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Assessment of Wind Impact on Building Air Leakage Measurements using a Model Scale Experiment

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ABSTRACT HEADING

Nowadays, many countries include requirements for building airtightness in their current national regulations or energy-efficiency programs, mainly for concern about reducing building energy consumption due to air leakage. Moreover, some countries impose a mandatory justification with an air leakage measurement. Therefore, the uncertainty of the measurement results has become a key concern in several countries over the past year. More specifically, the influence of wind speed has been identified as one of the major sources of error on the measurement result.

The goal of our work is to improve uncertainty estimates and test protocols starting from model scale experiments in controlled laboratory conditions. We first present the experimental facility we developed to perform pressurization tests at model scale, which includes: 1- a model at 1/25th, 2- a pressurization device that pressurizes the model up to 100 Pa and 3- a wind tunnel in which the wind is stable from 0 to 7 m s^{-1}. Secondly, we present the zero-flow pressure measurement results for 9 leakage distributions and 8 wind speeds: these results strongly depends on the leakage disbritbution, with an abdsolute value of zero-flow pressure difference that varies for strong winds from 1 Pa to more than 16 Pa. Finally, we calculate the error due to steady wind from 96 tests performed according to ISO 9972 in various wind conditions and for the 9 leakage distributions. At 4 Pa, the maximal error varies from 2% to 35%.

INTRODUCTION

Since the 1970s, many authors have discussed the impact of poor airtightness on building energy use, indoor air quality, building damage, or noise transmission (Carrié and Rosenthal, 2008; Jokisalo et al., 2009; Leprince et al., 2011; Logue et al., 2013; Richieri et al., 2016). Nowadays, because airtightness significantly affects the energy performance of buildings, and even more significantly with low-energy targets, many countries include requirements for building airtightness in their national regulations or energy-efficiency programs (Leprince et al., 2017). Different indicators are used depending on countries and programs, such as q_{a4} in France (called $Q_{4Pa\text{-}surf}$ in French: air leakage rate at 4 Pa divided by the loss surface area excluding the basement floor) and ELA_4 in the US (equivalent leakage area at 4 Pa). Building airtightness is widely evaluated from a building pressurization test according to a protocol described in ISO 9972 or ASTM 779-19. These tests are increasingly used for compliance checks to energy performance requirements and may result in severe penalties (Mees and Loncour, 2016). The uncertainty of measurement results has therefore become a key concern in several countries over the past few years, especially for indicators at 4 Pa as they are more impacted by environmental conditions (Delmotte and Laverge, 2011). More specifically, several studies (Carrié and Leprince, 2016; Modera and Wilson, 1990; Prignon et al., 2019; Walker et al., 2013) have shown the significant

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uncertainties induced by the wind. Some of these studies are based on analytical models that significantly simplify the physics and other are on-site measurements performed on few buildings that characterize the impact of the wind only for the specific situations of these buildings. There remains a need for further investigations to better understand the physics during airtightness tests. More specifically, it is necessary to understand how the wind affects pressurization tests to characterize the error induced by the wind on the test results. This would imply reproducing the wind speed, direction, and fluctuations to study all configurations, and perfectly knowing the airtightness of the building. A solution is to perform pressurization tests using model scale experiments. We first present the experimental facility we developed to perform pressurization tests at model scale. Secondly, we present the zero-flow pressure measurement results for 9 leakage distributions and 8 wind speeds. Finally, we calculate the error due to steady wind from 96 tests performed according to ISO 9972 in various wind conditions and for the 9 leakage distributions.

A NEW EXPERIMENT FACILITY TO REPRODUCE PRESSURIZATION TEST ON MODEL SCALE

We have designed an experimental facility to evaluate the impact of a steady wind on building airtightness measurements and to test solutions to reduce the uncertainty of the test results intrinsic to the wind effect. This entails to carry out pressurization tests in reduced scale, generate steady wind conditions at different wind speeds, and accurately measure pressure differences, wind speeds, and airflow rates. To meet these objectives, the experimental facility includes:

- a model of a single-zone building in reduced scale;
- a pressurization measurement device which will replace a blower door in reduced scale;
- a wind tunnel that will create steady wind conditions;
- necessary sensors and actuators.

