Airtightness measurement of large buildings by using multi-zonal techniques: a case study

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ABSTRACT

Nowadays the improvement of building airtightness is an essential condition to achieve high energy performance of buildings. Therefore, there is a need to precisely describe and quantify buildings infiltrations.
In France, building airtightness is determined by fan pressurization, as described in the international standard ISO 9972. Appliqued to large buildings however, several technical questions arise, such as the ability to generate a pressure difference of at least 50Pa, or to achieve a uniform indoor pressure for the whole building. For these reasons, it is suggested to divide large buildings into smaller elements. This approach, often referred as multi-zonal, was applied here to a case study. According to ISO 9972 standard, two different techniques can be used: providing an identical pressure in adjacent zones, or including inter-zonal air flows in the calculation of the airtightness of a room. Both techniques were applied here to a 32 000 m^3 building.
The building was made of offices, classrooms and four large halls devoted to research. For offices and classrooms, an airtightness level n_{50} lower than 1.47 h^{-1} has to be achieved. For the halls however, it should be lower than 2.89 h^{-1}. Consequently, both part had to be measured separately. In addition, the four halls could not be measured simultaneously as they were not contiguous.
A first step consisted in assessing inter-zonal airflows. Each part of the building should be isolated from the other, on an airflow point of view. However, many important leakages were detected: at the junction between the ceiling and separation walls, between the exterior wall and separation walls, at doorways where doorsills or seals were missing, and through the separation walls because of the crossing with beams, sheathes, and networks ducts.
Next, the building airtightness was measured according to several multi-zonal methods. First, halls were measured one by one, then each hall was measured while the adjacent halls were simultaneously depressurized, and finally the four halls were measured simultaneously, with depressurized adjacent offices and classrooms. Offices and classrooms were tested with and without depressurization of adjacent halls.
The results showed that inter-zonal airflows were non-negligible and significantly influenced the measured airtightness: the n_{50} value was overestimated and ranged from about 70% to 100%. On average, a higher difference (+92%) was obtained for the halls while it reached as much as 80% for offices and classrooms.
According to ISO 9972 standard, all multi-zonal measurement methods used in this study are allowed to determine the airtightness of this building. The huge difference between results is a problem, especially when airtightness is measured for compliance with a specification of a building code or standard, in the context of calculation of energy performance of buildings.

KEYWORDS

Airtightness, multi-zonal techniques, inter-zonal airflows

1 INTRODUCTION

The improvement of building airtightness is an essential condition to achieve high energy performance of buildings. Therefore, there is a need to precisely describe and quantify buildings infiltrations. In France, building airtightness is determined by a fan pressurization test, as described in the international standard ISO 9972 (AFNOR, NF EN ISO 9972, 2015). When applying to large buildings, two methods are allowed to measure airtightness: to

achieve a measurement for the whole building, thanks to the use of several fans or the building ventilation and air conditioning system fans (single-zonal techniques), or to divide the building into smaller elements (multi-zonal techniques).
A single-zonal technique often requires several fans. Table 1 shows examples of large buildings measured with common blower door fans (7000-8000 m^3/h), presented in (Dorschky, Simons, & Rolfsmeier, 2005), (Blomsterberg & Burke, 2012), and (Szymanski, Gorka, & Gorzenski, 2014).

Table 1: Measurements results for large buildings, measured with one or several blower door fans

Building use	Volume (m^3)	n_{50} (h^{-1})	Airflow at 50 Pa (m^3/h)	Number of fans
School	13 500	0.13	1 786	1
Home for the elderly	11 000	0.18	1 965	1
Industry	191 000	0.01	2 674	1
School	8 995	0.34	3 043	1
Office	15 171	0.43	6 558	1
Office	31 500	0.21	6 615	1
Food store	8 000	1.11	8 916	2
Industry	46 500	0.22	10 230	2
Shop	61 090	0.20	12 131	3
Research building	50 000	0.30	15 000	3
School	14 000	1.28	17 870	3
Research building	50 000	0.44	22 000	3
Industry	17 100	1.30	22 230	3
Care center	27 400	1.60	43 840	7

