Measuring Airtightness in a Tall Multi-Family Passive House when Exposed to Wind and Thermal Lift (Stack Effect)

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Abstract. The effects of wind and thermal lift (Stack effect) present particular challenges when measuring the air permeability of large and tall buildings. In high-rise buildings, even small temperature differences between the indoor and outdoor air can lead to undesirably high natural pressure differences on the building envelope. Extreme fluctuations in natural pressure difference can also be caused by wind. This paper presents and compares sets of measurements taken on a 60 m high multi-family Passive House. The building was measured on two separate days in different weather conditions. This paper outlines the extended measurement setup and the measuring process adapted to this setup, as well as the results and findings.

1. Test object and measuring task
The 16-storey multi-family house is approx. 60 m high (Figure 1) and has a volume of 22,600 m³. It is situated in Freiburg, Germany and was retrofitted to the Passive House Standard in 2010/2011. The airtightness measurements were carried out in order to verify that the building complies with the air change rate for Passive House buildings, namely \( n_{50} \leq 0.6 \) h\(^{-1}\).

2. Effects of wind and thermal lift (stack effect) on a building
The differences in wind and temperature between inside and outside a building can generate pressures differences across the building envelope, an effect known as natural pressure difference. The following two sections offer an insight into the impact of pressure differences.
2.1. Effects of Wind
The wind creates airflows which force outdoor air into a building through leakages on the side of the building facing the wind. The pressure exerted on the exterior of the building envelope is greater than the pressure on the interior. The situation is completely reversed on the side of the building facing away from the wind, which experiences a suction force. There, the external pressure is lower than the interior pressure, and indoor air flows outwards through leakages (Figure 2).

Figure 2. Airflows caused by wind

Figure 3. Airflows and the natural pressure differences caused by thermal lift in the building

2.2. Effects of Thermal Lift (Stack Effect)
Air currents because of thermal lift (stack effect) are created when the air temperature within a building differs from the outdoor air temperature, as the warm air is lighter than the cold air due to its lower density. During the heating periods, warm air in the building rises upwards and flows out through leakages at the top of the building. Cold outdoor air, on the other hand, flows into the building through leakages in the lower part of the building. If the leakages are evenly distributed over the height of the building, a positive pressure is formed in the upper half of the building and a negative pressure in the lower half (Figure 3). The difference is balanced in the centre of the building, where the pressure difference between inside and outside is zero. This zone is referred to as the neutral pressure plane. [Zeller] gives an estimate of the natural pressure differences caused by thermal currents [2]:

$$\Delta p_{th} = 0,04 \text{ Pa/(K m)} * \text{h} * \Delta T$$

($$\Delta p_{th}$$: pressure difference between the indoor and outdoor sides caused by thermal lift in Pa; h: height measured from the neutral pressure plane in m; $$\Delta T$$: temperature difference between indoor and outdoor sides in K).

The formula shows that: With a constant temperature difference, the higher the building, the greater the natural pressure difference.

3. Setup of the Test Equipment
The test equipment was installed in the main entrance door on the ground floor of the building. Thanks to careful planning and observation of the air barrier, one BlowerDoor Standard System was sufficient to measure the large building volume (Figure 1).

The natural pressure differences that were measured are larger than +/- 5 Pa permitted under the standards [3] and [4] on both days because of the weather conditions. For this reason, five additional measuring points were set up to measure the pressure in the building (Figure 4). The differential pressure measuring devices (DG-700) achieve an accuracy of 1 % of the measured value. The connected data logger (TELCOG3) recorded the differential pressure curve.
The three measuring points, 1, 2 and 3, located on the lowest storey (ground floor) measured the pressure differences (caused by wind and thermal lift) on three sides of the building. It was not possible to gain access to the fourth side of the building, so no measuring point was set up there. In addition to this, these measuring points and the measuring points 4 and 5 on the top floor, also displayed the pressure difference curve against the height of the building due to thermal lift. The insights into the pressure distribution in the building gained in this way enabled the measuring process to be adapted to the prevailing weather conditions.

4. Weather conditions on the measuring dates
The building was measured on two days in different weather conditions. On the first test date it was very windy: The wind force registered 4 on the Beaufort scale and there was a 9 °C difference between the indoor and outdoor temperature. On the second test date, a few weeks later, the difference in temperature between inside and outside was “very” high: The wind force registered 0 to 1 on the Beaufort scale and there was a 14 °C temperature difference.

5. Measuring process
The measuring process – that is, the positioning of the differential pressure measuring points on the ground floor and the determination of the leakage curves – was carried out in accordance with the standard [3]. The following additional measures were adopted to take into account the weather conditions:

5.1. Series of negative and positive pressure measurements
An average airflow at 50 Pa building pressure was calculated from a multi-point depressurization test and a multi-point pressurization test and was used to determine the air change rate $n_{50}$.

The mean was calculated to reduce the risk of a one-sided influence, as currents caused by wind and thermal lift can generate different positive or negative pressure differences across the building cross-section or height. Furthermore, significantly varied airflows from negative and positive pressure may indicate problems on the building envelope.
5.2. Measuring baseline pressure from three sides building sides to determine the leakage curve

The leakage curves were determined from the average of baseline pressure differences on three sides of the building on the ground floor (measuring points 1, 2 and 3). In comparison to using a single measuring point as is recommended in the standards [3] and [4], using the mean value helps to lessen the fluctuations in differential pressures and peaks arising from changeable wind conditions.

5.3. Test points at the top of the building to measure the effect of thermal lift

In addition to this, the measuring points 1, 2 and 3 on the ground floor and 4 and 5 on the top floor (Figure 4) served to determine the smallest pressure stage to be generated with the measuring device. This was set high enough to ensure that there was a negative and positive pressure in the entire building during negative and positive pressure measurements respectively.