We have first defined the sizes of the model and the wind tunnel section from the scale ratios we defined to meet similarity conditions. The methodology for the design of the experimental facility is detailed in (Mélois et al., 2020).

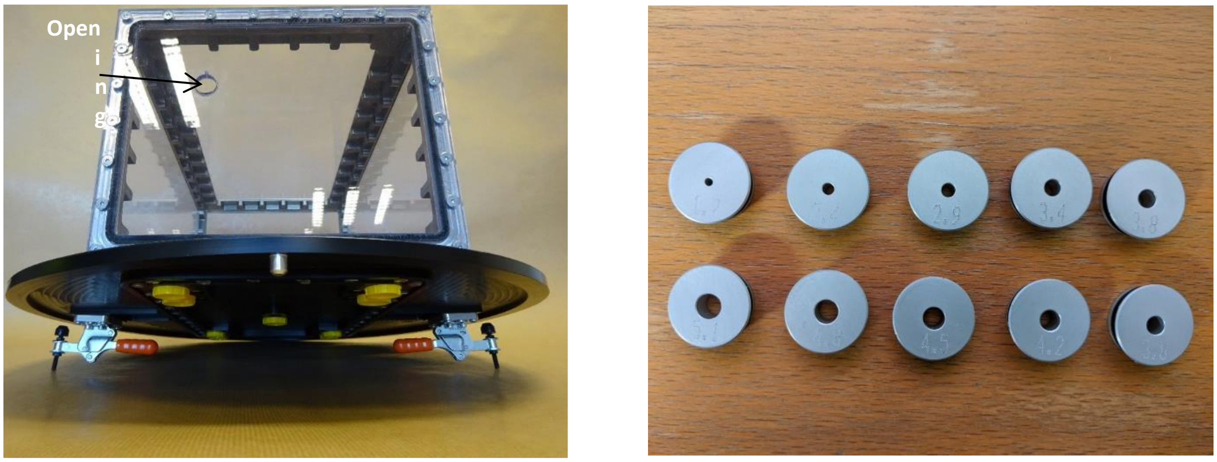
Single-zone model

In accordance with (Carrié and Leprince, 2016), we assume that the building can be represented by a single zone separated from the outside by two 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 all leaks on the windward (respectively, leeward) side can be represented as a single opening at a given height subjected to the same pressure difference. Our model correspond to a 2-story house at a scale ratio 1/25th, with an air permabality at 4 Pa equal to $ELA_4 = 1.8\ 10^{-5}$ m² (corresponding to the limit value for new single-family house in France). The leakage area is distributed on the two openings of the model for 9 differents leakage distributions: from $r_{LD} = 0.1$ to 0.9 with a step of 0.1, r_{LD} is defined according to equation 1.

$$r_{LD} = \frac{A_1}{A_1+A_2} \tag{1}$$

With r_{LD}= the ratio of leakage distribution, A_1= the leakage area of the windward opening and A_2= the leakage area of the leeward opening.

To avoid boundary layer turbulence and impact of one opening on the other one, both openings are therefore located 0.13 m away from the bottom of the model, 0.07 m away from the right-hand side of each facade. The model is composed of a metallic frame with removable Plexiglax® facades fixed to the frame with screws and seals (Figure 1(a)). This solution will make it possible in the future to test new facades with more openings, for example. Two opposite facades include a large circular opening each. Several metallic disks are drilled to correspond to the different leakage distributions (Figure 1(b)). These cylinders are plugged onto the large circular opening like corks. This solution enables us in the future to design as many different opening sizes and shapes as possible. To fix the model into the tunnel, the floor of the model is made up of a large circular plane that includes one block, making it possible to place the model always at the same location, with a defined angle from 0° to 360° in relation to the axis of the tunnel. Two clamps let to fix the model into the wind tunnel and prevent it from moving during a test. To allow accurate measurement of physical parameters inside the model, the floor of the model includes 2 taps to which we can connect flexible tubes to measure pressure differences or to supply air to pressurize the model, and several other circular airtight openings to insert a thermometer, for example. For each of the openings, a sealing system is used to ensure perfect airtightness when the opening is not used.



(a) (b)

Figure 1 (a) Final reduced model and (b) Metallic disks with openings corresponding to different r_{LD} values..