It is possible to measure large buildings with a unique fan, either if the building is airtight enough (see Table 1), or if the fan capacity is higher than standard models ones. Table 2 summarizes measurements for which special fans were used: BGV capacity is about 72 000 m^3/h, whereas Megafan capacity is around 300 000 m^3/h. These results are presented in (Boithias, Berthault, & Juricic, 2013), (Litvak, Boze, & Kilberger, 2001), and (Biaunier, Berthault, Huet, & Charrier, 2010).

Table 2: Measurements results for large buildings, by using two special fans

Building use	Volume (m^3)	n_{50} (h^{-1})	Airflow at 50 Pa (m^3/h)	Fan
Industry	6 982	0.28	1 955	Megafan
School	7 426	1.07	7 968	BGV
School	4 237	3.54	15 004	BGV
Shop	14 061	1.25	17 576	Megafan
School	4 563	3.95	18 015	BGV
School	4 862	3.83	18 601	BGV
Industry	4 083	7.87	32 133	Megafan
School	6 610	6.81	45 003	Megafan
Industry	53 000	0.91	48 230	Megafan
Industry	53 000	0.93	49 290	Megafan
Gymnasium	7 408	8.98	66 524	Megafan
Industry	14 910	10.42	155 346	Megafan
Commercial Center	27 858	29.20	813 454	Megafan

As concerned the single zonal approach applied to a large building, (Szymanski, Gorka, & Gorzenski, 2014) and (Blomsterberg & Burke, 2012) proposed to use the building ventilation and air conditioning system fans, if they were able to generate a sufficient airflow rate. The international standard ISO 9972 allows this method, if the uncertainty of the measured airflow rate is lower than 7% of the reading. Yet, this condition is hard to meet. Indeed for the cases studied in (Szymanski, Gorka, & Gorzenski, 2014), the authors acknowledged that additional efforts were required to obtain accurate results.

For the multi-zonal approach, large buildings are divided in smaller elements, measured separately as mentioned above. Two different techniques can be used. They consist in:

1. Providing an identical pressure in adjacent zones (named "the guarded test" approach);
2. Including the airflow from adjacent zones into the calculation of the airtightness of the targeted zone.

In (Szymanski, Gorka, & Gorzenski, 2014), both techniques were applied to a large building split in two zones. The difference between the n_{50} values was about 30%. In (Hult & Sherman, 2014), the authors exposed methods to quantify leakage between house and garage, and estimated the uncertainty of each method. They concluded that balancing the pressure was the method the most consistent, which can be achieved by using two blower doors. The inter-zonal leakage was determined with an accuracy of 20%.The authors extended this method to multi-zone buildings, by simulating the guarded test method (see Figure 1). They showed that using a non-guarded test method could overestimate the n_{50} value between 30% and 100%, depending on airtightness of adjacent zones, and leaks between zones.

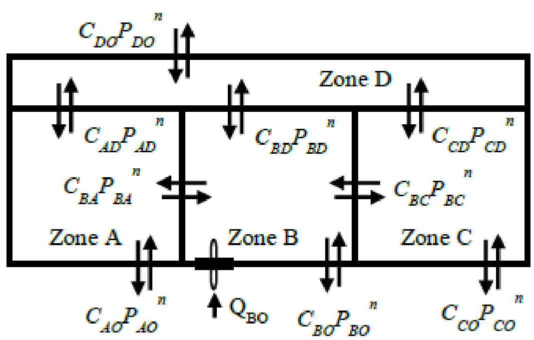


Figure 1: Scheme of a guarded test method on a multi-zone building.

The present paper deals with multi-zonal techniques applied to a large non-residential building. The case study and measurements techniques are exposed in section 2. The main results are presented and discussed in section 3, and section 4 gives complementary analyses.

