INTERLABORATORY TESTS FOR THE DETERMINATION OF REPEATABILITY AND REPRODUCIBILITY OF BUILDINGS AIRTIGHTNESS MEASUREMENTS

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ABSTRACT

The issue of the uncertainty of building airtightness measurements has built up a greater importance since this topic was introduced in many regulations regarding the energy performance of buildings. Different studies have contributed to the evaluation of the uncertainty but the question is still incompletely solved in practice.

To contribute to the determination of the repeatability and reproducibility of these measurements in practice, the Belgian Building Research Institute organized interlaboratory tests with 10 other laboratories.

This paper presents the details of the study together with the repeatability and reproducibility standard deviation calculated at different pressure differences. The issue of unweighted vs. weighted least square regression is also discussed.

The reproducibility standard deviation calculated at 50 Pa was 2.4%. It was below 3% between 30 and 100 Pa but was noticeably higher at 4 and 10 Pa. However the application of a weighted least square regression showed a possibility to reduce the standard deviation of the results calculated at low pressure difference.

KEYWORDS

Airtightness, blower door, uncertainty, round robin

INTRODUCTION

In European countries, increasing importance has been given to airtightness of buildings since the first publication of the directive on the energy performance of buildings in 2002. In some countries there are even requirements or considerable financial incentives linked with the airtightness level. It is therefore more and more important to pay attention to the uncertainty of airtightness measurements.

The issue of uncertainty of airtightness measurements has already been dealt with in various publications (e.g. [8]) but is still incompletely solved in practice. This is also a point of discussion in the current revision of the related ISO standard [6].

Beside the traditional mathematical analysis of the problem, a contribution to a better knowledge of uncertainty of airtightness measurements can be made through the determination of their repeatability and reproducibility in practice. Such study was organized during the summer 2011 by the Belgian Building Research Institute (BBRI) in collaboration with 10 other laboratories.

This paper presents the details of the study together with the repeatability and reproducibility standard deviation calculated at different pressure differences. The issue of unweighted vs. weighted least square regression is also discussed.

OPERATING MODE

According to ISO 5725-1 [3], repeatability is the precision under conditions where independent test results are obtained with the same method on identical test items in the same laboratory by the same operator using the same equipment within short intervals of time. While reproducibility is the precision under conditions where test results are obtained with the same method on identical test items in different laboratories with different operators using different equipment. Thus repeatability and reproducibility are the two extremes of precision, the first describing the minimum and the second the maximum variability in results.

Taking into account the time required for a full measurement (about 2 hours), the limited financial resources and the availability of the test building, the BBRI made 10 replicate tests (depressurisation and pressurisation) under repeatability conditions and 10 other laboratories made 1 test each under reproducibility conditions. One of them however made 2 replicate tests on one’s own initiative. All tests took place between 14/06/2011 and 15/07/2011. The preparation of the building was the same for all tests.

During the tests, external temperature and wind speed on the measurement site were monitored by the BBRI. The maximum wind speed varied from 1.3 to 5.1 m/s and the mean temperature varied from 11.7 to 28.1°C with a maximum of 4.2°C variation during a test.

The tests were made according to EN 13829:2001 (ISO9972:1996 modified) [2]. The measurements were taken in the range of 10 to 100 Pa indoor-outdoor pressure difference in increments of about 10 Pa.

10 laboratories used a Minneapolis Blower Door Model 4 while only one laboratory used a Retotec 2200 blower door. All of them used electronic manometers connected to dedicated software that automatically manages the tests and stores the data (Tectite Express plus Blower Door Excel sheet or Fan Testic). One laboratory however used semi-automatic software (Teclog plus own Excel sheet).

THE BUILDING

Description of the building

The building subject to the tests is located in the premises of the BBRI in Limelette, Belgium (Building X2). It is an unoccupied single family house built around 1980 and fully dedicated to research work.

