Non-intrusive experimental assessment of air renovations in buildings and comparison to tracer gas measurements

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ABSTRACT

The work reported in this paper extends previous work on the feasibility to characterise air leakage and mechanical ventilation avoiding intrusiveness of traditional measurement techniques. The feasibility to obtain the air renovation rate itself, as well as the possibilities to express it as function of other variables (such as wind speed, atmospheric pressure, etc.), are studied. Tracer gas measurements based on N_2O have been used as reference. Experimental relations between air renovations and wind speed, indoor-outdoor air temperature difference, and atmospheric pressure have been analysed. The reliability of an alternative method based on the evolution of metabolic CO_2 using wall mounted sensors of CO_2 concentration is evaluated. Two full size buildings are considered as case studies. First a very simple single zone building, without mechanical ventilation, is considered. Afterwards, rooms in an office building have been studied with and without mechanical ventilation. One month test campaigns have been used for the reference test campaigns based on tracer gas measurements using N_2O, in both buildings. Longer periods are available for the analysis based on CO_2 concentration.

The following conclusions are extracted from the tests when mechanical ventilation is not active: Significant correlation between air renovation rate and wind speed has been observed in both buildings. The agreement between the values obtained using N_2O and the evolution of metabolic CO_2 increases when the starting value of CO_2 concentration increases.

The following conclusions are extracted from the tests when mechanical ventilation is active: Large variations have been observed among the different values obtained along the test campaign using N_2O tracer gas. However these values don't show any correlation with any of the considered boundary conditions. Consequently the observed spread has been used to estimate an uncertainty of the air renovations rate. The measurements based on CO_2 concentrations don't show good agreement to the values obtained using N_2O tracer gas. This issue will be further investigated, but in principle it is attributed to the low level of CO_2 measured along the analysed test campaign when the mechanical ventilation is active. This explanation is in agreement with previous works carried out regarding the air renovation in the same building.

KEYWORDS

Building Energy, Building Envelope, Performance assessment, air renovation, non-intrusive measurements

1 INTRODUCTION

The building sector accounts for about 40% of total final energy use and has significant potential to save energy and reduce CO_2 emissions. A growing interest to promote energy efficiency in buildings has led to the progressive implementation of related regulations, highlighting the need to increase knowledge about energy performance of buildings and pushing research activities in this field. Currently, most compliance checks and labelling of the energy performances of buildings are based on theoretical calculations and design values. However, studies have shown that the performance of a building may deviate significantly from this theoretical performance as discussed in several published papers (de Wilde, 2014). The availability of reliable test procedures to assess the thermal performance of as built buildings would be very useful to overcome the problems brought by this performance gap. The actual energy consumption is one of the priority topics considered in the Strategic Plan of the EBC Programme of the IEA (Sawachi, 2013). The building envelope is one of the key elements influencing the energy behavior of buildings. Its energy performance assessment can be done by means of data analysis techniques requiring direct or indirect measurement of all the contributions to the energy balance of the room confined by the building envelope to be characterized (Jiménez et al, 2016). One of the contributions to this energy balance is which is due to the air renovation either by natural or mechanical ventilation.

There are several procedures for the experimental assessment the air renovation rate in rooms. Some of these procedures are based on pressurisation and others are based on tracer gas techniques (Sherman, 1989). These traditionally applied methods that could give precise results are complex, expensive and highly intrusive for the building users and inhabitants. The work reported in this paper is focused on the experimental assessment of the air renovation rate analysing the reliability of cheaper and more cost effective techniques regarding the traditional techniques based in tracer gas.

2 CASE STUDIES

Two full size extensively monitored buildings are considered as case studies. Both buildings are located at the Plataforma Solar de Almeria (PSA) in Tabernas (37.1ºN, 2.4ºW), Almería (Spain). They are in a rural area with semi-arid climate with large day-night temperature variations. These buildings are briefly described in sections 2.1 and 2.2 respectively.

2.1 Single-zone building. Natural ventilation

This building is a small workshop, 31.83 m^2 area (Figure 1a and b). It is available for test campaigns unoccupied and with low occupancy patterns. It was constructed in 2002. It is a single-zone area building and constructed in an open area free of other buildings and obstacles around that could shade it except for a twin building located 2 m from its east wall.