Pressurization device

The pressurization device should make it possible to perform a pressurization test in a similar way to a blower door. We evaluate the airflow rate that has to be provided by the pressurization device for wind speeds from 0 to 7 m s^{-1}, at each of the pressure differences of the test sequence, for all configurations of leak distribution. The pressurization device should provide airflows to impose a pressure difference from 10 Pa to 100 Pa pressure difference. That corresponds to a range of [3.0 10^{-5}; 3.0 10^{-4} m^3 s^{-1}]. The pressurization device includes a flow controller that meets the design requirements: it provides airflow rates from 6.7 10^{-6} m^3 s^{-1} to 1.7 10^{-3} m^3 s^{-1}. As the flow controller can only supply air and not exhaust air, our experimentation will only include pressurization tests. For a real building, there is often a significant difference between pressurization results and depressurization results, especially due to the existence of valve effect in the walls. Due to the nature of the walls of our model, we do not expect any difference. Performing tests only on pressurization should not induce a significant bias in our results. Another difference between our pressurization device and a blowerdoor is that our device will not be placed on the envelope of the model. For real building, the blowerdoor is placed on either the entrance door or another external door. Thus, the wind impacts not only the envelope including the leaks but also the fan of the pressurization device.

The flow controller (Figure 2(a)) is connected to a compressor (Figure 2(b)) that provides air at 3.0 10^5 Pa. The flow controller is managed using the LabVIEW environment. The application we developed defines the target airflow supplied in the model depending on the pressure difference measured by a manometer (Figure 2(c)). The LabVIEW interface is connected to the flow controller, the manometer, the frequency driver of the wind tunnel ventilator, anemometers, and temperature sensors. A VBA program to reproduce pressurization tests in repeatability conditions for different wind speeds calls the LabVIEW application.

(a) (b) (c)

Figure 2 (a) Airflow controller, (b) Compressor and (c) Manometer.

Wind tunnel

Standard ISO 9972 indicates that for a meteorological wind speed above 6 m s^{-1} the zero-flow pressure difference requirement (one of the requirements defined in this standard for performing such a test) is unlikely to be respected. To evaluate the relevance of this requirement, the wind speed will vary from 0 to at least 7 m s^{-1}. The wind tunnel has therefore been sized to provide a steady wind from 0 to at least 7 m s^{-1} in the test chamber. The wind tunnel is then designed according to the methodology explained by (Mauro et al., 2017). It includes five components: 1-a settling chamber with a honeycomb and 2 screens, 2-a contraction component, 3-a test chamber, 4-a diffuser, and 5- a fan.

The settling chamber includes a honeycomb and two screens; each of these components is 2.0x2.0 m^2. The honeycomb is made of aluminium with the following characteristics: diameter = 6 mm; sheet thickness = 0.7 mm; length = 45 mm. The porosity of the honeycomb is 0.8 and the ratio between length and hydraulic diameter is 7.5. The screens are made from two types of perforated plates: one made of galvanized steel with a porosity of 0.64 and one made of steel with a porosity of 0.74.

To generate wind speeds up to 7 m s^{-1} in the testing chamber, the fan will need to provide a maximum airflow rate equal to 25,200 m^3 h^{-1}. Thus, our wind tunnel includes an axial fan with a maximum airflow rate which can reach around 43,000 m^3 h^{-1}, depending on the pressure drop. This fan can be controlled with a frequency converter. Its diameter is equal to 1.0 m. As the diameter of the fan corresponds to the size of the testing chamber, there is no minimum length for the diffuser.

Thus, we designed and installed a wind tunnel that is 4.11 m long with a maximal cross-sectional area of 4.0 m² for the settling chamber and 1 m² for the test chamber (Figure 3).

Figure 3 Installed wind tunnel.

Thanks to our new experimental facility, we performed 96 pressurizations tests based on the ISO 9972 protocol, that include 864 measurements under steady wind conditions: for the nine configurations of leakage distribution of our model and under eight different wind speeds (from 0 to 7 m s^{-1} with a step of 1 m s^{-1}). In the next section, we analyze the zero-flow pressure differences as it is considered as an indicator of the environmental conditions.