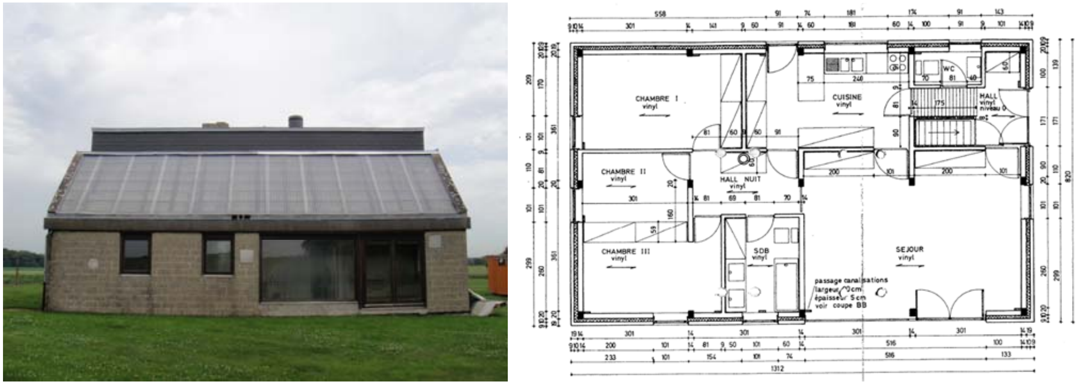

Figure 1: Southern façade and plan of the building subject to the tests

Only the ground floor was subject to the test. The basement and the attic were excluded. The internal volume of the ground floor is equal to 221 m³, while the net floor area is equal to 92 m². The building is equipped with electrical convection heaters and a fan assisted balanced ventilation system. It is also equipped with four externally mounted air transfer devices.

REPETABILITY

Results of the measurements

The 10 tests made by the BBRI under repeatability conditions resulted in air leakage rate at 50 Pa ranging from 699 to 738 m³/h for depressurisation and from 732 to 754 m³/h for pressurisation. The average value between depressurisation and pressurisation ranged from 715 to 744 m³/h. (Figure 2 - Table 1)

According to EN 13829:2001 [2], the air flow coefficient C_L and the air flow exponent n were determined using an <u>unweighted</u> least square regression. The air leakage rate $q_{\Delta pr}$ at a specified reference pressure difference was calculated using equation (1)

$$q_{\Delta pr} = C_L\,(\Delta p_r)^n \qquad (1)$$

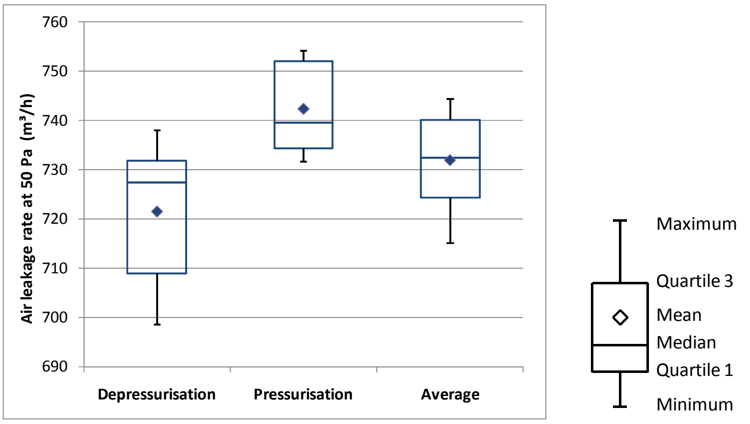

Figure 2: Variation of the air leakage rate at 50 Pa under repeatability conditions