The building was designed to reduce energy demand in both winter and summer using the following passive techniques: South orientation, Fixed shading devices for solar control (that avoid solar gains in summer and maximise them in winter), Double-glazed windows, Windows diagonally placed in a north-south arrangement in order to produce natural ventilation, Building envelope including thermal mass, External insulation, High ceilings.

2.2 Office building prototype. Natural and mechanical ventilation

The so called C-DdI PSA is a one floor building with most the regularly occupied offices facing south (Figure 1c and d). Net floor area: 1007.40m^2. It was constructed in 2007 in the PSE-ARFRISOL project. It is a prototype of a new plant, built on one floor longitudinal plan.

A double-wing structure, installed on the roof all along the building main axis, protects the building from solar radiation. This structure also supports two different types of solar collectors. On the north-facing wing, uncovered collectors are operated as radiant coolers by night, while flat plate collectors on the south-facing wing supply hot water for the heating, cooling and DHW systems. The central part of this structure also includes small solar chimneys to promote night ventilation of the offices. An overhang protects south windows providing shade during the summertime and winter passive heating.

This building is in use, but it must be taken into account that the experiments used for this work were carried out when the considered room was positively empty: at lunch time and once finalised the working day (identified every day as test 1 and test 2 respectively).

(a) Single-zone building. View of the exterior

(b) Single-zone building. View of the interior

(c) Office building. View of the exterior

(d) Office building. Interior of one office

Figure 1: Buildings considered for the study

3 EXPERIMENT SET UP

A tracer gas device combined with a gas analyser has been used to carry out Decay experiments based on the evolution of N_2O in both buildings.

The two buildings are extensively monitored. The monitoring system records minutely read measurements of the following variables:

- N_2O concentration when the Decay experiments are being conducted.
- Indoor and outdoor air temperature, relative humidity, concentration of CO_2. Tow sensors are installed to measure this variable. An accurate and expensive sensor used as reference and a cheaper and less accurate sensor (Identified as $CO_{2\ ref}$ and CO_2 respectively in this document).
- Temperature of walls, floor and glass surfaces.
- Energy delivered by the heating system (radiant floor): water and air flows and inlet and outlet temperatures
- Electric consumption due to computers and lighting

- Whether doors and windows are closed or “not closed”.
- Ground temperature.
- Beam, diffuse, global horizontal, global vertical south and global vertical north Solar Irradiance.
- Longwave radiation.

4 METHODOLOGY

For both buildings, as well as natural and mechanical ventilation, tracer gas measurements based on N_2O have been used as reference. The air renovation rate has been obtained using the Decay method (Sherman, 1989). Experimental relations between the air renovation rate and the following variables have been analysed.

- Difference between indoor and outdoor air temperatures (T_i-T_e).
- Wind speed (W).
- Product of wind speed and difference between indoor and outdoor air temperatures (W(T_i-T_e)).
- Product of wind speed and difference between indoor and outdoor air temperatures (W^2(T_i-T_e)).
- Atmospheric pressure.

Additionally, the reliability of an alternative method based on the evolution of metabolic CO_2 using wall mounted sensors of CO_2 concentration is evaluated in a room of the office building. A reference value $CO_{2infinite}$ has been used, such that the variable used for the Decay method is CO_2-$CO_{2infinite}$. This value was obtained as the average of CO_2 concentration in a period when the room is positively non-occupied, stating when the Decay curve has reached its asymptotic value (9pm-7am). An error obtained as the deviation regarding the reference value (based on N_2O) has been represented as function of the maximum value of the CO_2 concentration at the beginning of the decay method curve.

5 RESULTS

5.1 Single-zone building. Natural ventilation

The results obtained for the single zone building are summarised in Table 1.

