Article

A Discussion Regarding the Measurement of Ventilation Rates Using Tracer Gas and Decay Technique

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Abstract: The measurement of ventilation rates is crucial in understanding buildings' performances, but can be a rather complex task due to the time-dependency of wind and buoyancy forces, which are responsible for the pressure differences that induce air movement across the envelope. Thus, assessing air change rate through one-time measurements during brief periods of time may not be a reliable indicator. In this paper, the variability in the measurement of ventilation rates using the decay technique was evaluated. To that end, two compartments of a typical single-family detached dwelling were selected as a case study and 132 tests were performed, considering two different boundary conditions (door closed and door open). This work allowed the large variability of the results to be highlighted, as the coefficient of variation ranged from 20% to 64%. Wind speed had a key effect on the results, especially because during the measurements indoor–outdoor temperature differences were not so significant. The possibility of using occupant-generated carbon dioxide as tracer gas was also analyzed, but problems of cross-contamination were identified.

Keywords: air change rate; decay technique; measurement variability; tracer gas; ventilation

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1. Introduction

The importance of buildings' ventilation is enhanced by the growing energy concerns across the European Union [1,2], pointing to a reduction of the energy demand for ventilation. The importance of infiltration (uncontrolled and unintentional airflows) was clearly identified in recent studies, which indicate that it can be responsible for up to 27% on the energy balance of buildings [3]. On the other hand, adequate ventilation is crucial to maintain a comfortable indoor environment with good indoor air quality, since ventilation is the process of supplying (fresh) and removing (contaminated) air to and from any confined space. To completely understand the performance of a building, the ventilation rate is a key parameter [4]. The ventilation rate is particularly relevant in the context of mild climate countries where window opening is the main source for fresh air admission and is thus highly influenced by user behavior [5–7].

Moreover, in mild climate countries, natural ventilation is the most common strategy. The air movement required for natural ventilation occurs due to pressure differences produced by the combined effect of wind and buoyancy forces, which are both time-dependent [8]. Due to the unstable conditions that occur outdoors (wind and air temperature), one-time measurements of the ventilation rate, made over a short period, may not be an accurate indicator of the performance of the building [9–11].

This aspect is confirmed by several examples found in the literature in which differences between buildings real performance and prediction at design stage have been reported and discussed [12–15]. These issues reinforce the relevance of in-situ measurements to provide reliable data.

Several studies have already reported the time-variability of ventilation rates. This phenomenon is particularly important in naturally ventilated buildings, since ventilation is strongly dependent on the weather conditions. However, the uncertainty level of the measurement of the ventilation rates is also dependent on other factors such as the distribution and mixing of the tracer gas and the number and position of sampling points [16–18].

This paper aims to evaluate the variability in the measurement of ventilation rates using the decay technique and two different tracer gases. Two compartments of a typical single-family detached dwelling were selected as a case study and a large number of measurements were performed, considering two different situations: door closed and door open. A discussion about the strengths and weaknesses of the measurement technique was carried out. It is intended to:

- Assess the variability that can be found in the measurement of ventilation rates with tracer gas;
- Discuss the use of tracer gases other than sulfur hexafluoride (SF_6) as its use is nowadays limited by environmental constrains;
- Compare the use of SF_6 and occupant generated carbon dioxide (CO_2) as tracer gases, stressing the importance of controlling cross-contamination of CO_2;
- Evaluate the importance of the outdoor climate conditions on the results by tackling a relationship between the attained ventilation rates and the corresponding wind speed and indoor–outdoor temperature difference.

2. Literature Review

Accurately measuring ventilation rates can be a complex task. The most common technique to measure ventilation rates is using a tracer gas dilution method [8]. However, in very specific conditions as in very airtight buildings where airflows occur in ductwork, velocity transverse methods can be used to estimate airflow rates [19]. Infiltration rates in buildings are frequently assessed by pressurization techniques, commonly known as the Blower Door Test [20–22], sometimes in association with infrared thermography to obtain information about the air leakage pathways [23,24]. Bracke et al. [25] discussed the durability and measurement uncertainty of airtightness, focusing on the issues of repeatability and reproducibility, the impact of weather conditions, the impact of the age of the construction, and the reproducibility in repeated construction of virtually identical houses. A review of direct and indirect methods developed for measurement of airflow rates can be found in Ogink et al. [16].

The tracer gas dilution method is based on a mass balance of the tracer gas in the indoor air. There are three different techniques to measure ventilation rates in dwellings using this method [26]: (1) constant injection, the flow release rate must be known; (2) constant concentration, the gas concentration is kept constant and the flow release rate must be known; (3) concentration decay, the gas is released, mixed into the system, and the concentration decrease is then measured. The simplest approach is using the decay technique as it is cheaper and the system is far less complex. A comparison between constant concentration and decay techniques can be found in Chao et al. [27].