IMPACT OF THE WIND ON THE ZERO-FLOW PRESSURE

In the ISO 9972 protocol, the zero-flow pressure difference is the indicator related to environmental conditions that validates the test. In our study, only the wind impacts the zero-flow pressure difference, depending also on the leak distribution. For each of the nine configurations of leakage distributions of the model, we measured the zero-flow pressure difference for wind speed from 0 to 7 m s^{-1}. The external pressure tap is equipped with a T connector to measure only static pressure. It is placed at the entrance of the testing chamber, on the floor, upstream the model. The internal pressure tap is located on the floor inside the model, away from the pressure device connector and the openings. For each fan pressurization test, we measured an initial ($\Delta p_{0,1}$) and a final ($\Delta p_{0,2}$) zero-flow pressure differences, each lasts 60 seconds and includes 30 measurements. The zero-flow pressure difference (Δp_0) is equal to the average of these measurements, according to equation (2).

$$\Delta p_0 = \frac{\Delta p_{0,1} + \Delta p_{0,2}}{2} \tag{2}$$

In Figure 4, for each of the 9 leakage distributions, we compare the zero-flow pressure difference Δp_0 to the absolute limit value 5 Pa required by the ISO 9972. First, we observe that the zero-flow pressure value strongly depends on the leakage distribution, with extreme values at 7 m s^{-1} from -16.7 Pa when leakage is mostly on leeward to +11.6 Pa when leakage is mostly on the windward facade. We also observe than for a particular configuration, the zero-flow pressure can stay extremely stable and low with a maximum value at 1 Pa. That confirms that the impact of the wind on Δp_0 strongly depends on the leakage distribution, but also that the Δp_0 is not a direct indicator for environmental conditions. Secondly, we observe that the 5 Pa limit does not eliminate the same conditions from all leakage distributions: when the leakage is mostly on leeward, only tests performed under calm conditions are validate whereas when the leakage is mostly on the windward, tests can be performed up to 5 m s^{-1}. Morover, in some particular conditions, there is not limit for wind speed. These results show that the 5 Pa limit for Δp0 does not prevent all strong wind conditions.

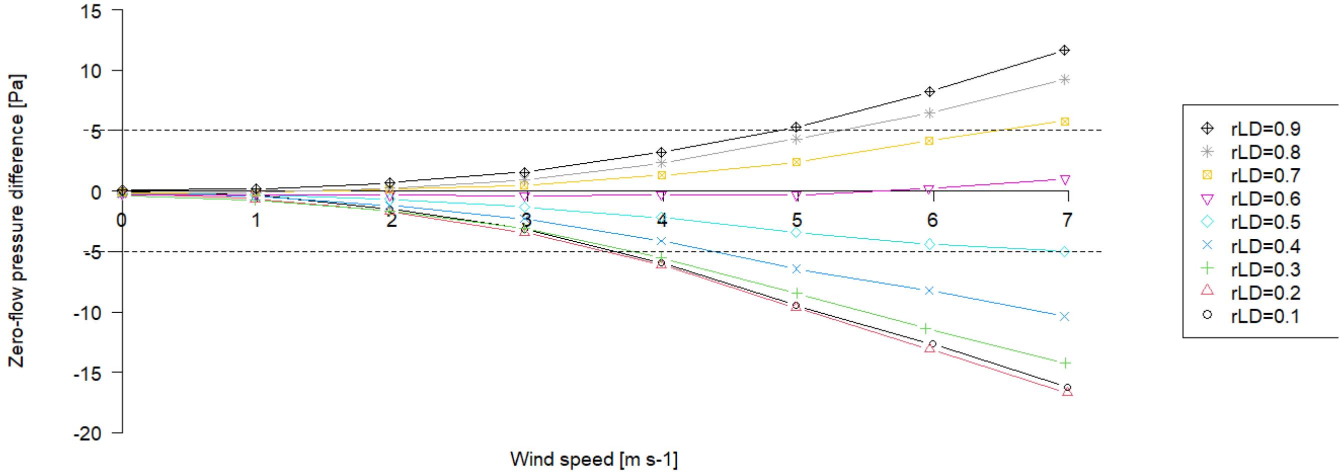


Figure 4 Experimental zero-flow pressure difference for 9 configurations of leakage distribution depending on wind speed.