2 METHODE

The case study is a building of 32 000 m^3, made of offices, classrooms and four large halls devoted to research (Figure 2). For offices and classrooms, an airtightness level n_{50} lower than 1.47 h^{-1} has to be achieved. For the halls however, it should be lower than 2.89 h^{-1}. Consequently, both part had to be measured separately. In addition, the four halls could not be measured simultaneously as they were not contiguous, except for hall C.1 and C.2. Thereafter, if the interconnecting door is opened, the addition of the two halls will be called Hall C.

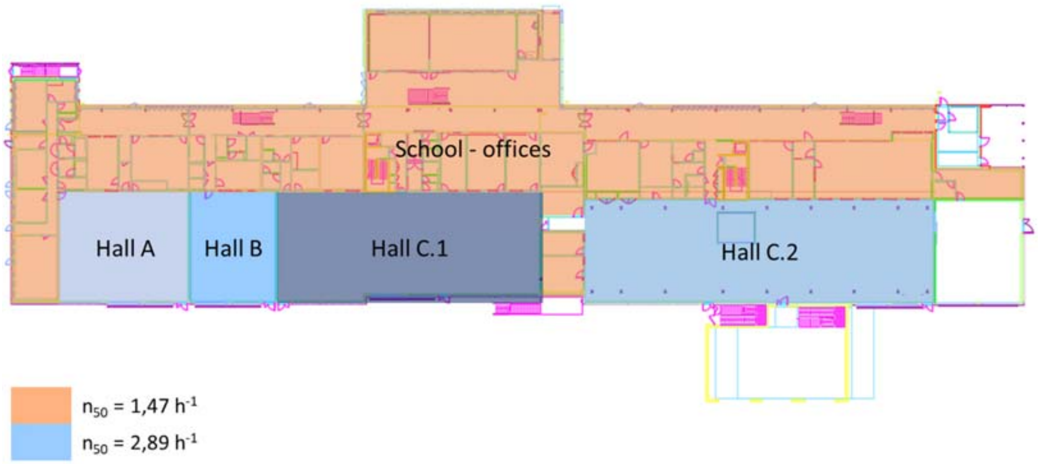


Figure 2: Building plan of the case study

A first step consisted in assessing inter-zonal airflows. To do so, each zone of the building was isolated from the other ones, on an airflow point of view.
Second, the building airtightness was measured according to ISO 9972 and using the following protocol for the halls:

1. The halls were measured separately, with no action taken for the adjacent zones;
2. Each hall was measured while the adjacent halls were simultaneously depressurized;
3. The four halls were measured simultaneously, with depressurized adjacent offices and classrooms.

Concerning the offices and classrooms, the tests were performed twice, with and without depressurizing the adjacent halls. Table 3 summarizes the notations used for the airtightness tests results (q_{50} values).
It was assumed that airflows were not depending on the direction, which means there was no valve effect. Inter-zonal airflows are evaluated by calculation, assuming that the pressures in adjacent zones, that were not depressurized, were the same as outdoor pressure, ie depressurization of one zone did not disturb the pressure in adjacent zones. Notations used for calculated q_{50} values and equations are given in Table 4. Figure 3 illustrates all calculated airflows.