	Depressurisation			Pressurisation			Average
	C_L	n	q_{50}	C_L	n	q_{50}	q_{50}
Replicate	**m³/(h.Pa^n)**	**-**	**m³/h**	**m³/(h.Pa^n)**	**-**	**m³/h**	**m³/h**
1	63.76	0.6155	708.5	79.43	0.5753	754.1	731.3
2	60.93	0.6277	710.2	79.31	0.5687	733.6	721.9
3	74.25	0.5865	736.4	70.58	0.6049	752.4	744.4
4	72.30	0.5918	732.1	74.87	0.5901	753.1	742.6
5	72.86	0.5890	729.8	66.80	0.6125	733.4	731.6
6	68.58	0.6028	724.9	78.42	0.5741	741.1	733.0
7	77.13	0.5749	731.0	83.97	0.5599	750.6	740.8
8	73.22	0.5906	738.0	73.54	0.5895	737.9	738.0
9	70.75	0.5880	705.9	72.00	0.5943	736.3	721.1
10	66.95	0.5995	698.6	67.29	0.6100	731.6	715.1

Table 1: Results of the 10 tests made under repeatability conditions

Variability of the results

The average air leakage rate had a repeatability standard deviation ranging from 3.5% at 4 Pa to 1.2% at 100 Pa through 1.4% at 50 Pa (Figure 3 - Table 2).

The variability of the depressurisation and pressurisation tests taken alone was slightly higher:

- From 5.2% at 4 Pa to 1.7% at 100 Pa through 2.0% at 50 Pa for depressurisation;
- From 5.1% at 4 Pa to 1.4% at 100 Pa through 1.2% at 50 Pa for pressurisation.

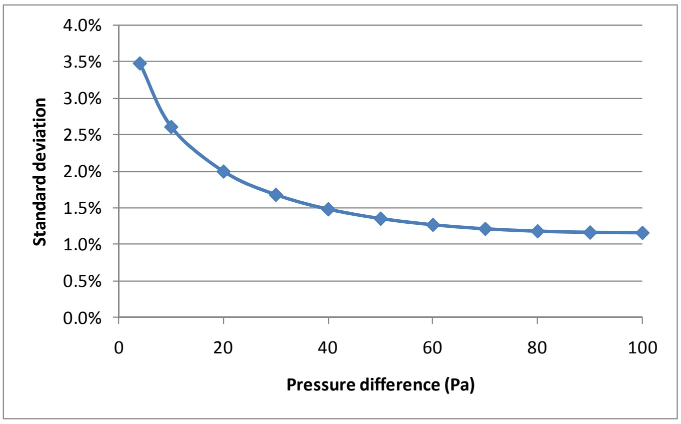

Figure 3 : Repeatability standard deviation s_r of the average air leakage rate

Δp (Pa)	4	10	20	30	40	50	60	70	80	90	100
	q_4	q_{10}	q_{20}	q_{30}	q_{40}	q_{50}	q_{60}	q_{70}	q_{80}	q_{90}	q_{100}
Replicate						**(m³/h)**					
1	163.0	280.9	424.1	539.7	640.3	731.2	815.0	893.2	967.1	1037.3	1104.4
2	160.0	276.2	417.6	532.0	631.8	721.9	805.0	882.7	956.1	1025.9	1092.7
3	165.3	285.4	431.2	549.1	651.7	744.4	829.8	909.6	984.9	1056.5	1125.0
4	166.9	286.9	432.1	549.1	650.9	742.6	827.1	906.0	980.4	1051.0	1118.6
5	160.5	278.3	421.9	538.3	639.8	731.6	816.3	895.5	970.3	1041.5	1109.6
6	166.0	284.5	427.6	542.7	642.8	733.0	816.0	893.4	966.5	1035.8	1102.1
7	176.8	297.3	440.5	554.4	652.7	740.8	821.5	896.6	967.2	1034.0	1097.7
8	166.3	285.5	429.8	545.9	647.0	738.0	821.8	900.1	973.9	1043.9	1110.9
9	162.0	278.4	419.5	533.1	631.9	721.1	803.1	879.8	952.0	1020.7	1086.3
10	155.2	270.2	410.9	525.1	624.9	715.2	798.6	876.6	950.4	1020.5	1087.7
Mean	164.2	282.3	425.5	540.9	641.4	732.0	815.4	893.4	966.9	1036.7	1103.5
Repeatability	5.7	7.4	8.5	9.1	9.5	9.9	10.4	10.9	11.4	12.1	12.8
standard deviation s_r	3.5%	2.6%	2.0%	1.7%	1.5%	1.4%	1.3%	1.2%	1.2%	1.2%	1.2%
Repeatability	16.0	20.6	23.8	25.5	26.7	27.8	29.0	30.4	32.0	33.9	35.9
limit r[1]	9.7%	7.3%	5.6%	4.7%	4.2%	3.8%	3.6%	3.4%	3.3%	3.3%	3.3%