Table 1: Summary of calculations for natural ventilation and boundary conditions. Monozone building

Day	Test	n (N_2O) (ren/h)	r^2 (NO_2) (·)	Ti-Te (ºC)	W (m/s)	W(Ti-Te) [m/s][°C]	W^2(Ti-Te) [(m/s)^2][°C]	P_{atm} (mbar)
09/02/2016	**Test 2**	0.74	0.9756	-2.49	9.20	-21.88	-214.9	956
10/02/2016	**Test 2**	0.60	0.9125	-0.79	10.27	-9.58	-121.6	954
11/02/2016	**Test 2**	0.50	0.9708	0.28	9.27	2.66	25.8	951
12/02/2016	**Test 2**	0.97	0.9942	-0.61	11.55	-7.07	-87.0	951
15/02/2016	**Test 2**	0.22	0.9776	9.44	3.75	32.07	157.8	952
16/02/2016	**Test 2**	0.19	0.9874	12.07	2.45	25.39	78.9	960
17/02/2016	**Test 2**	0.31	0.9550	9.54	4.48	39.96	201.3	955
18/02/2016	**Test 2**	0.16	0.9965	9.57	3.04	29.71	107.1	955
19/02/2016	**Test 2**	0.22	0.9936	9.68	4.44	42.93	213.0	958
22/02/2016	**Test 2**	0.16	0.9666	6.58	2.84	18.40	78.8	958
23/02/2016	**Test 2**	0.17	0.9976	10.42	2.21	18.26	46.1	959
24/02/2016	**Test 2**	0.31	0.9935	6.30	4.73	26.75	131.4	952
25/02/2016	**Test 2**	0.22	0.9608	10.12	3.82	29.83	141.6	952

This table shows that the air renovation rate (n) presents a large variation. It is between 0.16 and 0.97 renov/hour. Its average is 0.37 renov/hour, and its standard deviation is 0.26 renov/hour. Figure 2 (a, c, e, g and i) shows that the n value has evident correlation with all the considered boundary variables except the atmospheric pressure (Figure 2). The most relevant correlation detected is regarding the wind speed (Figure 2c).