Several tracer gases can be used and its selection is an important issue. The tracer gas should be easily monitored and, normally, is not present in the atmosphere (this technique is also applicable if the outdoor concentration of the gas is known). A discussion regarding the potential and limitations of several tracer gases can be found in Grimsrud et al. [28]. The most common gas was, until a few years ago, SF_6, however nowadays its use is limited by environmental constrains. Several studies can be found in the literature where CO_2 is used as tracer gas, as it is considered reliable, simple and cheap. In fact, CO_2 is often used as a "natural" tracer gas (occupant-generated) for estimating ventilation rates, especially because it is present in all buildings, usually well dispersed, and can be measured accurately with inexpensive logging instrumentation [29]. A comparison between the use of these two

gases can be found in Edouard et al. [30]. In this study, both methods gave similar ventilation rates, being 10–12% lower with the CO_2 mass balance method.

Another important issue is the sampling position. Buggenhout et al. [17] demonstrated that the errors could rise up to 86% in naturally ventilated spaces where perfect air mixing is sometimes hard to achieve. Bjerg et al. [31] studied five sampling locations and concluded that measuring in the middle of the building is the most accurate scenario. Nevertheless, this is still an open issue [16].

Some different approaches to measure ventilation rates have recently been tested. Vereecken et al. [32] used measured relative humidity to determine the ventilation rate and the moisture buffer potential of room enclosures. The main advantage of this methodology is that it allows a comprehensive characterization of the hygric inertia of the whole building enclosure. An attempt to determine ventilation rates through moisture balance was also made by Samer et al. [33], finding reliable results especially during winter seasons. The release rate of solid carbon dioxide (dry ice) in an insulated box was used by Cheng and Li [34]. The method was compared with traditional approaches and an uncertainty of less than 10% was found.

Besides the weather condition, one of the key aspects when assessing the uncertainty in building ventilation rates is the user behavior, such as window-opening habits and use of exhaust fans [8]. Howard-Reed et al. [35] made more than 300 air change rate experiments in two homes to evaluate the effect of opening windows. They concluded that, compared with temperature differences and wind effects, window opening produced the greatest increase in the air change rate. The influence of door opening on interzonal air exchange was quantified by Lee et al. [36]. The results showed that the interzonal air exchange volume through the door was higher with a swing door, in comparison with a sliding door.

3. Materials and Methods

3.1. Framework

The measurement campaign lasted from April to June. Throughout this period, the following data were recorded to evaluate both the indoor and the outdoor environmental conditions: the air temperature and relative humidity and the CO_2 concentration in the living room and in the bedroom; and the outdoor air temperature and relative humidity and wind speed and direction. The set-up included two sensors in each compartment and the sampling interval was 5 min. The sensors were placed at a height of 0.90 m.

When using CO_2 as a tracer gas to assess the ventilation rate by the decay technique, only the unoccupied periods were used to guarantee that the gas generation was null. The users' presence in the rooms was therefore monitored both visually and through a questionnaire when no research team member was present and that information was combined with the decay of the CO_2 concentration for estimating the ventilation rate. The measurements of the ventilation rate using SF_6 as tracer gas were performed on a daily basis. For both gases, two boundary conditions were tested: (i) door open (O); and (ii) door closed (C). These conditions were applied to all interior doors. The information regarding the door position (open/closed) was also gathered through a questionnaire.

3.2. Tracer Gas Measurements

In this research, both SF_6 and CO_2 were used as tracer gases for estimating the ventilation rate by the concentration decay technique. This method is well established in the literature and the procedure is fully described in the standards ISO 12,569 [37] and ASTM E 741 [38], considering the linear regression method. Special attention was paid to guarantee the correct mixing of the tracer gas. According to this procedure the outdoor concentration of the tracer gas should be zero, which is not the case for the CO_2. In this situation, the difference between the indoor and the outdoor concentration should be used as established in ASTM D6245 [39].

The method formulation that inside a single space, the mass balance of the tracer gas can be expressed by Equation (1).

$$V \cdot \frac{dC(t)}{dt} = G + Q \cdot C_{ex} - Q \cdot C(t) \tag{1}$$

where V [m^3] is the volume of the space; $C(t)$ [ppm] is the concentration of the tracer gas at instant t; t [s] is the time; G [cm^3/s] is the generation rate of the tracer gas; Q [m^3/s] is the internal–external exchange rate; and C_{ex} [ppm] is the external concentration of the tracer gas.