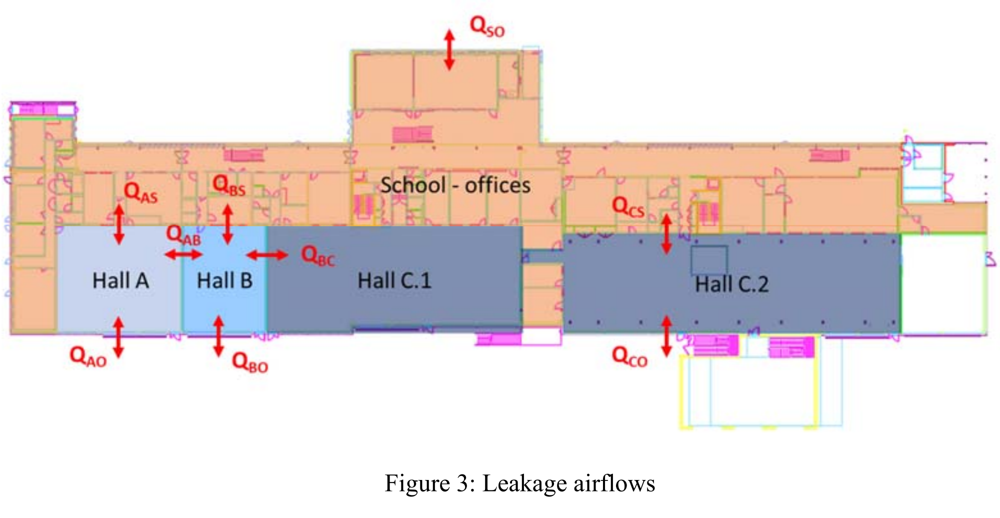


Figure 3: Leakage airflows

Table 3: Airtightness tests notations

Measurement	q_{50} notation	Equation
Hall A alone	Q_1	$Q_1 = Q_{AO} + Q_{AS} + Q_{AB}$
Hall A, Hall B depressurized	Q_2	$Q_2 = Q_{AO} + Q_{AS}$
Hall A, guarded test method	Q_3	**$Q_3 = Q_{AO}$**
Hall B alone	Q_4	$Q_4 = Q_{BO} + Q_{BS} + Q_{AB} + Q_{BC}$
Hall B, Hall A and Hall C depressurized	Q_5	$Q_5 = Q_{BO} + Q_{BS}$
Hall B, guarded test method	Q_6	**$Q_6 = Q_{BO}$**
Hall C alone	Q_7	$Q_7 = Q_{CO} + Q_{CS} + Q_{BC}$
Hall C, Hall B depressurized	Q_8	$Q_8 = Q_{CO} + Q_{CS}$
Hall C, guarded test method	Q_9	**$Q_9 = Q_{CO}$**
School – offices alone	Q_{10}	$Q_{10} = Q_{SO} + Q_{AS} + Q_{BS} + Q_{CS}$
School – offices, guarded test method	Q_{11}	**$Q_{11} = Q_{SO}$**

Table 4: Inter-zonal airflows notations

Interzonal leakage	q_{50} notation	Equation
Between Hall A and Hall B	Q_{AB}	$Q_{AB} = Q_1 – Q_2$
Between Hall A and School - offices	Q_{AS}	$Q_{AS} = Q_2 – Q_3$
Between Hall B and Hall C	Q_{BC}	$Q_{BC} = Q_4 - Q_5 - Q_1 + Q_2$
Between Hall B and School - offices	Q_{BS}	$Q_{BS} = Q_5 – Q_6$
Between Hall C and School - offices	Q_{CS}	$Q_{CS} = Q_8 – Q_9$

3 MAIN RESULTS

3.1 Detection of leakage location

Each zone was depressurized successively. The main leaks between the depressurized zone and the outdoors (thereafter called "actual leakage") were manually detected near to:

- the external doorways;
- Roll up doors in the halls;
- Skylights and smoke removal systems in the halls, classrooms and offices;
- Intermittent air barriers;
- Expansion joints.

