# Comparison of experimental methodologies to estimate the air infiltration rate in a residential case study for calibration purposes

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## ABSTRACT

The air renovation of a building should be controlled in order to ensure a proper level of indoor air quality while minimize heat losses. It is a crucial point for the future energy efficiency goals. However, air infiltration rate in buildings is a complex parameter which is influenced by several boundary conditions. Although a detailed dynamic analysis could be used to properly characterize the phenomenon, estimated values can be obtained from experimental methods, as Blower Door test and gas concentration-based approaches. Given that, the market provides affordable sensors which permit recording $CO_2$ concentration, the present study has implemented those methodologies using $CO_2$ as a gas tracer to estimate the air infiltration rate.

For the present study, $CO_2$ concentration measurements have been carried out in a typical Spanish residential building. Weather data have been provided by a nearby meteorological station. Using data collected during unoccupied hours, the $CO_2$ decay method has been implemented. Furthermore, Blower Door tests have been performed and compared with the $CO_2$ concentration-based method.

Infiltration rate results using the decay method differ between different time periods in a considerable way, ranging between 0.08 and 0.49 air changes/hours. These variations are mainly due to differences in wind speed, wind direction and temperature gradient between the interior and the exterior of the building. Although these factors clearly influence the external air infiltration level, they alone are unable to describe in a complete way the air tightness of the building envelope due to the complexity of the phenomenon (building shape, local wind distribution and wind gusts). This paper aims to contribute enhancing awareness regarding infiltration field study and suggest a simple and not invasive methodology to obtain the $n_{50}$ parameter useful as input for building models calibration.

## KEYWORDS

Air infiltration; Residential building; Blower Door; Decay method; $CO_2$ measurements.

## 1 INTRODUCTION

According to ASHRAE indications [1], the air change rate (ACH) of a building is defined as the volumetric flow rate of air entering into the considered spaces. It is the combination of two phenomena called infiltration and ventilation. Particular emphasis has been put on considerations regarding air infiltration in residential buildings. It is an uncontrolled behaviour which, especially for buildings having leaky envelopes, has a considerable impact on the overall energy consumption. Regarding building energy simulations, Hopfe et al [2] performed a sensitivity analysis on several physical parameters demonstrating that heating and cooling load are highly sensitive to the ACH parameter. The two main driving forces which create a pressure gradient between inside and outside of buildings are stack effect and wind pressure [3]. Since these two forces are highly dynamics, the ACH is not constant. However, in order to provide guidelines, experimental methodologies as tracer gas approach and Blower Door test have been developed. This last refers to a standardized and well known methodology to estimate the airtightness of the building (UNE-EN 13829:2002 [4]).

Regarding tracer gas approaches, which implementation is described in the ASTM standard E741-83 [5], Cui et al [6] implemented the tracer gas decay method using in-situ $CO_2$ measurements carried out in a controlled environment and Roulet et al [7] compared decay processes of $SF_6$ and $CO_2$ in an auditorium showing a good reliability of $CO_2$ results. Batterman [8] provided a complete review about $CO_2$-based methods to evaluate the ventilation rates, demonstrating that the decay method is the most simple method. Finally, Montoya et al [9] evaluated the ACH of several residential dwellings in Catalonia using the same methodology, obtaining a mean value around 0.23 $h^{-1}$. Concluding, tracer gas approach results in easy application, and the use of $CO_2$ as a tracer gas sounds interesting since it is not affecting human health and it is generated by the human metabolic process.

In this study, $CO_2$ concentration measurements have been carried out in a residential building in Catalonia. With the data collected during unoccupied periods, when there is not indoor generation of $CO_2$, the exponential decay method has been implemented. The results have been related to weather conditions provided by a nearby weather station. Moreover, a Blower Door test and a thermographic analysis have been performed. Results of the Blower Door tests have been compared with the results of the decay method. The objective of the work is to show how simple and repeatable $CO_2$ measurements might be useful to provide an estimated range of the ACH of residential buildings which can be used as input parameter to enhance the reliability of building energy simulations.