The analytical solution of Equation (1) is as indicated in Equation (2).

$$C(t) = C_{ex} + \frac{G}{Q} + \left(C_{in} - C_{ex} - \frac{G}{Q} \right) \cdot e^{-\frac{Q}{V} \cdot t} \tag{2}$$

where C_{in} [ppm] is the initial concentration of the tracer gas.

Since during the test there was no generation of the tracer gas, Equation (2) can be simplified, as presented in Equation (3).

$$\frac{Q}{V} = n = \frac{\ln\left(\frac{C_{in}}{C(t)}\right)}{t} \tag{3}$$

where n [h^{-1}] is the air change rate.

The statistical treatment of the results was implemented using the software *IBM SPSS Statistics 24*.

3.3. Equipment

Two portable thermohygrometers with data-logging capacity were placed inside each compartment for the recording of the interior air temperature and relative humidity. The precision and the resolution of these devices are ±0.35 °C and ±2.5% and 0.03 °C and 0.03%, for temperature and relative humidity, respectively. The CO$_2$ concentration was recorded with a non-disperse infra-red (NDIR) type unit (two in each compartment) that has a resolution of ±1 ppm and a maximum accepted error resulting from the highest of two values (±50 ppm or 5% of the reading).

The outdoor air temperature and wind speed and direction were measured using a portable weather station. The air temperature sensor has an accuracy of ±1 °C and a resolution of 0.1 °C. The wind direction range includes 16 positions (accuracy of ±11.25°; resolution of 22.5°).
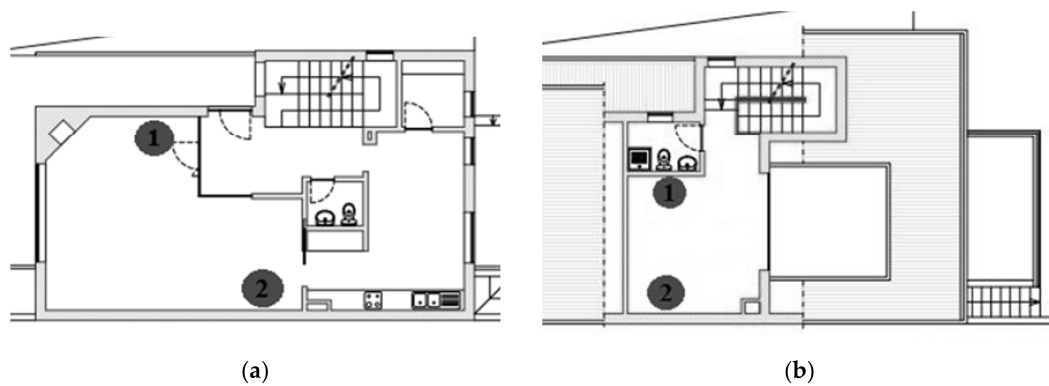
4. Case Study

4.1. Description

A two-storey single-family detached dwelling located near Porto, north of Portugal, was selected as the case study due to its proximity to the sea, which in this region typically corresponds to a high wind exposure area. The region of Porto has a mild climate with dry summers.

The living room (LR), on the ground floor, and a bedroom (BR), on the first floor, were chosen for the measurement campaign. Figure 1 shows the floor plans, including the sensors location in each compartment, and Table 1 summarizes the most relevant geometric data. The geometric characteristics of the two spaces are quite similar, except the door area, which is significantly higher in the LR. The other difference between the two spaces is their orientation: the LR is north oriented and the BR is south oriented.

The case study has a concrete frame structure and a two-layer brick wall with 3 cm of XPS in the air cavity. The interior doors have a 7 mm air gap in the base and are airtight in the remaining boundaries. The windows are composed of sliding aluminium frames with double glazing and have external aluminium shutters (tilt blades).

(**a**)　　　　　　　　　　　　　　　　　　　　　(**b**)

**Figure 1.** Case study and location of the sensors: (**a**) Living room; (**b**) Bedroom.

Table 1. Case study. Geometric characterization.

	Living Room	**Bedroom**
Floor	Ground floor	First floor
Orientation	North	South
Area (m^2)	35	33
Volume (m^3)	84.5	72.2
Window area (m^2)	3.8	3.8
Door area (m^2)	4.4	1.9

4.2. Characterisation of the Indoor and Outdoor Environment

The experimental campaign was carried out during the mid-season period and, thus, no large air temperature fluctuations were expected. In fact, the standard deviation was 2.8 °C with an average air temperature of 18.0 °C. The range of variation was 20.6 °C with a maximum of 32.2 °C. The prevailing winds were easterly and south-easterly oriented and the average wind speed was 0.40 m/s. The maximum wind speed recorded was 3.2 m/s. The interior air temperature varied identically in the two compartments, ranging between 16.8 °C and 24.7 °C in the LR, and between 16.4 °C and 24.6 °C in the BR. The average value was 19.8 °C and 20.7 °C, respectively. The slightly higher average temperature in the BR, which is located on the first floor, is explained by the periods of higher outdoor temperature experienced from the beginning of June and the south orientation of the BR. The maximum indoor–outdoor temperature gradient was 9.1 °C and occurred in the LR.