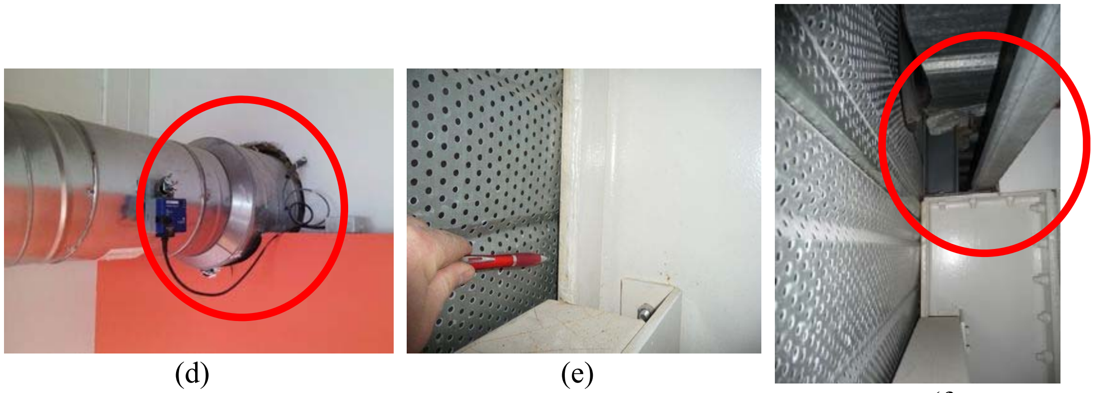
Many significant inter-zonal leaks were also detected (Figure 4) close to:

- The junction between the ceiling and separation walls (Figure 4a);
- Through the separation walls because of crossing beams, sheathes, and networks ducts (Figures 4b, 4c, 4d);
- Between the exterior wall and separation walls (Figures 4e and 4f),
- At interconnecting doorways where doorsills or seals were missing.

(a)

(b)

(c)



(d) (e) (f)

Figure 4: Main inter-zonal leaks detected by depressurization

3.2 Results from the air tightness tests and discussion

Table 5 presents the detailed results from all the experiments, where actual leakages of each zone are highlighted in bold. Measurements referred to as "alone" include all of the leakages (inter-zonal ones and actual ones), whereas airflows measured with the guarded test method are actual leakage.

The uncertainty on q_{50} was calculated in accordance with ISO 9972.

Table 5: Airtightness measurements

Measurement	q_{50} (m^3/h)	Uncertainty on q_{50} (%)	n_{50} (h^{-1})
Hall A alone	Q_1 = 12 006	5.6%	5.29
Hall A, Hall B pressurized	Q_2 = 9481	1.6%	4.17
Hall A, guarded test method	Q_3 = 7071	2.8%	**3.11**
Hall B alone	Q_4 = 11622	1.2%	7.73
Hall B, Hall A and Hall C pressurized	Q_5 = 7305	2.2%	4.86
Hall B, guarded test method	Q_6 = 6640	3.2%	**4.41**
Hall C alone	Q_7 = 47086	0.8%	4.47
Hall C, Hall B pressurized	Q_8 = 40492	1.5%	3.85
Hall C, guarded test method	Q_9 = 24412	2.8%	**2.32**
School – offices alone	Q_{10} = 56317	1.2%	3.44
School – offices, guarded test method	Q_{11} = 31328	2.6%	**1.91**

The n_{50} value for "school-offices" was higher than the threshold (1.47 h^{-1}). On the other hand, satisfying results were obtained for the halls given that the mean value was 2.67 h^{-1}, yet the threshold was also higher (2.89 h^{-1}).

To go on further, the global inter-zonal airflow was calculated by subtracting the result from the guarded test to one of the zone alone. The results are presented in Table 6. Also the uncertainty was added using the principle of propagation of uncertainty (type B, uncorrelated variables).

Table 6: Calculation of global inter-zonal airflows, zone by zone

	Hall A	Hall B	Hall C	School-offices
Global inter-zonal airflow (m^3/h)	4935	4982	22674	24989
Uncertainty (%)	14%	5%	3%	4%
Inter-zonal airflow compared with actual leakage (%)	70%	75%	93%	80%

From these results, it can be concluded that inter-zonal airflows should not be neglected, neither for halls nor for school-offices. For this case study, the results obtained with the standard method highly overestimated the actual leakage. Therefore, it seems necessary to use a guarded test method instead, even if 8 blower door fans and a specific fan are required.