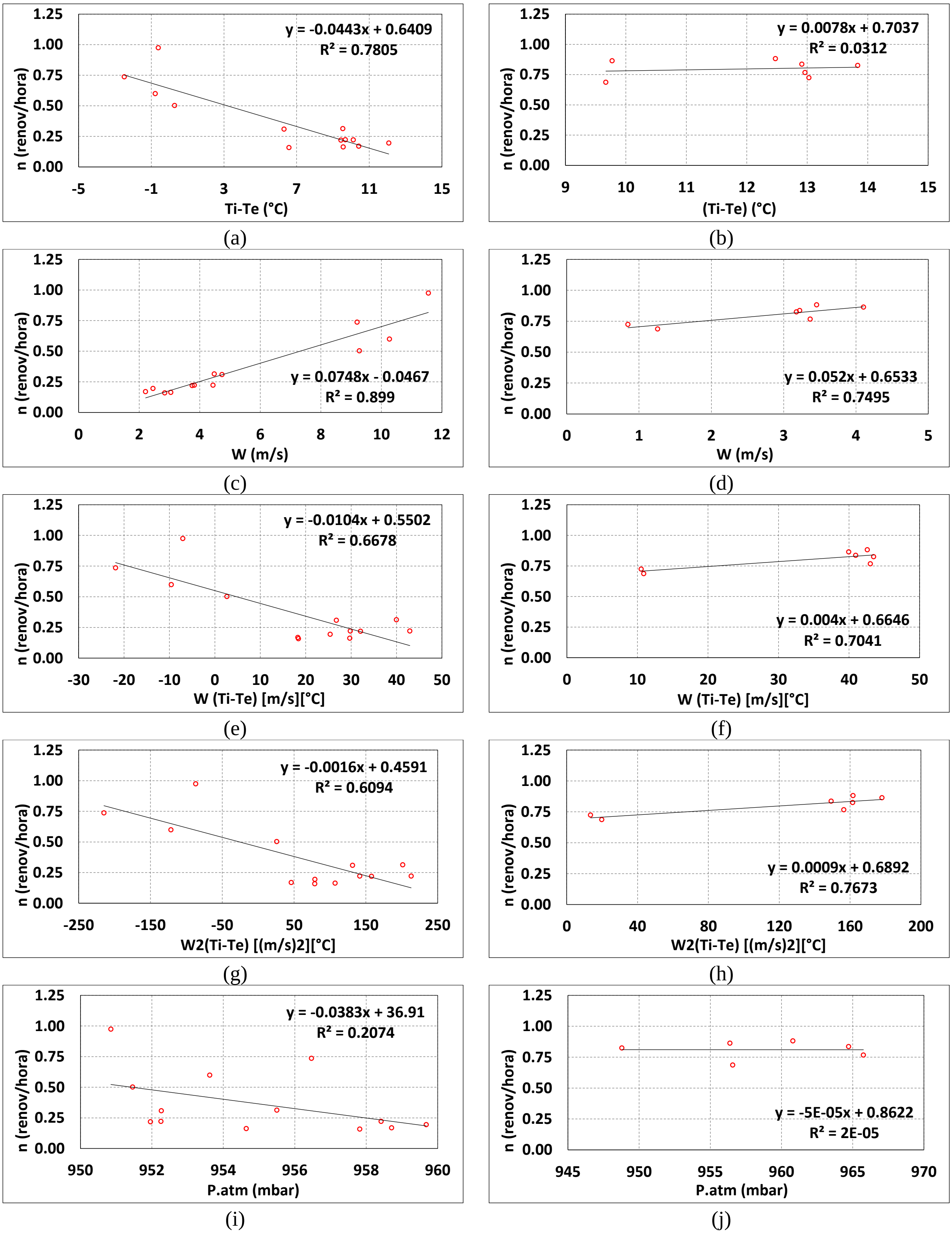


Figure 2: Experimental relations between air renovations and climatic variables. Left: single-zone building. Right: Room of office building.

5.2 Office building prototype

Natural ventilation

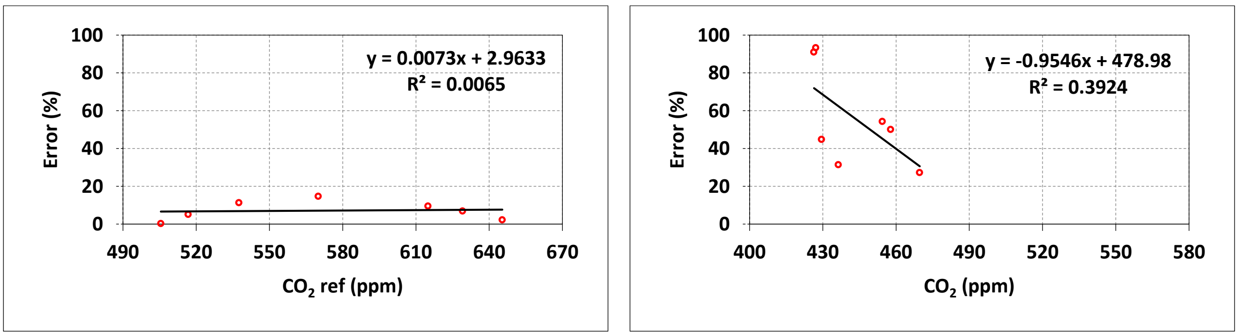
The results obtained for the studied room are summarised in Table 2. Considering the analysis based on N_2O, the air renovation rate (n) presents some variation. However the observed variation isn't so large as in the single-zone building. The n value is between 0.61 and 0.75 renov/hour. Its average is 0.67 renov/hour, and it standard deviation is 0.05 renov/hour. Figure 2 (b, d, f, h, j) shows that the n value has relevant correlation with all the considered boundary variables except the temperature difference and atmospheric pressure (Figure 2i). The most relevant correlation detected is regarding the wind speed (Figure 2d).

It is noticeable the different behaviour observed for the dependence of the n value with the indoor-outdoor temperature difference in this heated room regarding the single zone free running building. The n value for the heated office doesn't show relevant dependence with this variable (Figure 2b). However, a linear tendency is seen for the free running single-zone building (Figure 2a). This different behaviour could be explained by the different ranges of indoor-outdoor temperature differences in the two cases (Figure 2a and b).