Figure 2 shows the fluctuation of the air temperature in the two compartments and in the exterior and Figure 3 presents the wind speed and direction. During the experimental campaign, there were a few issues in the link between the weather station and the data-logger. For that reason, some gaps can be observed in Figures 2 and 3.
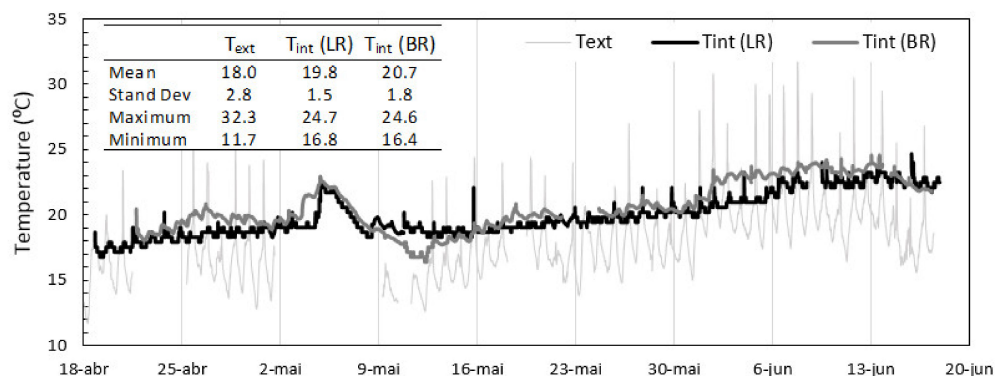
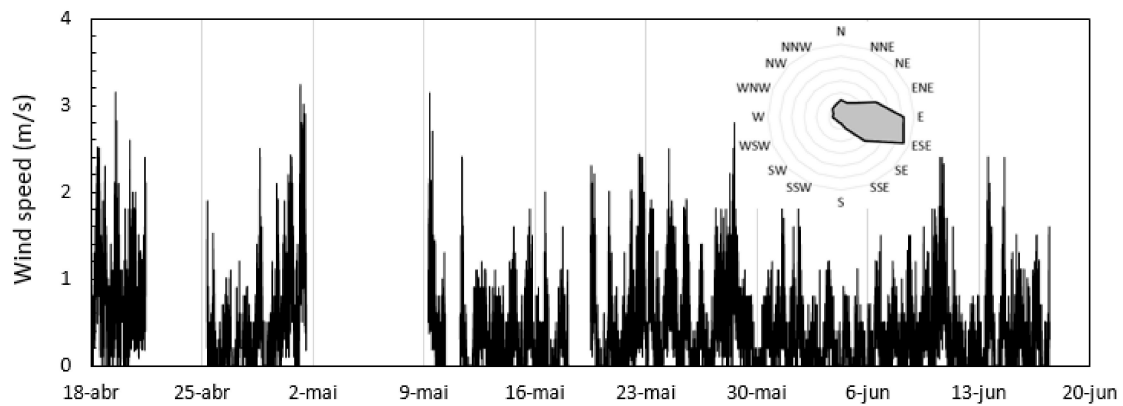**Figure 2.** Indoor and outdoor air temperature during the monitoring period.

Figure 3. Wind speed and direction during the monitoring campaign.