6. Results

Initially, a section of the natural pressure differences was displayed over 60 seconds (measuring interval: 1 second) for each measuring date, and the results from the two measuring dates were then compared.

6.1. Natural Pressure differences in the building in strong wind and a temperature difference of 9 °C

Figure 5 shows the natural pressure differences (baseline pressures) in the building with a wind force of 4 on the Beaufort scale and a temperature difference of 9 °C.

The measurement values constituting the curves on the ground floor (1, 2 and 3) range from just below +10 Pa to –20 Pa, and on the top floor, they vary from well over +30 Pa to just below –30 Pa. All the curves differ widely from each other. The influence of thermal lift (negative values in the lower half of the building and positive values in the upper half) is barely perceptible on account of the strong wind. The considerable fluctuations in the individual curves can also be attributed to the inconsistent wind conditions. Short-term peaks indicate gusts of wind.

The mean value of the pressure differences from curves 1, 2 and 3 was used in determining the natural pressure difference. The smallest pressure stage was calculated using the measured values of curves 4 and 5 (top floor), in a deviation from the standard. The pressure stages in the series of negative pressure measurements ranged from –40 Pa to –75 Pa. A similar procedure was adopted for the positive pressure measurement. This ensured that there was a negative or positive pressure in the entire building during the measurement.
6.2. **Natural Pressure differences in the building at light wind and a large temperature difference**

Figure 6 shows the natural pressure differences in the building with a wind force of 0–1 on the Beaufort scale and at a temperature difference of 14 °C.

![Figure 6](image)

The measuring points 1, 2 and 3 (ground floor) recorded values of around –10 Pa, and 4 and 5 (top floor) of approximately +20 Pa. The course of the curves was clearly determined by thermal lift. A negative pressure and a positive pressure were found at the bottom and the top of the building respectively. The light wind was barely perceptible.

The mean value of the pressure differences (1, 2 and 3) was also incorporated in the evaluation of the series of differential pressure measurements. Measuring points 4 and 5 (top floor) were also taken into consideration when selecting the pressure stages. Therefore, the pressure stages of the series of positive pressure measurements ranged from +25 Pa to +80 Pa, for example, thereby ensuring a positive pressure in the entire building during measuring.

The neutral pressure plane was at around one third of the height of the building. A comparison of the measurement results with the theoretical calculations according to Zeller [2] reveals a high level of correlation:

- Natural pressure difference below: \( \Delta p_{th} = 0.04 \text{ Pa/(K m)} \times (-1/3) \times 60 \text{ m} \times 14 \text{K} \approx -11 \text{ Pa} \)
- Natural pressure difference above: \( \Delta p_{th} = 0.04 \text{ Pa/(K m)} \times (2/3) \times 60 \text{ m} \times 14 \text{K} \approx +22 \text{ Pa} \)

6.3. **Comparison of the airtightness tests**

Table 1 shows the negative and positive pressure measurement of the airflow \( V_{50} \) at 50 Pa building pressure difference between inside and outside, and the mean values on both measuring days.

| TEST 1 (Wind 4 Bft; \( \Delta T= 9 \text{ °C} \)) | TEST 2 (Wind 0-1Bft; \( \Delta T= 14 \text{ °C} \)) | Difference |
|---------------------------------|---------------------------------|------------|
| Airflow V\(_{50}\) (m\(^3\)/h) | Airflow V\(_{50}\) (m\(^3\)/h) |            |
| Negative pressure | 5567 | 4833 | -13% |
| Positive pressure | 4219 | 4859 | +15% |
| Mean value | 4893 | 4846 | -1% |
Due to a light wind and higher temperature difference of 14 °C on the second test date, the airflow V₅₀ of the negative pressure measurement is 13% lower than on the first measuring date. The reverse applies to the positive pressure measurement, where the airflow is 15% higher. There is, however, only 1% difference in the mean values of the measurements. It can therefore be seen from this example, that the second measuring date confirms on average the results of the first measuring date. This clearly shows the importance of measuring the positive AND negative pressure in all scenarios.

The air change rate of the building is n₅₀ = 0.22 h⁻¹ and therefore clearly falls below the Passive House requirement of n₅₀ ≤ 0.6 h⁻¹.

7. Conclusion
Wind and thermal lift are more relevant for large and tall buildings than for small buildings when performing an airtightness test.

Comparing the airtightness measurements in the 60 m tall multi-family house shows that it was possible to obtain reproducible measuring results for the average negative and positive pressure, even under difficult weather conditions.

By averaging the measured values of the test points located on the ground floor on different sides of the large building, the pressure fluctuations caused by wind and gusts could be reduced. Brennan et al. also confirmed an improvement in measuring accuracy when using several measuring points instead of one [1].

The effects of thermal lift (stack effect) in the tall building were monitored by measuring the differential pressure at various locations in the ground and top floors. This enabled the pressure steps of the depressurization test and the pressurization test to be set in such a way that in the entire building there was a negative pressure during the depressurization test and positive pressure during the pressurization test. This allowed airflows through the building envelope to be avoided in the opposite direction to the artificially generated pressure difference of the test equipment.

Zeller suggests a good method for assessing the influence of thermal currents before the measurement date [2]. If this reveals high pressure differences, it can be considered whether further measures need to be taken, such as postponing the measurement date.

In this study, a good reproducibility of the overall result was found once in the performance of a series of depressurization and pressurization tests. However, the measurements taken by Brennen et al. were not taken to a significantly higher level of accuracy [1]. Further studies are desirable to obtain boundary conditions for airtightness tests of large and tall buildings not covered by the standards [3] and [4].

References
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