Acceptable agreement is observed for the values obtained using the metabolic $CO_{2\ ref}$ concentration measured with the wall mounted sensors Table 2 regarding the reference n values based on N_2O (Figure 3a). The agreement is very poor when the less accurate CO2 sensor is used (Figure 3b). This behaviour is explained taking into account that the office has just one user and consequently the level of CO_2 concentration produced by metabolic activity is very low which is leading to relevant uncertainties in the estimations of n values if the used sensor don't have enough resolution. These uncertainties show a decreasing tendency when the CO_2 concentration increases (Figure 3b). Taking into account this behaviour a better performance of this sensor is foreseen for large CO_2 concentrations that would be present in rooms with more occupants. This issue will be further investigated.

Table 2: Summary of calculations for natural ventilation and boundary conditions. Office number 1

Day	Test	*n* (N_2O) (ren/h)	*n* *(CO_2)* (ren/h)	*n* *(CO_{2_ref})* (ren/h)	r^2 (N_2O) (·)	r^2 *(CO_2)* (·)	r^2 *(CO_{2_ref})* (·)	Ti-Te (ºC)	W (m/s)	W(Ti-Te) [m/s][°C]	W^2(Ti-Te) [(m/s)^2][°C]	P_{atm} (mbar)	$CO_{2ref.max}$ (ppm)	Error (%)	CO_{2max} (ppm)	Error (%)
09/02/2017	**2**	0.72	0.07	0.72	0.9994	0.0334	0.9639	13.03	0.85	10.5	13.5	800	506	0.2	426	91.0
10/02/2017	**2**	0.83	0.57	0.78	0.9994	0.7564	0.9864	13.83	3.18	43.5	161.5	949	517	5.1	436	31.4
14/02/2017	**2**	0.88	0.64	0.82	0.9997	0.7520	0.9923	12.47	3.46	42.6	161.7	961	629	6.9	470	27.3
15/02/2017	**2**	0.77	0.38	0.78	0.9991	0.7900	0.9909	12.96	3.37	43.0	156.5	966	645	2.2	458	50.1
16/02/2017	**2**	0.84	0.38	0.74	0.9996	0.8052	0.9913	12.91	3.22	40.9	149.3	965	538	11.3	454	54.3
21/02/2017	**2**	0.86	0.48	0.78	0.9990	0.6157	0.9888	9.77	4.10	40.0	178.0	956	615	9.5	430	44.8
01/03/2017	**2**	0.69	0.05	0.59	0.9941	0.0446	0.9677	9.67	1.26	10.9	19.8	957	570	14.7	427	93.3



(a) (b)

Figure 3: Office number 1. Percentage of error of the Decay experimental method using CO_2 as analysed gas. Natural ventilation. Reference (left) and cheaper sensor (right).

Mechanical ventilation

The results obtained for the studied room are summarised in Table 3. Considering the analysis based on N_2O, the air renovation rate (n) presents a large variation. It is between 0.95 and 3.08 renov/hour. Its average is 1.98 renov/hour is very close to the design value (2 renov/hour), and it standard deviation is 0.59 renov/hour. However the n value does not show relevant correlation with any of the considered boundary variables. The observed large spread could be caused by the instability of the electricity that powers the mechanical ventilation system that transmits such instability to the ventilation rate. Other effect such as hysteresis of the mechanical components of the ventilation system could contribute to produce the detected variations. The causes of the detected large spread will be further investigated in future research works.

Large uncertainties are observed for the values obtained using the metabolic CO_2 concentration measured with the wall mounted sensors (Table 3 and Figure 4). These uncertainties are remarkably larger than those observed for the same room with natural ventilation. This high uncertainty is attributed the low level of metabolic CO_2 concentration produced by just one user. This issue is also leading to large uncertainties in the case of natural ventilation using the less accurate sensor. However, such uncertainty is worsened in the case of mechanical ventilation taking into account that the time interval available for each calculation of n value is shortened regarding natural ventilation.

Table 3: Summary of calculations for mechanical ventilation and boundary conditions. Office number 1.