## 2 METHODOLOGY

### 2.1 Building description

The building under description is a residential apartment of 109 $m^2$ located in Terrassa, Spain. It is a structure built in the early '90 and its envelope construction elements follow the building code of the period (NRE-AT-87) and they are representative of the common Spanish buildings stock. More details regarding internal zones division, orientation and a general overview of the apartment are provided in Fig. 1. The heating system comprehends radiators and a gas boiler. There is not mechanical ventilation installed.


Figure 1: Building overview

### 2.2 Tracer gas decay method description

$CO_2$ concentration decay method is based, as for the other tracer gas methods, on a mass balance equation applied for a specific control volume. The mass balance differential equation, considering the background concentration of $CO_2$ in the outside air ($C_{bg}$) and without internal generation, can be written as:

$$V\frac{dC_t}{dt} = \left(Q \cdot C_{bg}\right) - \left(Q \cdot C_t\right) \tag{1}$$

Where $V$ is the control volume considered in $m^3$, $Q$ is the air mass flow rate entering/exiting the control volume in $m^3/h$ and $C_t$ is the $CO_2$ concentration of the indoor air in ppm/$m^3$.
Defining the ACH as the resulting air mass flow rate divided by the total volume ($ACH = Q/V$) and considering a constant background level of the concentrations, it is possible to reformulate the equation as follow:

$$\frac{dC_t}{C_{bg} - C_t} = ACH_t \cdot dt \tag{2}$$

ASTM standard [5] provides two approaches for the decay method: two point method and regression analysis. Assuming that the ACH varies during the considered periods, the two point method has been implemented as first approach since it ensures an unbiased estimation of the average value [10]. Integrating equation (2) between initial and final time of measurement leads to:

$$\overline{ACH} = \frac{1}{\Delta t} \cdot \left[\frac{\ln\left(C_{t=0} - C_{bg}\right)}{\ln\left(C_{t=f} - C_{bg}\right)}\right] \tag{3}$$

On the other hand, with the assumption of constant ACH during the considered periods, a regression method has been used to compare the two approaches. Plotting data of $\ln C_t$ against time allows to perform a linear regression and to find the coefficients of equation 4.

$$\ln C_t = -At + \ln C_{t=0} \tag{4}$$

In this case, the slope of the linear regression ($A$) represents the ACH value. Equations fitting and error analysis are implemented. Among the $CO_2$-based methodologies mentioned in the review [8], the decay method is the easiest to implement and it is especially suitable to be dealt with periods when there is a step down decrease or a complete evacuation of the building occupants [3]. Periods selected are characterized by a first part of people occupation, when $CO_2$ is injected in the space, followed by a complete evacuation. This reflects in an exponential decay. As suggested by the study of Cui et al [6], for both methods, as initial point of the decay curve has been considered the starting point of the exponential process while the final one in the way that the time-span considered is equal to the nominal time constant of the exponential decay curve. This constant represents the time to reach the 63.5% of the concentration difference between initial and final point. As example, periods P6 and P7 are shown in Fig. 2.

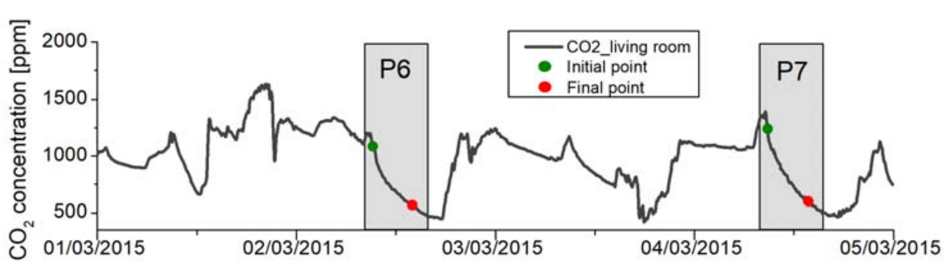


Figure 2: Example of selected periods for the tracer gas decay method

It is important to notice, that some assumptions established for the decay method implementation are not completely satisfied (ASTM E741-83, [5]), due to work in a residential case study which is a not controlled environment. The limitations of the study are: multi-space sampling is not performed, which is needed to ensure the homogeneity of $CO_2$ concentration; single zone approach has been considered since a single house can be assumed like a single zone [8]; Most of the uncertainties could come from inter-zone air flows due to the different $CO_2$ generation between persons and rooms. Despite of these limitations, the selection of the periods has been done carefully to reduce those uncertainties.