Table 2: Average air leakage rate for the 10 tests made under repeatability conditions

[1] Repeatability limit (r): The value less than or equal to which the absolute difference between two test results obtained under repeatability conditions may be expected to be with a probability of 95 %.
$r = 2.8 \cdot s_r$

The observed higher repeatability standard deviation s_r for low pressure differences can be explained by the combination of two phenomenons:

1. Considering all measurements, the values at low pressure difference were more variable (in relative terms) than those at high pressure difference;
2. For each regression, the standard deviation of the logarithm (ln) of the air flow rate around the regression line grows as one goes away from the mean value of the logarithm of the pressure differences achieved during the measurement (mean value was 45.3 Pa).

Note: The estimate of the standard deviation of y (y = ln(q)) around the regression line at the value x (x = ln(Δp)) is given by [2] :

$$s_y(x) = s_n \sqrt{\frac{N-1}{N} s_x^2 + (x - \bar{x})^2} \quad (2)$$

s_n : standard deviation of air flow exponent n
N: total number of test readings
s_x : standard deviation of x
$\bar{x}$: mean value of x

For low pressure differences, the combination of higher variability with the distance from the mean pressure led to high standard deviation while for high pressure differences, the lower variability tended to counterbalance the effect of the distance from the mean pressure.

Supplementary tests

On the basis of the observations by Murphy et al. [7] stating that variability of the results correlates with the air leakage rate, 2 times 10 supplementary tests with higher and lower air leakage rate were carried out by BBRI. The same building with a slightly different preparation was used for these tests.

Note: There was a fortuitous change in the preparation of the building between the two days of test with lower leakage rate so the data were split into two series.

The average air leakage rate had a repeatability standard deviation ranging:

- From 3.0% at 4 Pa to 0.4% at 100 Pa for higher leakage (mean q_{50} = 1523 m³/h);
- From 2.7% at 4 Pa to 0.6% at 100 Pa for lower leakage (mean q_{50} = 284 m³/h);
- From 1.7% at 4 Pa to 0.6% at 100 Pa for lower leakage (mean q_{50} = 297 m³/h).

These supplementary tests are probably not extensive enough to come to any conclusion about the correlation between the variability of the results and the air leakage rate. However they could not strengthen the earlier observations.

Weighted vs unweighted regression

According to EN 13829:2001 (ISO9972:1996 modified) [2], an unweighted least square regression was used for the calculation of the air flow characteristics. However experts in the field seem to be inclined to favour a weighted regression. So the air flow characteristics of the original tests were calculated again with the weighted regression of CAN CGSB-149.10-M86 [1] in order to see the difference (In this standard, ln Δp_i and ln q_i are weighted with q_i^2)

Compared to the unweighted regression (Table 2 and Figure 3), the weighted regression (Table 3 and Figure 4) showed lower standard deviations for the results at low pressure difference (4 to 30 Pa) while there was no noticeable difference at higher pressure difference

(40 to 100 Pa). As far as the mean air leakage rates are concerned, there was no noticeable difference whatever the pressure difference.