5. Results

5.1. Sulfur Hexafluoride (SF$_6$) Measurements

A total of 132 tests using SF$_6$ as tracer gas were carried out, 66 in each compartment. The results were statistically analysed and Figures 4 and 5 depict the histogram of the results separately for each compartment. The most important descriptive statistical indicators are also included.
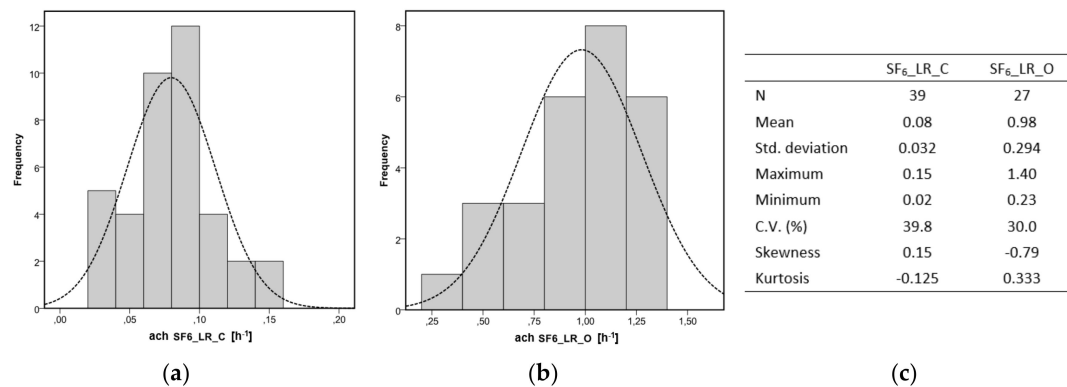

	SF$_6$_LR_C	SF$_6$_LR_O
N	39	27
Mean	0.08	0.98
Std. deviation	0.032	0.294
Maximum	0.15	1.40
Minimum	0.02	0.23
C.V. (%)	39.8	30.0
Skewness	0.15	-0.79
Kurtosis	-0.125	0.333

(a)   (b)   (c)

Figure 4. Sulfur hexafluoride (SF$_6$) measurements of the air change rate in the living room (LR): (**a**) Histogram—door closed (SF$_6$_LR_C); (**b**) Histogram—door open (SF$_6$_LR_O); (**c**) Descriptive statistics indicators.

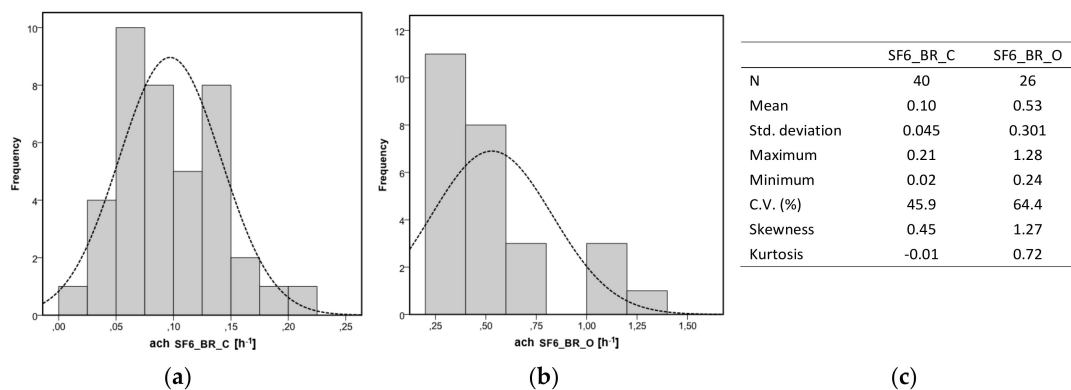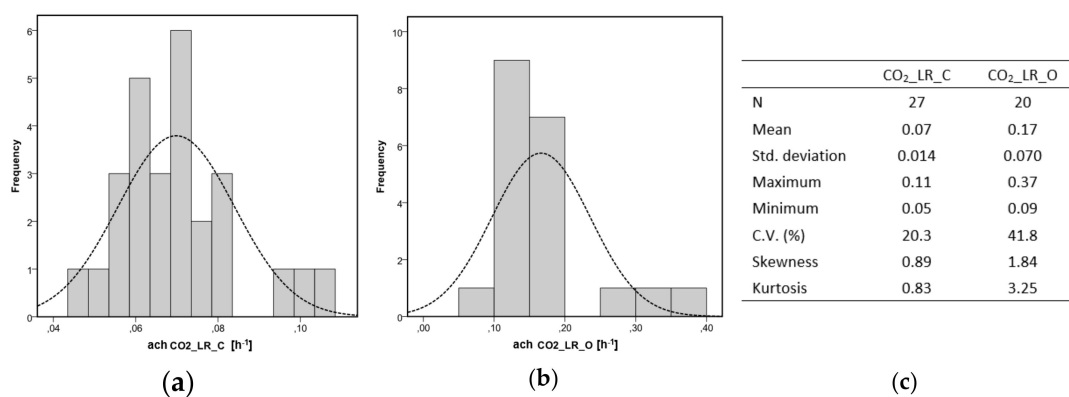|	SF$_6$_BR_C	SF$_6$_BR_O
N	40	26
Mean	0.10	0.53
Std. deviation	0.045	0.301
Maximum	0.21	1.28
Minimum	0.02	0.24
C.V. (%)	45.9	64.4
Skewness	0.45	1.27
Kurtosis	-0.01	0.72