### 2.3 Measurement campaign

The measurement campaign has been carried out during four winter periods. The main aim is to not affect family daily life. Consequently, a simple procedure and not invasive sensors have been used. Temperature and $CO_2$ sensors are located in almost each indoor room and in the outdoor terrace. However, only results regarding the living room have been analysed in the study. $CO_2$ sensors have been calibrated with the period-related background levels as suggested from the manufacturer. Sensors data loggers are set to collect data each 5 minutes.
Wind speed and direction data have been collected from a weather station which is 1 km far from the building. Values collected have been corrected accounting for the height of the building. Although specific local wind distribution could be influenced by several factors (e.g. wind gusts frequency [11]), these data have been used to correlate between the ACH and wind conditions. In particular, the related wind parameter is the average speed value at the most frequent direction of each considered period.

### 2.4 Blower Door tests: building preparation and tests performed

The Blower Door test is used to study the air tightness and air leakage of building envelopes. This consists in a pressurisation/depressurisation test which is performed with a Blower Door device that measures the air flow and pressure, establishing the infiltration air flow rate of the building. This test should be supplemented with an infrared thermography to detect where the uncontrolled cracks and openings of the envelope are located.
In this study, the Fan pressurization test, as it was also known, was performed using a Minneapolis Blower Door™ device, the Tectite software (v.5.0.7.3) and a Flir T1020 thermography camera. To conduct this test, all the windows in the dwelling were closed, all the doors were left open and all the intentional openings were sealed: natural vents (bathroom and laundry room ducts); mechanical vents (kitchen exhaust fan) and others (chimney).
The following is a brief description of the software settings of the test:

- Test standard: European standard UNE-EN 13829:2002 [4] that has a minimum of 5 Pa target building pressures, where the maximum must not be less than 50 Pa and the interval between the target must not exceed 10 Pa.
- Building preparation method (from standard UNE-EN 13829:2002): Method B, because the test is performed to calculate the building envelope infiltration.
- Wind class using the Beaufort scale. It associates qualitative descriptions of wind conditions with quantitative values, the wind speed. It is detailed in the Annex D of the UNE-EN 13829:2002. In our test Light Breeze: 1.8 to 3.1 m/s is used, which is within the limits to minimize error due to wind speeds. [12]
- Building Wind Exposure: Partly Exposed.
- Difference between indoor and outdoor temperature: Between 6-7ºC.

During the test the Blower door device was placed in the entrance door to depressurise (remove) and pressurise (force) the air into the dwelling until a positive or negative pressure of 50 Pa was reached.
For this study, two Blower Door tests are performed: one testing all the dwelling with all the shutters open, and one for the main room with the shutters open. These tests are conducted to

check the degree of uniformity of the envelope (all the dwelling vs the main room). Fig. 3 shows the results of these last two tests.

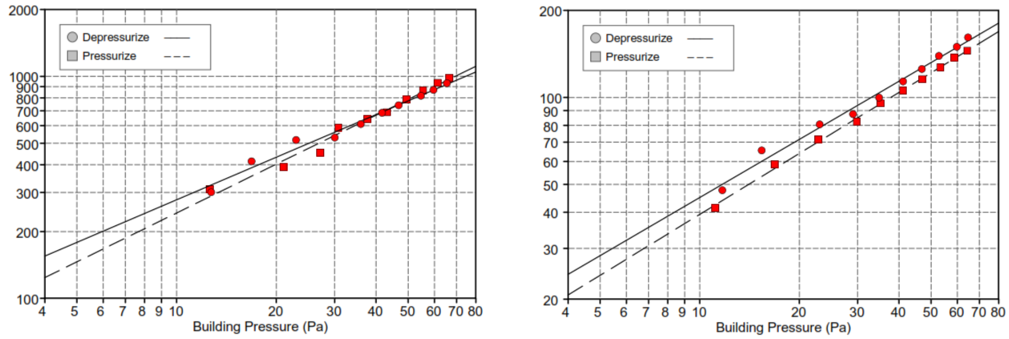


Figure 3: Blower Door test result. Left: All dwelling. Right: Main room (E4)

In section 3.3 the numeric results of the tests and the degree of uniformity of the obtained infiltration rate are analysed in detail.