Day	Test	*n* (N_2O) (ren/h)	*n* (*CO_2*) (ren/h)	*n* (*CO_{2_ref}*) (ren/h)	r^2 (N_2O) (·)	r^2 (*CO_2*) (·)	r^2 (*CO_{2_ref}*) (·)	Ti-Te (°C)	W (m/s)	W(Ti-Te) [m/s][°C]	W^2(Ti-Te) [$(m/s)^2$][°C]	P_{atm} (mbar)	$CO_{2ref.max}$ (ppm)	Error (%)	CO_{2max} (ppm)	Error (%)
31/01/2017	**1**	2.41	0.41	0.65	0.9983	0.7064	0.9819	2.12	1.06	2.3	3.2	953	537	73	489	83
	2	2.11	0.29	1.42	0.9979	0.7698	0.9911	6.75	2.12	14.1	32.6	954	544	33	489	86
01/02/2017	**1**	2.41	1.10	0.76	0.9982	0.8000	0.9872	2.08	2.19	4.5	11.6	955	564	68	463	54
	2	1.96	-0.29	1.21	0.9949	0.3562	0.9823	5.47	1.11	5.5	8.0	955	529	38	443	115
02/02/2017	**1**	2.12	0.26	0.73	0.9963	0.5889	0.9852	6.21	1.64	10.1	18.6	953	646	65	516	88
	2	2.00	0.12	1.10	0.9960	0.5396	0.9894	6.08	1.03	6.2	7.8	954	535	45	470	94
03/02/2017	**1**	2.70	-0.98	0.97	0.9984	0.2534	0.9405	1.97	5.04	9.9	54.5	956	543	64	433	136
06/02/2017	**2**	2.25	0.56	0.98	0.9949	0.7154	0.9835	2.36	3.37	6.4	24.7	960	490	56	470	75
07/02/2017	**1**	2.61	0.63	1.05	0.9971	0.8246	0.9941	0.30	4.61	0.8	3.7	958	716	60	520	76
	2	1.34	-0.17	0.86	0.9988	0.1874	0.9901	4.10	3.30	13.7	53.2	957	519	36	461	113
08/02/2017	**1**	2.45	0.07	0.50	0.9959	0.0427	0.9694	5.74	3.91	22.3	98.9	800	612	80	486	97
	2	1.33	0.43	1.04	0.9997	0.6881	0.9916	8.91	1.65	14.0	30.0	800	515	22	458	68
09/02/2017	**1**	2.50	0.61	0.81	0.9973	0.7653	0.9795	7.63	3.89	29.7	128.6	800	615	68	454	76
10/02/2017	**1**	2.31	0.30	0.91	0.9954	0.6379	0.9789	9.50	1.76	16.9	44.5	949	611	61	488	87
13/02/2017	**1**	3.08	-0.11	1.23	0.9993	0.0015	0.9823	6.44	3.81	24.5	111.8	947	558	60	436	104
	2	0.95	0.04	0.76	0.9826	0.0970	0.9128	8.90	2.55	22.4	69.2	951	577	20	409	96
14/02/2017	**1**	2.61	0.14	0.68	0.9966	0.2700	0.9487	7.32	2.92	21.4	71.9	959	613	74	470	95
15/02/2017	**1**	2.41	0.14	0.69	0.9973	0.2015	0.9894	7.77	4.32	33.6	159.1	964	663	71	525	94
16/02/2017	**1**	2.39	-0.04	0.61	0.9959	0.0133	0.9682	9.06	5.74	52.0	323.7	965	619	74	446	102
17/02/2017	**1**	1.51	0.33	0.71	0.9965	0.7170	0.9889	9.60	2.07	19.9	50.8	962	640	53	498	78
	2	1.22	0.71	1.07	0.9767	0.8458	0.9208	11.91	2.65	31.2	94.4	961	545	12	495	42
20/02/2017	**2**	0.95	0.51	1.38	0.9992	0.7741	0.9104	11.29	7.22	81.3	618.8	958	531	44	409	47
21/02/2017	**1**	2.41	1.34	0.60	0.9935	0.6193	0.9612	8.13	8.48	68.9	605.3	957	606	75	461	44
22/02/2017	**1**	2.26	0.54	0.58	0.9955	0.7501	0.9738	5.63	5.94	33.4	207.4	954	697	74	473	76
	2	1.12	0.39	0.99	0.9844	0.7994	0.9958	8.21	3.54	29.0	121.8	952	563	11	473	65
23/02/2017	**1**	1.57	-0.65	0.77	0.9984	0.0542	0.9751	6.17	4.87	29.9	166.5	948	654	51	433	142
	2	1.42	0.41	1.07	0.9983	0.7682	0.9951	9.87	1.74	16.9	34.1	948	559	25	486	71
24/02/2017	**1**	1.54	0.09	0.52	0.9995	0.0588	0.9776	6.92	1.39	9.5	18.8	950	684	66	603	94
	2	1.36	0.30	1.33	0.9800	0.1849	0.9935	9.48	1.02	9.3	12.4	951	565	2	440	78
02/03/2017	**1**	2.64	0.02	0.47	0.9980	0.0014	0.9794	1.47	1.57	2.3	4.4	955	587	82	461	99
	2	1.46	0.83	1.60	0.9965	0.3075	0.9893	6.54	1.33	7.9	13.2	954	547	9	439	43