IMPACT OF THE WIND ON TESTS PERFORMED ACCORDING TO ISO 9972

We consider tests performed according to ISO 9972 protocol: only tests with a zero-flow pressure difference less than 5 Pa and at least 5 stations. This means that depending on the leakage distribution, maximal wind speed varies from 3 to 7 m s^{-1}. For all of the nine configurations of leakage distribution and all wind speeds, we calculate the airleakage airflow rates q_4 [m^3 h^{-1}] according to equation (3), in compliance with ISO 9972 (with the airflow coefficient C [m^3 h^{-1} Pa^{-n}] and the flow exponent n [-] evaluated from an ordinary least square analysis) (Figure 4).

$$q_4 = C * 4^n \tag{3}$$

First, when leakage is mostly on the leeward ($0.1 \leq r_{LD} \leq 0.4$): as tests are valid only under calm conditions, we do not observe a significant impact of the wind on the q_4 value. Secondly, when the leakage is equally or almost equally distributed (r_{LD}=0.5 or 0.6), tests are valid up to 6 or 7 m s^{-1}. For these configurations, we observe a decrease of the q_4 value that can be very important when the wind increases. Last, when the leakge is mostly on the windward façade ($r_{LD} \geq 0.7$), we observe a significant increase of the q_4 value when the wind speed increases. We have evaluated this impact by calculating the error due to the wind on q_4. For each configuration, we have defined the error Ew_4 according to equation (4) as the relative difference between the measured value of the airflow rate at 4 Pa $q_{4,m}$ and the reference value $q_{4,ref}$ we have precisely measured without wind from tests according to ISO 9972 and direct measurements at 4 Pa. The reference varies from 0.163 to 0.170 m^3 h^{-1} depending on the configuration.

$$Ew_4 = \frac{q_{4,m} - q_{4,ref}}{q_{4,ref}} \tag{4}$$

First, when leakage is mostly on leeward ($0.1 \leq r_{LD} \leq 0.4$), as we have observed no significant variation of q_4 under calm conditions, the maximal error is 6.6 %. The error is even lower when the leakage is exactly equally distributed (r_{LD}=0.5). On the contrary, when the leakage becomes bigger on the windward side, the error increases a lot up to almost 35% at 7 m s^{-1} for r_{LD}=0.6. Even if the error decreases for leakage distribution ratio 0.8 and 0.9, it reaches 18%. We thus observe that the impact of the wind on q_4 strongly depends on the leakage distribution with a maximal error (that means for a maximum authorized wind speed) varying from 2% to 35%. This shows that the Δp_0 correction does not prevent from high error due to wind depending on the leakage distribution.

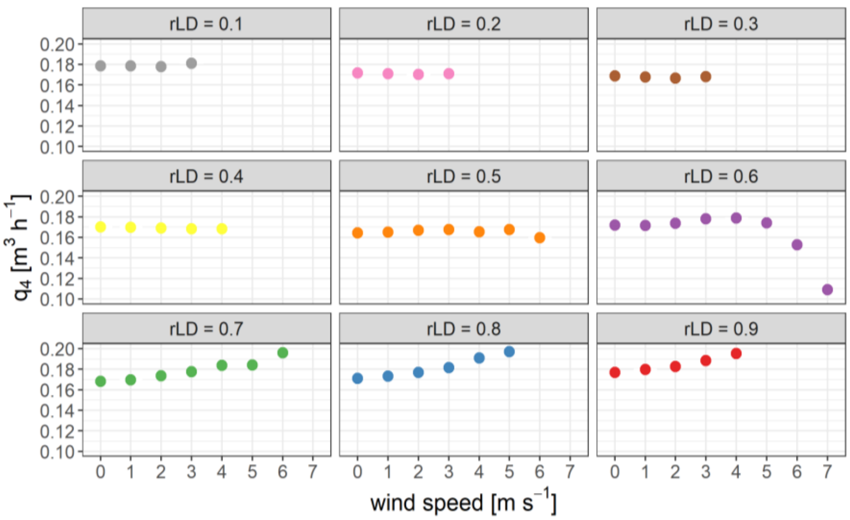


Figure 4 Variation of q_4 values measured according to ISO 9972 depending on wind speed and leak distribution.