# 3 RESULTS AND DISCUSSION

## 3.1 Tracer gas decay method results

Table 1 shows the estimated values of the ACH for both tracer gas approaches, the duration of the decays and their error analysis of the regression approach. Values indicate a good agreement between the two approaches with differences lower than 10%, except for period P6 and P7. Decays range from 2 to 8 hours depending on the initial concentration value and the real ACH. Confidence intervals have been estimated with a 99% level of confidence. Moreover, as evaluation of the fitting quality, the R-square values are provided, presenting values greater than 0.98. The ACH [$h^{-1}$] results obtained with the regression method are used in the following sections.

Table 1: Decay methods results

| | | | | Regression analysis | | |
|---|---|---|---|---|---|---|
| Period | **From** | **To** | **Two Point ACH [$h^{-1}$]** | **Regression ACH [$h^{-1}$]** | **Confidence band** | **$R^2$** |
| P1 | 25/12/2012 - 22:41 | 26/12/2012 - 09:06 | 0.074 | 0.080 | ± 0.0021 | 0.98745 |
| P2 | 31/12/2012 - 20:06 | 01/01/2013 - 01:11 | 0.191 | 0.198 | ± 0.0017 | 0.99970 |
| P3 | 04/01/2013 - 10:13 | 04/01/2013 - 17:32 | 0.135 | 0.144 | ± 0.0013 | 0.99892 |
| P4 | 22/01/2013 - 21:21 | 23/01/2013 - 05:06 | 0.103 | 0.107 | ± 0.0014 | 0.99769 |
| P5 | 24/02/2015 - 08:48 | 24/02/2015 - 10:42 | 0.501 | 0.489 | ± 0.0146 | 0.99541 |
| P6 | 02/03/2015 – 09:03 | 02/03/2015 - 11:51 | 0.320 | 0.370 | ± 0.0127 | 0.99099 |
| P7 | 04/03/2015 - 08:33 | 04/03/2015 - 11:36 | 0.323 | 0.364 | ± 0.0162 | 0.98453 |
| P8 | 25/12/2017 - 17:39 | 26/12/2017 - 00:33 | 0.135 | 0.135 | ± 0.0008 | 0.99917 |

Regarding the regression study, Fig. 4 demonstrates how the slope of the logarithmic regression normalized upon the initial concentration gives a graphical representation on the ACH results.

P5, P6 and P7 are the periods with higher slope, and correspond with the periods with high infiltration rates (0.3 – 0.5 $h^{-1}$). On the contrary, periods P1, P3, P4 and P8 are the ones with lower slope and consequently, lower level of infiltration (< 0.15 $h^{-1}$).