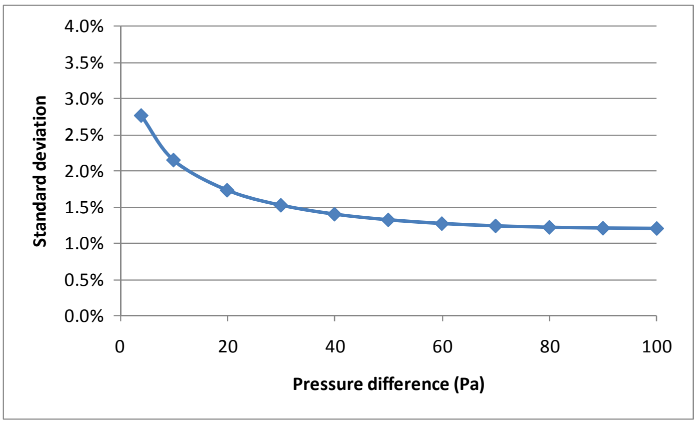

Figure 4: Repeatability standard deviation s_r of the average air leakage rate (original tests - weighted regression)

Δp (Pa)	4	10	20	30	40	50	60	70	80	90	100
	q_4	q_{10}	q_{20}	q_{30}	q_{40}	q_{50}	q_{60}	q_{70}	q_{80}	q_{90}	q_{100}
Replicate						**(m³/h)**					
1	165.3	283.5	426.4	541.5	641.6	731.9	815.0	892.6	965.7	1035.3	1101.7
2	162.8	279.5	420.8	534.6	633.6	722.8	804.9	881.6	954.0	1022.7	1088.3
3	164.7	284.7	430.6	548.6	651.4	744.2	829.8	909.8	985.3	1057.1	1125.7
4	168.4	288.6	433.7	550.3	651.7	743.0	827.0	905.4	979.3	1049.4	1116.5
5	161.1	279.0	422.6	538.9	640.2	731.8	816.3	895.3	969.9	1040.8	1108.6
6	164.6	283.0	426.3	541.8	642.3	732.9	816.4	894.3	967.8	1037.6	1104.3
7	173.9	294.1	437.7	552.2	651.3	740.3	821.9	897.8	969.3	1037.1	1101.7
8	167.7	287.1	431.2	547.0	647.6	738.2	821.6	899.4	972.7	1042.3	1108.8
9	162.0	278.5	419.5	533.1	632.0	721.1	803.1	879.8	952.0	1020.7	1086.3
10	157.2	272.4	412.9	526.7	625.9	715.6	798.3	875.6	948.7	1018.2	1084.6
Mean	164.8	283.0	426.2	541.5	641.8	732.2	815.4	893.2	966.5	1036.1	1102.6
Repeatability	4.6	6.1	7.4	8.3	9.0	9.7	10.4	11.1	11.8	12.6	13.3
standard deviation s_r	2.8%	2.2%	1.7%	1.5%	1.4%	1.3%	1.3%	1.2%	1.2%	1.2%	1.2%
Repeatability	12.8	17.1	20.7	23.2	25.3	27.2	29.2	31.1	33.1	35.2	37.3
limit r	7.8%	6.0%	4.9%	4.3%	3.9%	3.7%	3.6%	3.5%	3.4%	3.4%	3.4%

Table 3: Average air leakage rate for the 10 original replicates of the test (weighted regression)

REPRODUCTIBILITY

Results of the measurements

The tests made by the BBRI and the 10 external laboratories under reproducibility conditions resulted in air leakage rate at 50 Pa ranging from 699 to 772 m³/h for depressurisation and from 704 to 793 m³/h for pressurisation. The average value between depressurisation and pressurisation ranged from 713 to 772 m³/h. (Figure 5).

Detailed information about the measurements (mean values) is given in Table 4.

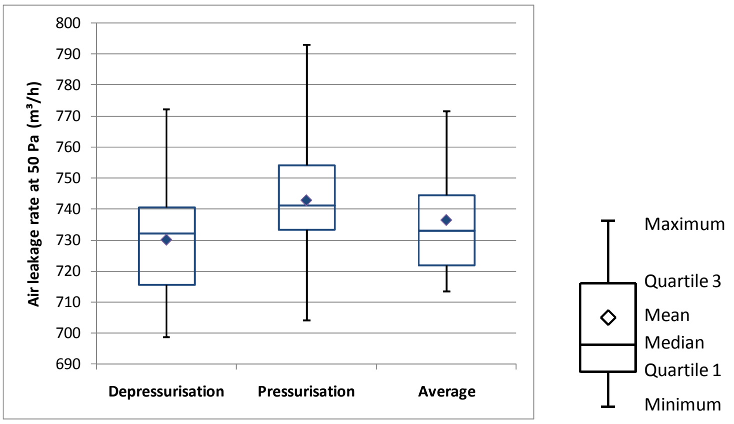

Figure 5: Variation of the air leakage rate at 50 Pa under reproducibility conditions