The inter-zonal airflows are presented in Table 7, and the uncertainty is calculated using the same principle as above. Significant differences were observed: uncertainties lower than 10% were obtained for Q_{AS} and Q_{CS}, whereas it was significantly higher for other inter-zonal airflows, up to 40%. These latest are significant, as only 20% were obtained for a “two blower doors method” in (Hult & Sherman, 2014), which can be taken as a reference.

Table 7: Estimation of inter-zonal airflows

Inter-zonal leakage	q_{50} (m^3/h)	Uncertainty in q_{50} (%)
Between Hall A and Hall B	Q_{AB} = 2525	27%
Between Hall A and School - offices	Q_{AS} = 2410	10%
Between Hall B and Hall C	Q_{BC} = 1792	40%
Between Hall B and School - offices	Q_{BS} = 665	40%
Between Hall C and School - offices	Q_{CS} = 16080	6%

To go more into the details, each inter-zonal airflow is compared against actual leakage of the zones (see Table 8). In Hall A, inter-zonal airflows came as much from Hall B as from adjacent classrooms and offices. In Hall B, the majority of inter-zonal airflows came from adjacent halls, contrary to Hall C, where main inter-zonal airflows came from classrooms and offices.

The airflow between Hall C and offices was, respectively, two thirds and one-half of the actual leakage of these zones. This was a problem, because delivery trucks came in Hall C, and exhaust gas could influence indoor air quality in classrooms and offices, depending on the airflow direction.

Airflows between the halls did not seem to be problematic, but an airflow between a hall and a classroom or an office could create an energy loss. Indeed, the indoor temperature in the halls was lower than in the classrooms and offices.

Table 8: Inter-zonal airflows, compared with actual leakage, zone by zone

	Q_{AO}	Q_{BO}	Q_{CO}	Q_{SO}
Q_{AB}	36%	38%		
Q_{AS}	34%			8%
Q_{BC}		27%	7%	
Q_{BS}		10%		2%
Q_{CS}			66%	51%
Total	70%	75%	73%	61%

The inter-zonal airflows were successfully estimated with the methodology presented in this paper. However, some limits were also exhibited. First, the sum of the calculated inter-zonal airflows did not fit exactly to the measured ones, given in Table 6. Moreover, different equations can be used to calculate the airflow rate, which may lead to significant differences or even absurd (negative) values. Finally, high uncertainties were obtained indicating that the results should be considered with caution.

4 ADDITIONAL RESULTS

4.1 Inter-zonal airflow between Hall C.1 and Hall C.2

The inter-zonal airflow between halls C.1 and C.2 is calculated by opening and closing the interconnecting door. Table 9 and Table 10 give respectively measurement results and calculated inter-zonal airflows, by using the same method as above.

Table 9: Measurement results of halls C.1 and C.2

Measurement	q50 notation	Equation	Result (m^3/h)	Uncertainty (%)
Hall C.1 alone	Q_{12}	$Q_{12} = Q_{C.1-O}+Q_{C.1-E}+Q_{C.1-B}+Q_{C.1-C.2}$	23199	1.1%
Hall C.1, hall C.2 depressurized	Q_{13}	$Q_{13}= Q_{C.1-O}+Q_{C.1-E}+ Q_{C.1-B}$	21724	1.5%
Hall C.2 alone	Q_{14}	$Q_{14} = Q_{C.2-O}+Q_{C.2-E}+ Q_{C.2-C1}$	26789	0.9%
Hall C.2, hall C.1 depressurized	Q_{15}	$Q_{15} = Q_{C.2-O}+Q_{C.2-E}$	25362	0.6%

Table 10: Airflow between halls C.1 and C.2, calculated by two means

Inter-zonal airflow	q50 notation	Equation	Result (m^3/h)
From hall C.2 to hall C.1	$Q_{C.1-C.2}$	$Q_{C.1-C.2} = Q_{12}-Q_{13}$	1475
From hall C.1 to all C.1	$Q_{C.2-C.1}$	$Q_{C.2-C.1}= Q_{14} - Q_{15}$	1427

The airflow between the two halls is calculated for the two directions (from Hall C.1 to Hall C.2, and vice versa). Results match very well (within 3%), meaning that there is no valve effect, and that calculation method is accurate enough in this case.