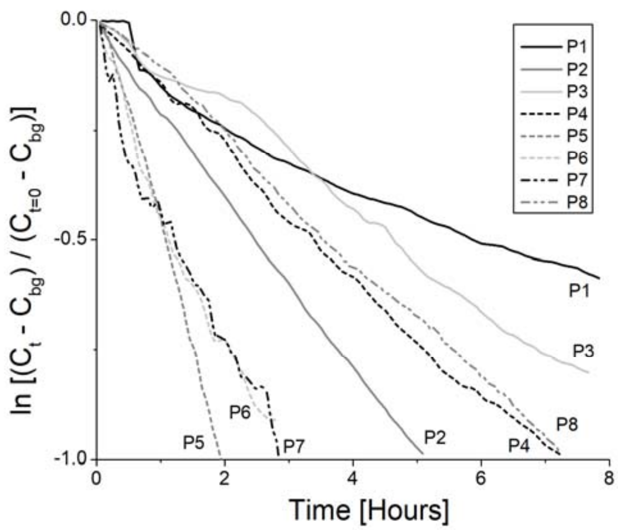


Figure 4: Logarithm of normalized $CO_2$ concentrations decays

### 3.2 ACH correlation with weather conditions

ACH relation with main driving forces of air infiltration has been investigated. As it is possible to notice from Fig. 5, there is a quite good correlation between high values of infiltration and high values of wind speed. P1, P3 and P5, which are characterized by wind blowing mainly from Northwest, show a direct correlation between wind average speed and ACH rate. This is not valid for the other periods where it is difficult to establish a clear correlation. This could be probably explained with the presence of the neighbouring buildings which have the possibility to create a tunnel effect and highly affect the local wind distribution. On the other hand, the temperature difference between the inside and the outside of the building seems not affecting in a relevant way due to relatively high wind speed values. Indeed, for relevant wind speeds, the main contribute to air infiltration in building is given by the wind pressure [3]. For this reason, it makes sense to analyse the correlations between ACH, temperature difference and wind speed only for periods with low wind speed (wind average speed < 3 m/s). In particular, in Fig. 5, P1 and P3 show how the ACH rate is varying according the temperature difference, while the wind speed is not relevant. However, these two forces are not able to explain the phenomenon in a complete way and the combination of the effects is really difficult to estimate due to local influences.

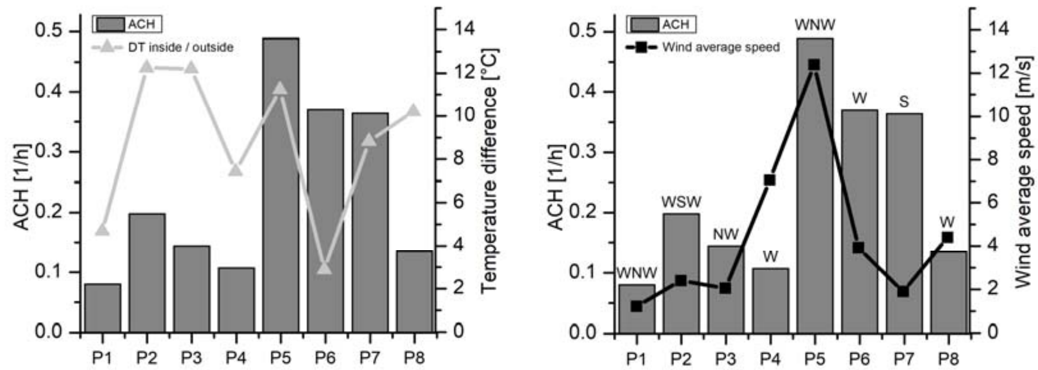


Figure 5: ACH and weather correlations: temperature difference (left) and wind average speed and predominant direction (right).

### 3.3 Blower Door results

Table 2 shows the numeric values obtained in all the tests performed. The results are given as air flow across the building envelope [7], infiltration air flow rate per internal volume (*n*), relationship between infiltration rate and floor area (*w*) and relationship between infiltration rate and envelope area (*q*). The sub-index indicates the pressure test for the obtained value (50 Pa or 4 Pa). The value of 4 Pa corresponds to the reference value of the building infiltration under natural conditions; however it can be lower than 4 Pa [13].

Table 2: Blower door results

| **Average results at 50 Pascals** | | **All dwelling** | **Main Bedroom** |
|---|---|---|---|
| $V_{50}$ | $m^3/h50$ (Airflow) | 782 | 127 |
| $n_{50}$ | 1/h (Air Change Rate) | 2.89 | 2.92 |
| $w_{50}$ | $m^3/(h.m^2$ Floor Area) | 7.23 | 7.29 |
| $q_{50}$ | $m^3/(h.m^2$ Envelope Area) | 2.41 | 1.57 |
| **Average results at 4 Pascals** | | | |
| $V_4$ | $m^3/h4$ (Airflow) | 140 | 23 |
| $n_4$ | 1/h (Air Change Rate) | 0.51 | 0.52 |
| $w_4$ | $m^3/(h.m^2$ Floor Area) | 1.28 | 1.3 |
| $q_4$ | $m^3/(h.m^2$ Envelope Area) | 0.43 | 0.28 |

The uniformity of the dwelling envelope is observed, obtaining similar results when testing the entire building and only one room.