	Depressurisation			**Pressurisation**			**Average**
	C_L	**n**	**q_{50}**	**C_L**	**n**	**q_{50}**	**q_{50}**
Laboratory	**$m^3/(h.Pa^n)$**	**-**	**m^3/h**	**$m^3/(h.Pa^n)$**	**-**	**m^3/h**	**m^3/h**
1	74.94	0.5858	741.1	69.82	0.5926	709.2	725.2
2	70.21	0.6023	740.7	52.32	0.6717	724.1	732.4
3	92.37	0.5233	715.7	59.02	0.6362	711.1	713.4
4	70.07	0.5961	721.5	74.62	0.5873	742.4	732.0
5	88.70	0.5458	750.3	80.84	0.5715	756.1	753.2
6	72.97	0.5922	740.2	76.17	0.5894	764.2	752.1
7	76.86	0.5787	739.5	42.32	0.7187	704.0	721.8
8	64.60	0.6243	742.9	77.48	0.5945	792.8	767.9
9	77.40	0.5879	772.1	75.60	0.5936	771.0	771.5
10	63.46	0.6240	728.9	77.31	0.5799	747.2	738.1
11	66.73	0.6038	708.2	76.53	0.5777	733.3	720.7

Table 4: Results of the airtightness tests made by 11 different laboratories under reproducibility conditions (mean values for the 2 laboratories that made more than 1 test)

Variability of the results

The average air leakage rate had a reproducibility standard deviation ranging from 5.9% at 4 Pa to 2.6% at 100 Pa through 2.4% at 50 Pa (Figure 6 - Table 5).

The variability of the depressurisation and pressurisation tests taken alone was slightly higher at 50 and 100 Pa and noticeably higher at 4 Pa:

- From 7.9% at 4 Pa to 2.9% at 100 Pa through 2.5% at 50 Pa for depressurisation;
- From 11.1% at 4 Pa to 3.2% at 100 Pa through 2.9% at 50 Pa for pressurisation.

At 50 Pa the reproducibility limit was 6.7% which means that the absolute difference between two test results obtained under reproducibility conditions may be expected to be less or equal to 6.7% with a probability of 95 %.