(a)   (b)   (c)

Figure 5. Sulfur hexafluoride (SF$_6$) measurements of the air change rate in the bedroom (BR): (**a**) Histogram—door closed (SF$_6$_BR_C); (**b**) Histogram—door open (SF$_6$_BR_O); (**c**) Descriptive statistics indicators.
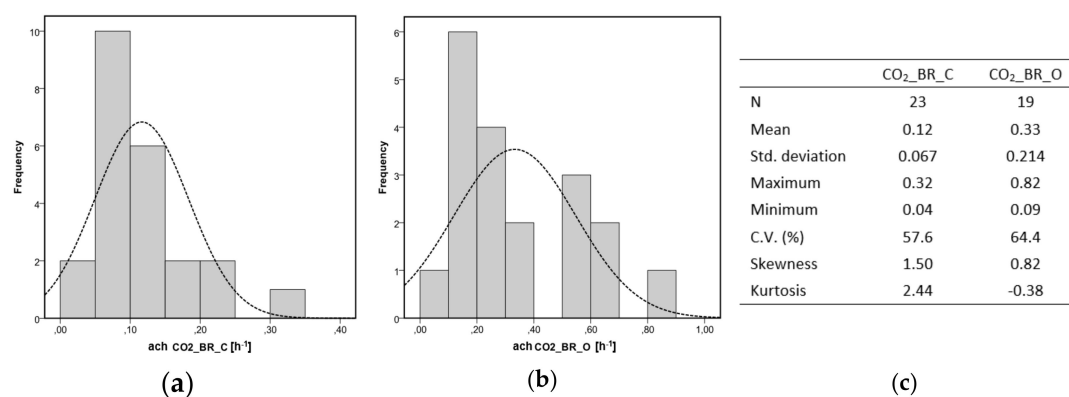
For the door closed situation, the performance of both compartments was very similar, revealing a very airtight envelope. The average air change rates were 0.08 and 0.10 h^{-1} in the LR and in the BR, respectively. The corresponding standard deviations were 0.032 and 0.045 h^{-1}. Although there are small differences in terms of absolute values, some variability can be pointed out as the coefficient of variation was 39.8 and 45.9%. Concerning the open door scenario, differences between the two rooms are more evident as the mean air change rate increases up to 0.98 h^{-1} in the LR and 0.53 h^{-1} in the BR. The results of the two compartments are now quite different and the most reliable reason to explain it is the door area, which is much larger in the LR. In terms of variability, the coefficient of variation decreased in LR (30.0%) and increased in the BR (64.4%). Considering the entire data set, the maximum air change rate was 1.40 h^{-1} and occurred in the LR for the door open scenario. Regarding the shape of the probability distribution, no clear trend was found for skewness and kurtosis in both compartments.

5.2. Carbon Dioxide (CO_2) Measurements

The procedure used for estimating the ventilation rates through the CO_2 concentration requires selecting the period immediately after users leaving the compartment. In most cases, this situation occurred in the beginning of the night period in the LR and in the morning in BR. In the end, a total of 89 periods were selected, 47 in the LR and 42 in the BR. The results were statistically analysed and Figures 6 and 7 depict the histogram of the results separately for each compartment. The most important descriptive statistical indicators are also included.

	CO_2_LR_C	CO_2_LR_O
N	27	20
Mean	0.07	0.17
Std. deviation	0.014	0.070
Maximum	0.11	0.37
Minimum	0.05	0.09
C.V. (%)	20.3	41.8
Skewness	0.89	1.84
Kurtosis	0.83	3.25

(a)　　　　　　(b)　　　　　　(c)

Figure 6. Carbon dioxide (CO_2) measurements of the air change rate in the living room (LR): (**a**) Histogram—door closed (CO_2_LR_C); (**b**) Histogram—door open (CO_2_LR_O); (**c**) Descriptive statistics indicators.

|	CO_2_BR_C	CO_2_BR_O
N	23	19
Mean	0.12	0.33
Std. deviation	0.067	0.214
Maximum	0.32	0.82
Minimum	0.04	0.09
C.V. (%)	57.6	64.4
Skewness	1.50	0.82
Kurtosis	2.44	-0.38

(a)　　　　　　(b)　　　　　　(c)

Figure 7. Carbon dioxide (CO_2) measurements of the air change rate in the bedroom (BR): (**a**) Histogram—door closed (CO_2_BR_C); (**b**) Histogram—door open (CO_2_BR_O); (**c**) Descriptive statistics indicators.