### 3.4 Methodologies comparison

The results obtained with the gas tracer approaches are compared with the Blower Door tests. It has to be taken into account that natural pressure difference between indoor and outdoor could be between 1-4 Pa. For this reason, using as reference the results of the Blower Door tests and an European standard [14] it is possible to correlate the $n_{50}$ values obtained with a pressure difference between indoor and outdoor of 1 Pa. ($n_1$), as equation 5 shows.

$$\frac{n50}{n1} = 13.59 \quad (5)$$

It is expected that the ACH values obtained with the decay methods range in the pressure interval of 1-4 Pa. The average result of the Blower Door tests of the entire dwelling ($n_{50}=2.89$ $h^{-1}$) has been converted to these two pressure interval, using equation (5) and the result of the test at 4 Pa. Fig. 6 demonstrates that almost the halves of the periods are inside the range. In particular, periods that are outside the range provides ACH lower than 0.15 $h^{-1}$, which could be associated to lower pressure difference (< 1 Pa).

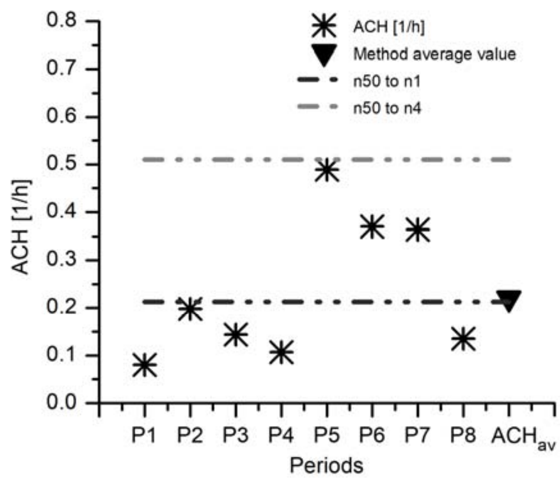


Figure 6: Decay method and Blower Door comparison

The objective is to provide a reasonable $n_{50}$ input value for residential building simulations without performing a Blower Door test. The suggested methodology consists in evaluating the average ACH excluding periods which wind speed average at most frequent direction is higher than 6 m/s, which is the limit established by the Blower Door methodology to obtain reliable results. In this study P6 and P7 have been excluded. Then, with the assumption that the average natural pressure difference between indoor and outdoor is around 1 Pa, as much of the obtained ACH are around this difference of pressure, it is possible to convert this average value to $n_{50}$ through equation 5. Table 3 shows the results for the method proposed, which are very close to the Blower Door results (differences lower than 5%).

Table 3: Comparison of $CO_2$ estimation approach

| | **Average ACH – $n_1$ [$h^{-1}$]** | **Average $n_{50}$ [$h^{-1}$]** |
|---|---|---|
| $CO_2$ estimation approach [$ACH_{av}$] | 0.22 | 2.92 |
| Blower Door test | 0.21 | 2.89 |

## 4 CONCLUSION

The study investigates the air infiltration in a Spanish residential case study. Different periods and weather conditions have been taken into account to show the dependency of the ACH with the main driving forces of infiltration. ACH has been evaluated implementing two tracer gas approaches using $CO_2$. Both methodologies are coherent providing consistent results with differences lower than 10% for most of the periods.

In order to contrast with a well-known and proven technique, Blower Door tests have been performed. The $n_{50}$ provided is 2.89 $h^{-1}$ and 2.92 $h^{-1}$ respectively for the entire building and the main bedroom (E4). These results show the homogeneity of the building envelope. In general, all the results reflect a good air tightness of the building envelope, especially considering the construction period of the building (90s).

Finally, a methodology has been suggested as simplified way to estimate an $n_{50}$ value without performing a Blower Door test based on the CO2 decay method. This procedure can be useful since the Blower Door is not always feasible, especially in residential occupied buildings. The proposed method provides a mean value of the infiltration rate of $n_1$ of 0.22 $h^{-1}$, and $n_{50}$ of 2.92 $h^{-1}$, which is very close to the Blower Door result. The suggested procedure should be applied to other residential case studies in order to confirm its validity.

Concluding, a simply and not invasive method is proposed to allow improving the hypothesis about air infiltration, in comparison to the tabulated values of different standards [14], which are classified by qualitative air tightness. The approach presents a good procedure to estimate the air infiltration parameter ($n_{50}$) of the building models and reduce the uncertainty when calibrating the building models by means of dynamic simulations.

## 5 ACKNOWLEDGEMENTS

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