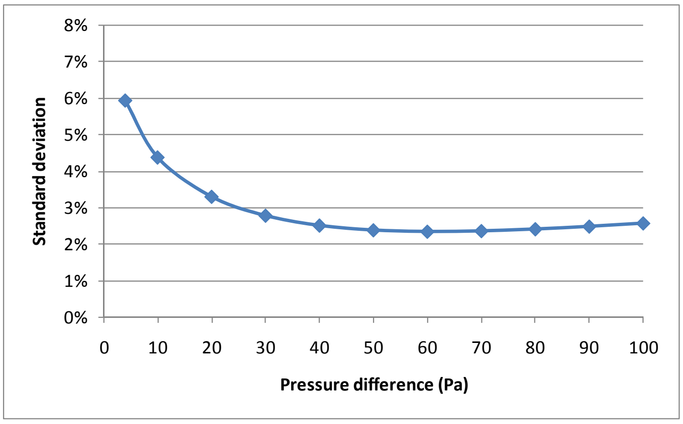

Figure 6: Reproducibility standard deviation s_R of the average air leakage rate

Δp (Pa)	4	10	20	30	40	50	60	70	80	90	100
	q_4	q_{10}	q_{20}	q_{30}	q_{40}	q_{50}	q_{60}	q_{70}	q_{80}	q_{90}	q_{100}
Laboratory						**(m³/h)**					
1	163.8	281.0	422.7	536.8	635.9	725.2	807.5	884.2	956.6	1025.4	1091.0
2	147.3	263.3	409.0	529.2	635.5	732.5	822.7	907.5	988.1	1065.1	1139.1
3	166.7	281.8	419.9	530.7	626.8	713.3	792.8	867.0	936.9	1003.3	1066.7
4	164.3	282.5	425.7	541.1	641.5	732.0	815.3	893.2	966.6	1036.4	1103.0
5	183.8	306.5	451.4	566.2	664.9	753.2	834.0	909.0	979.4	1046.0	1109.5
6	169.1	290.6	437.7	556.2	659.2	752.2	837.7	917.6	992.9	1064.4	1132.8
7	143.0	256.4	399.8	518.9	624.8	721.7	812.2	897.5	978.8	1056.6	1131.5
8	165.1	288.3	439.6	562.6	670.3	767.9	858.0	942.5	1022.3	1098.4	1171.2
9	173.5	298.1	449.0	570.5	676.2	771.4	859.2	941.1	1018.3	1091.7	1161.8
10	161.7	280.4	425.4	542.8	645.3	738.1	823.6	903.7	979.3	1051.3	1120.1
11	162.3	278.7	419.6	533.1	631.8	720.8	802.7	879.2	951.4	1019.9	1085.4
Mean	164.2	282.9	427.1	543.5	645.0	736.6	821.0	899.9	974.4	1045.3	1113.0
Reproducibility	9.75	12.39	14.12	15.16	16.25	17.62	19.31	21.32	23.58	26.06	28.70
standard deviation s_R	5.9%	4.4%	3.3%	2.8%	2.5%	2.4%	2.4%	2.4%	2.4%	2.5%	2.6%
Reproducibility	27.29	34.70	39.53	42.44	45.50	49.33	54.08	59.69	66.03	72.96	80.36
limit R[1]	16.6%	12.3%	9.3%	7.8%	7.1%	6.7%	6.6%	6.6%	6.8%	7.0%	7.2%

Table 5: Average air leakage rate for the tests made by 11 different laboratories under reproducibility conditions

DISCUSSION

The study showed that there can be a significant difference between the results in depressurisation and in pressurisation. It also showed that the uncertainty of the average value between depressurisation and pressurisation was globally lower than the uncertainty of both of them taken apart. So since natural conditions never lead to a fully pressurized or depressurized building, it seems preferable to favour tests in both modes.

Measurements taken in the range of 10 to 100 Pa showed relatively low reproducibility standard deviation (< 3%) for the results calculated at 30 to 100 Pa. The reproducibility standard deviation at 50 Pa was 2.4%. At lower pressure difference however, the standard

[1] Reproducibility limit (R): The value less than or equal to which the absolute difference between two test results obtained under reproducibility conditions may be expected to be with a probability of 95 %.
$R = 2.8 \cdot s_R$

deviation was larger. The standard test procedure from EN 13829 is therefore well suited for results calculated at 50 Pa like the well known n_{50} value but should be taken with greater care for results calculated at 4 or 10 Pa like the effective or equivalent leakage area for example.

The application of a weighted least square regression showed a possibility to reduce the standard deviation of the results calculated at low pressure difference. This option could therefore be evaluated for the revision of ISO 9972 [6].

For the tests, the mean air leakage rate at 50 Pa ranged from 284 m³/h to 1523 m³/h. This range matches with the airtightness of some new built single family dwellings in Belgium but other tests with higher air leakage rates should be done to cover a larger part of the building stock.

No correlation could be found between the variability of the results and the air leakage rate. The number of tests was however too low to come to a conclusion on that point. Extrapolation of the results of this study to higher air leakage rates should therefore be considered with care.

The tests of this study were made under favourable weather conditions in a low-rise building and with low temperature difference between inside and outside. It should be noticed that uncertainty of the results can increase with the wind, the height of the building and the temperature difference.

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