The average air change rates were 0.07 h^{-1} and 0.12 h^{-1} in the LR and in the BR, respectively, for the door closed scenario, and the corresponding standard deviations were 0.014 and 0.067 h^{-1}. The coefficient of variation was significantly higher in the BR. In the open door scenario the air change rate was once again clearly different in the two spaces. In the LR the average air change rate was 0.17 h^{-1}, while in the BR this value was 0.33 h^{-1}. This was a rather unexpected result since the door area is higher in the LR, as previously discussed. The most logical explanation is the cross contamination of CO_2 from the adjacent compartments. This issue is further discussed in Section 6.1. In line with the SF_6 measurements, no clear trend was found for skewness and kurtosis in both compartments.

6. Discussion

6.1. Sulfur Hexafluoride (SF_6) Versus Carbon Dioxide (CO_2)

Although theoretically both tracer gases should produce the same result, in reality some important differences arise. To assess those differences, the results attained with the two methodologies were compared and a statistical analysis was performed. Figure 8 shows the box-plot representation of the results, separately for each compartment and boundary condition. Very similar distributions can be observed in the closed door scenarios; however, a very different situation can be observed when the door is open, especially in the living room. Moreover, a trend for higher ventilation rate is also noticeable when measured with SF_6.
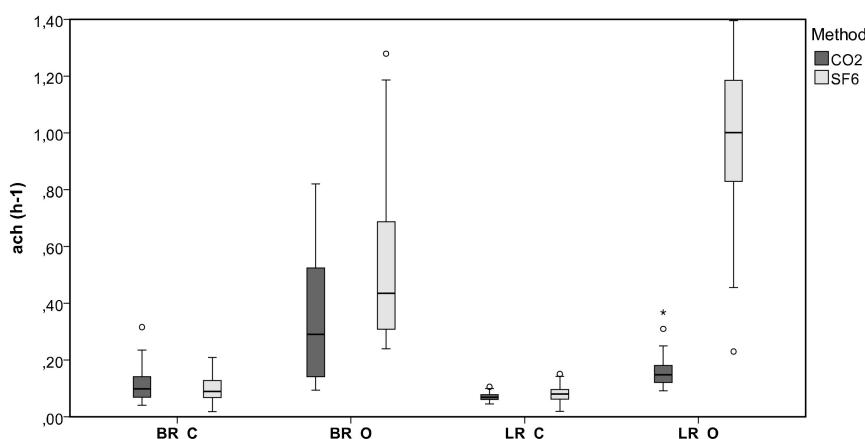
Figure 8. Air change rate using Sulfur hexafluoride (SF_6) and Carbon dioxide (CO_2) as tracer gas.

Using SF_6 as tracer gas provides a more reliable result, since CO_2 has a non-zero outdoor concentration, and presence of users in other spaces of the building affects the results due to the internal airflow. It is noteworthy that, when using occupant generated CO_2 as tracer gas, most of the results in the BR were attained in the morning period, while the occupants were leaving the house. On the other hand, measurements in the LR occurred in the night, when the occupants left the space and went to bed in the upper floor. Thus, the results confirm that the impact of occupancy, even on another floor, cannot be neglected, since it leads to important differences in the ventilation rate. Indeed, in the LR, with the door open, the average air change rate attained in the measurements with SF_6 was 0.98 h^{-1}, decreasing up to 0.17 h^{-1} when using the occupant generated CO_2 as tracer gas.

The statistical analysis of variance exposed differences between the data sets. The four groups of measurements were compared: living room with door closed (LR_C); living room with door open (LR_O); bedroom with door closed (BR_C); and bedroom with door open (BR_O). A significance level of 0.05 was used in the analysis.

In the closed door scenarios (LR_C and BR_C), the P-value of Levene's test for equality of variances was 0.001 and the null hypothesis of equal variances was, thus, rejected. Therefore, additional robust

tests of equality of means were carried out (Welch and Brown–Forsythe). Once again, no significant differences between means were found (P-value > 0.05).

In the open door scenarios, the result was different in the two spaces. In the BR_O, the resulting P-value of Levene's test for equality of variances was 0.226, confirming the null hypothesis of equal variances. However, no significant differences between means were found (ANOVA; P-value > 0.05). On the other hand, in the LR_O, the resulting P-value of Levene's test for equality of variances was 0.000, and the null hypothesis of equal variances was, once again, rejected. However, in the scenario, the additional robust tests of equality of means (Welch and Brown–Forsythe) revealed significant differences between means (P-value < 0.05).