4.2 Additional measurement in Hall A

A fourth measurement is realized in Hall A, while the doors on Hall B were maintained opened during the test. Therefore, the pressure in Hall B was effectively the one from the outdoor. The four q_{50} values are represented in Figure 5, along with the uncertainties, and $Q_{1'}$ stands for the result obtained with this latest test.

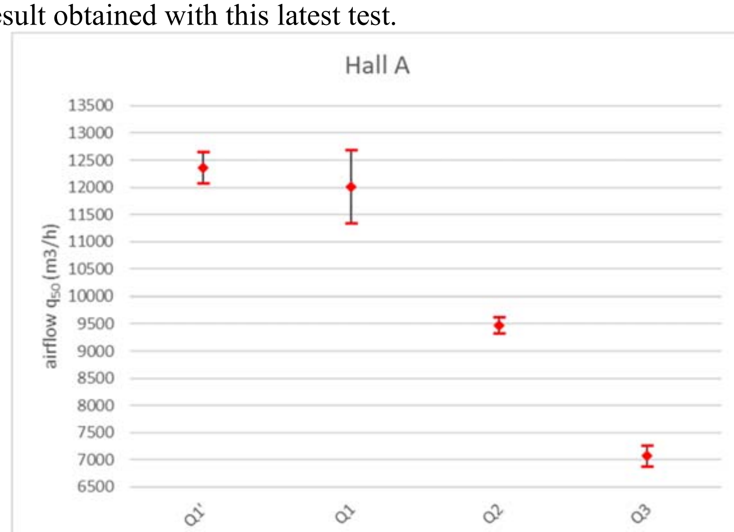


Figure 5: Four measurement results in Hall A

$Q_{1'}$ is higher than Q_1. However, $Q_{1'}$ confidence interval is fully enclosed in Q_1 interval, and the difference between $Q_{1'}$ and Q_1 (360 m^3/h) is shorter than the width of confidence intervals of $Q_{1'}$ and Q_1 (respectively, 574 m^3/h and 1349 m^3/h). Therefore, it can be concluded that the influence on the result of Hall A sounds negligible, compared with the high influence of depressurization of adjacent zones (Q_2 and Q_3).

In this case, it is acceptable to assume that unpressurized Hall B was at outdoor pressure, in order to calculate inter-zonal airflow rate, because Hall B was sufficiently large and not airtight. However we induced by this way an error on Q_1 value, and hence on Q_{AB} value.

4.3 Hall B: air flow rate at 4 Pa pressure difference

As the French thermal regulation considers that the air leakages are occurring under a 4 Pa pressure difference, this was also studied in the present paper. Figure 6 shows the air leakage graphs of the three measurements in Hall B.