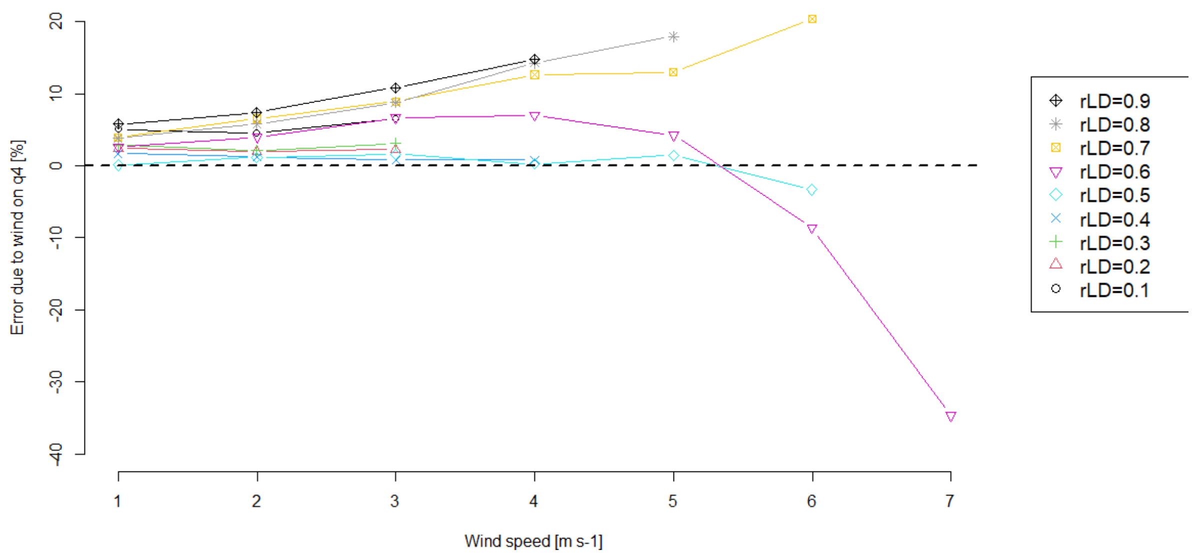


Figure 5 Error due to wind on q_4 for tests performed according to ISO 9972

CONCLUSION

The experimental facility we designed and constructed includes a model (scale 1/25th) that represents a single-zone building, a pressurization device that replaces a blowerdoor, and a wind tunnel that reproduces steady wind conditions. The model is scalable and provides nine configurations of leakage distribution between windward and leeward façades, with a similar averaged total airtightness for all configurations $q_{4,ref}$=0.17 $m^3\ h^{-1}$. Our pressurization device includes a flow controller connected to a compressor. The wind tunnel is 4.11 m long and includes a 1.0*1.0*1.5 m^3 testing chamber. The wind speed inside the testing chamber is homogeneous and can be stabilized from less than 1 $m\ s^{-1}$ to 7.5 $m\ s^{-1}$. Our experimental facility is controlled by a VBA program coupled to Labview applications we have developed to control all components and collect all experimental data. Thanks to our new experimental facility, we have performed 96 pressurizations tests that include 864 measurements under steady conditions: for the nine configurations of leakage distribution (r_{LD} from 0.1 to 0.9) of our model and under eight different wind speeds (from 0 to 7 m s^{-1}). We first analyzed the zero-flow pressure differences as it is considered as an indicator of the environmental conditions. More important, it is one of the major criteria to validate a pressurisation test according to the ISO 9972 standard. We observed that the variation of the absolute zero-flow pressure difference induced by the wind strongly depends on the leakage distribution: from less than 1 Pa to more than 16 Pa. Moreover, we showed that we can obtain very low zero-flow pressure differences (1 Pa) for strong winds (7 m s^{-1}), which indicates that the zero-flow pressure difference is not always a relevant indicator of the windy conditions. Then, we evaluated the error due to wind for tests performed according to ISO 9972. We observed that the error on q_4 induced by the wind strongly depends on the leakage distribution for q_4, with a maximal error varying from 2% (leaks equally distributed) to 35% (60% of the leakage on the windward facade).

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