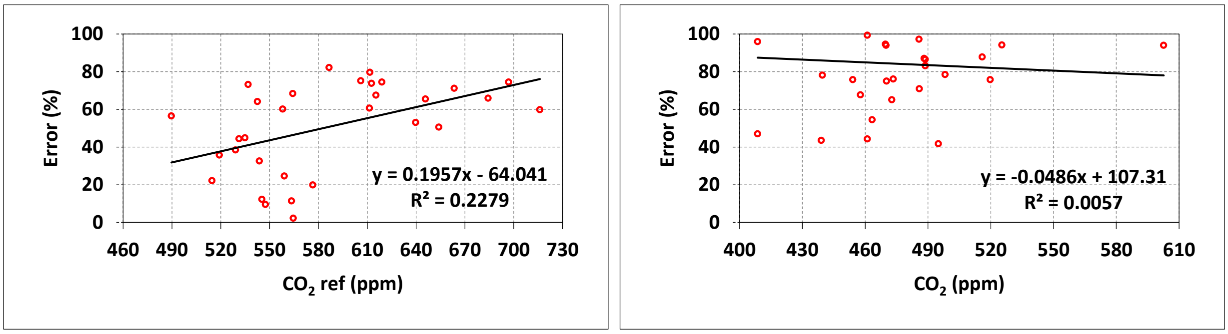


Figure 4: Office number 1. Percentage of error of the Decay experimental method using CO_2 as analysed gas. Mechanical ventilation. Reference (left) and cheaper sensor (right).

6 CONCLUSIONS

The following conclusions are extracted regarding the air renovation rate from the different tests carried out:

- Mechanical ventilation non-active: Significant correlation between air renovation rate and wind speed has been observed in both buildings. The agreement between the values obtained using N_2O and the evolution of metabolic CO_2 increases when the starting value of CO_2 concentration increases.
- Mechanical ventilation active: Large variations have been observed among the different values obtained along the test campaign using N_2O tracer gas. However these values don’t show any correlation with any of the considered boundary conditions. Consequently the observed spread has been used to estimate an uncertainty of the air renovations rate. The measurements based on CO_2 concentrations don’t show good agreement to the values obtained using N_2O tracer gas. This issue will be further investigated, but in principle it is attributed to the low level of CO_2 measured along the analysed test campaign when the mechanical ventilation is active. This explanation is in agreement with previous works carried out regarding the air renovation in the same building.

The following conclusions are extracted regarding the influence of the air renovation rate on the behaviour of the “Heat Transmission Coefficient (HTC)”:

- The behaviour observed in the air renovation rate, showing large variability in natural as well as mechanical ventilation, can contribute to understand and explain the behavior of the HTC experimentally assessed and its uncertainties (Farmer et al., 2016; Marshall et al., 2017). Regarding natural ventilation, the dependencies of the n value with wind speed could explain some variability of the HTC and some uncertainty when it is assumed as a constant value. Further analysis of this wind dependence is an interesting issue regarding future research works that could lead to a wind dependent HTC reducing the uncertainties of this coefficient in experimental assessments under natural ventilation conditions.
- The behavior observed in the n value for the case of mechanical ventilation lead to conclude that the experimental assessment of an HTC assuming n as constant could lead to large uncertainties. The work presented in this paper hasn’t identified any variable that contributing to model such variability reducing the associated uncertainty. But this issue is identified as relevant topic regarding future research.

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