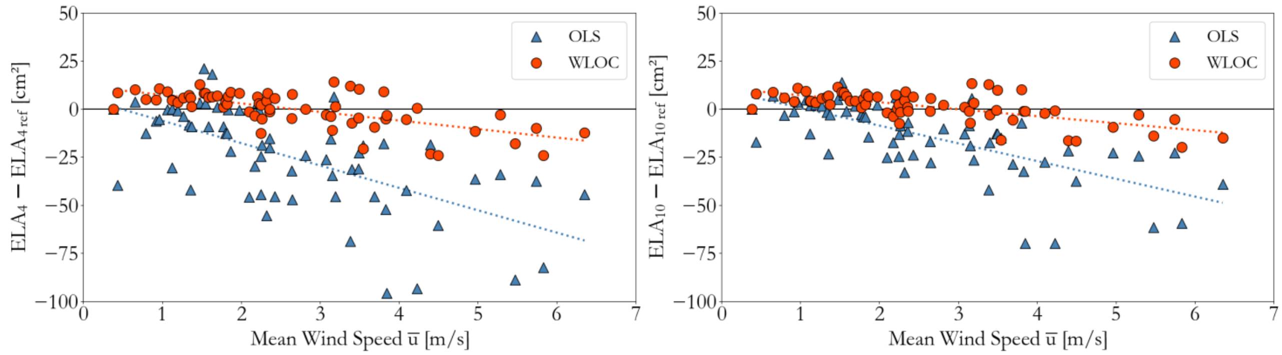
Equivalent Leakage Area. In addition to the airflow rate at low pressures, the equivalent leakage areas (ELA) at the same pressures have been investigated. The equivalent leakage area is the area of a single sharp-edged orifice which has the same airflow as the whole building envelope. The ELA is roughly equivalent to the sum of all openings in the building envelope. The definition and calculation procedure of the ELA at 4 Pa pressure difference is part of the ASTM standard (ASTM 2019) and is at 10 Pa part of the Canadian CGSB standard (CAN/CGSB 2019). Therefore, ELA has been evaluated at these pressures.



a) b)

Figure 2: Relative airflow rate as a function of the mean wind speed at (a) 4 Pa and (b) 10 Pa pressure difference.

Again, the differences of the estimated equivalent leakage areas and a reference value at the lowest mean wind speed are plotted in figures 3 (a) and (b) over the mean wind speed for both pressure differences for OLS and WLOC fittings. These plots show again a higher underestimation of ELA for increasing mean wind speed for both fitting techniques but a substantially higher error for the conventional OLS fitting. Even though, standards allow blower-door measurements at wind speeds up to 6 m/s, these results show that the error of extrapolation using OLS is high compared to WLOC in this range.



a) b)

Figure 3: Relative equivalent leakage area as a function of the mean wind speed at (a) 4 Pa and (b) 10 Pa pressure difference.

Furthermore, the mean absolute and root-mean-square (RMS) errors between the predicted and reference value are displayed in table 1 for this example configuration. All errors are calculated for the airflows and equivalent leakage areas at 4 and 10 Pa as well as for OLS and WLOC. These numbers confirm that the prediction errors for WLOC are lower. The reduction of the mean absolute and RMS prediction errors from WLOC to OLS for values evaluated at 4 Pa is between 72 and 75 % and for values at 10 Pa between 63 and 68 %. Therefore, the relative difference between the prediction error of WLOC and OLS increases with the decreasing pressure differences for this dataset.

Table 1. Mean absolute and RMS errors between predicted and reference value for the example dataset

	Q_4 [m³/h]	Q_{10} [m³/h]	ELA_4 [cm²]	ELA_{10} [cm²]
Mean abs. error OLS	27.22	27.32	27.19	16.92
Mean abs. error WLOC	7.20	9.61	7.42	6.20
RMS error OLS	35.93	37.80	36.06	23.50
RMS error WLOC	9.07	11.99	9.23	7.73

In table 2, the mean absolute and RMS errors are displayed as fractions of the reference value. When represented as fractions, a better comparison between configurations with different overall air flows and leakage areas is possible and biases towards the leakier configurations are eliminated.

Table 2. Mean absolute and RMS errors between predicted and reference value for the example dataset in %

	Q_4 [%]	Q_{10} [%]	ELA_4 [%]	ELA_{10} [%]
Mean abs. error OLS	21.23	13.51	20.51	12.77
Mean abs. error WLOC	6.57	5.14	6.49	5.03
RMS error OLS	28.03	18.69	27.20	17.74
RMS error WLOC	8.25	6.41	8.08	6.27

The above analysis for the example configuration was repeated for all 109 test configurations in the dataset. The results for all configurations are summarized in Table 3. In comparison to the example dataset in Table 2, the overall errors are smaller here. The reason for this is that over all 109 considered leak configurations, the differences between the predictions of WLOC and OLS are smaller than for the example dataset. Nevertheless, the differences between both fitting techniques are still significant:

about a 41% error reduction for 4 Pa results and 33% for 10 Pa results. Roughly 91 % of all considered configurations show similar results where WLOC was superior in estimating the airflow rates and equivalent leakage areas at low pressures compared to OLS. These results are broadly in line, though not directly comparable, with some studies. Prignon et al. (2018) compared the OLS and WLOC methods on a series of 30 tests on an apartment. They found that the standard deviations of fitted air leakage parameters (C and n) were reduced by about 30-50% using the WLOC method compared to OLS. Okuyama and Onishi (2011) tested five buildings and calculated the confidence limits for C and n using OLS and two different weighting schemes: weighting by residuals and weighting by measurement uncertainty. Their results showed a reduction in confidence limits of roughly a factor of two or more using the weighting approach in the least squares fitting.

Table 3. Mean absolute and RMS errors between predicted and reference value for the whole dataset in %

	Q_4 [%]	Q_{10} [%]	ELA_4 [%]	ELA_{10} [%]
Mean abs. error OLS	13.48	9.40	13.17	9.00
Mean abs. error WLOC	8.05	6.32	7.93	6.18
RMS error OLS	17.76	12.20	17.31	11.66
RMS error WLOC	10.30	7.97	10.12	7.76

CONCLUSION AND FUTURE WORK

These results show a far better prediction (by about 40% for Q_4 and ELA_4) of the airflow rate and equivalent leakage area at low pressures using the WLOC regression technique even though the influence of wind on the measurements increases. In more than 90 % of all considered configurations the WLOC was superior in estimating the airflow rates and equivalent leakage areas at low pressures compared to OLS. Even though WLOC requires more effort in calculation and data recording, the authors strongly recommend the use of a WLOC fitting for applications where the extrapolation of blower-door measurements to low pressures is needed and recommend an adoption by building test standards, such as ASTM E779, CAN/CGSB 149.10 and ISO 9972.

In the future, alternative weighting stratgegies could be investigated to see if more improvement is possible, together with more sophisticated data analyses, such as eliminating data points above given uncertainty thresholds. In addition, the cases where OLS gives better results than WLOC is not as good as OLS could be further investigated in order to find explanations for these results.

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NOMENCLATURE

σ	=	Standard uncertainty	[-]
ΔP	=	Pressure difference	[Pa]
C	=	Flow coefficient	[$m^3/(h\ Pa^n)$]
ELA	=	Equivalent leakage area	[cm^2]
n	=	Pressure exponent	[-]
OLS	=	Ordinary least square method	[-]
Q	=	Airflow rate	[m^3/h]
v, w	=	Weights	[-]

WLOC = Weighted line of organic correlation [-]

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