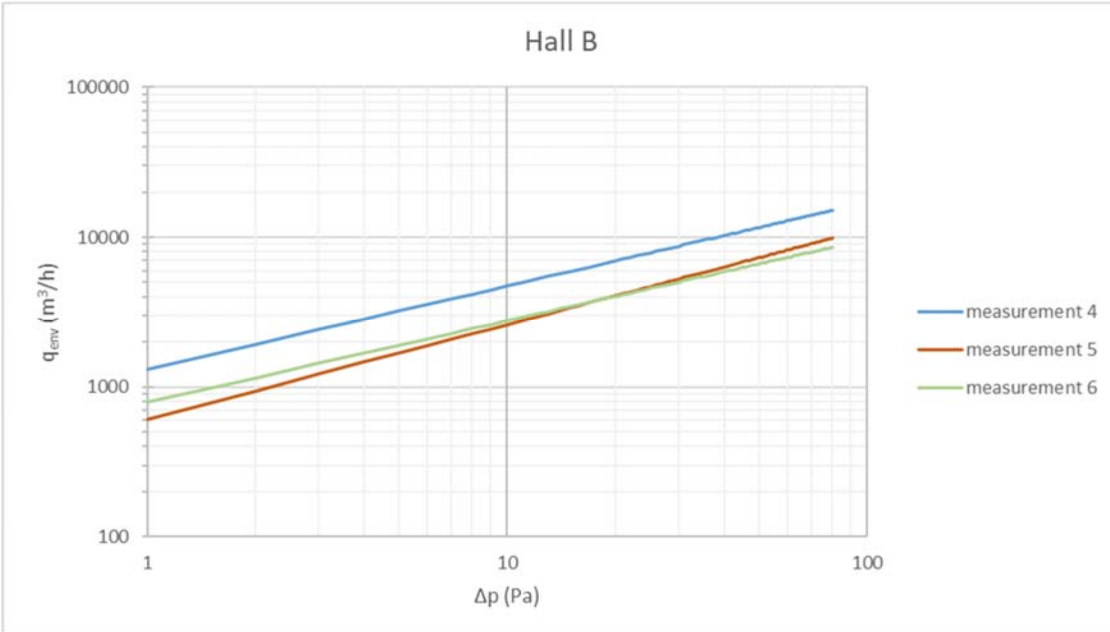


Figure 6: Air leakage graph of Hall B

It can be observed that the curves do not remain parallel. Indeed the ones obtained from measurements no. 5 and 6 are crossing at approximately 20 Pa. This is because the airflow exponents n are quite different (respectively, 0.637 and 0.543). As explained in (Sherman & Rengie, 2004), this exponent is representative of the nature of the leakages: the "actual leakage" (measurement 6) is quite like an orifice, whereas inter-zonal leakages between Hall B and offices and classrooms were longer.
However, these results at 4 Pa are absurd: the airflow rate obtained with the guarded test method should have been lower than the one obtained when the leakages between Hall B and classrooms were included. This inconsistency was not observed in the other zones.

5 CONCLUSION

The airtightness of a large multi-zone building was measured according to a classic multi-zonal technique, then according to a guarded test method. The results showed that inter-zonal airflows were non-negligible, and had a significant influence on the measured airtightness: the n_{50} value was overestimated from about 70% to 100%. On average, a higher difference (+92%) was obtained for the halls while it reached as much as 80% for offices and classrooms.
Thus, the guarded test method is much more accurate, yet it requires a specific equipment; in our case, a specific fan and 8 blower door fans. This high strain encourages using a classic multi-zonal technique then subtracting inter-zonal airflows. These ones were calculated for each separating wall in this case study, assuming:

(1) That depressurization of one zone did not disturb the pressure in adjacent zones. This hypothesis was found to be acceptable in one zone, but it may induce an error, particularly in little or airtight adjacent zones. The influence of this assumption should be evaluated for other cases, by means of simulation for example.
(2) That inter-zonal airflow rates were the same in the two directions, which means there was no valve effect. This assumption was checked for one separating wall.
(3) That the guarded test method did not change the nature of the leakages, so that it remains valid whatever the pressure difference. Yet this hypothesis was not verified for one hall, which prevented from working at low pressure differences.

This method gave some consistent results, and allowed to point high inter-zonal airflow rates, with their potential consequences: energy losses and a negative influence on interior air quality. But high uncertainties and inconsistent results harden the analysis.
For these reasons, it is advised to use a guarded test method when measuring a large multi-zone building, especially when airtightness is measured for compliance with a specification of a building code or standard. If a classic multi-zonal technique is used however, inter-zonal airflows should be calculated and subtracted from the measurement result. In order to reduce uncertainties, the method to evaluate inter-zonal airflows should take account of pressure in adjacent zones. Despite of some of the considerations in the French regulation, a pressure difference of 50Pa is preferable to lower values.

6 ACKNOWLEDGEMENTS

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