## 6.2. Air Change Rate Versus Outdoor Conditions

Wind speed and indoor–outdoor temperature difference (buoyancy forces) are the natural causes for pressure differences to occur and, therefore, the main drivers of natural ventilation. Since both are time-dependent, a relation between the measured air change rate and their absolute values is expected. Figure 9a,b plots the wind speed versus the air change rate attained in each compartment using SF_6 as tracer gas, separately for the closed and the open door scenarios.
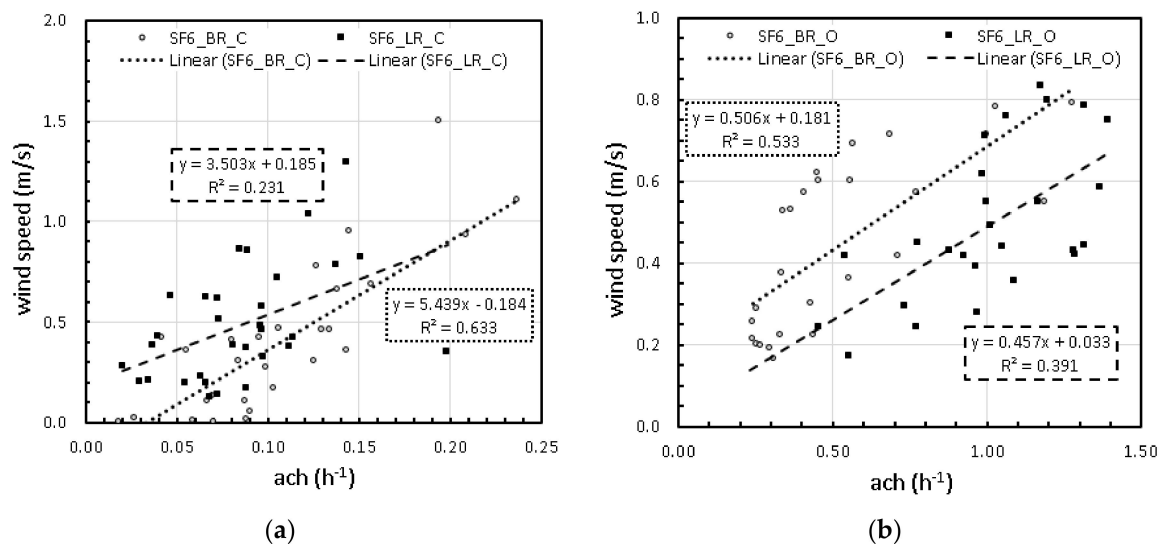
Figure 9. Air change rate versus wind speed: (**a**) Sulfur hexafluoride (SF_6)—door closed; (**b**) Sulfur hexafluoride (SF_6)—door open.

Despite the relatively low value of the wind speed, a trend for a correlation can be observed in the four data sets. However, the coefficient of determination, R^2, is too low for a definitive conclusion as it varied between 0.231 and 0.634. This relation is stronger in the BR, which can be explained by the fact that this compartment is located on the first floor and, thus, more exposed to the wind pressure on the façade. If one compares the results attained with different boundary conditions, no clear difference can be identified.

Figure 10 depicts the same result when using the occupant generated CO_2 as tracer gas. For this situation, only the door closed scenario was tested, due to the cross-contamination problems identified in the open door scenario and already discussed in the previous section. The linear correlation between the two parameters is now only evident in the BR. Once again, the problems of cross-contamination in the LR can help explain this situation. Moreover, the wind speed found during these measurements is clearly lower with obvious consequences in the possible correlation between the two variables.
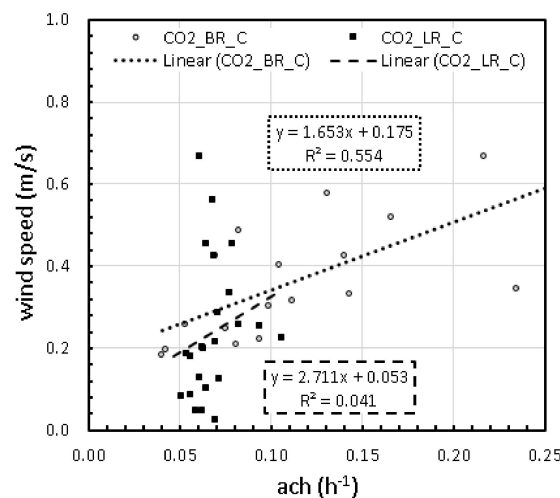
Figure 10. Air change rate versus wind speed: Carbon dioxide (CO_2)—door closed.

The same analysis is performed for the temperature gradient between the inside and the outside. Figure 11a,b shows the results separately for the open door and closed door scenarios, when using SF_6 as tracer gas. Concerning the temperature gradient, a strong dispersion of the results was found and thus no clear relation was identified. Since the tests were performed during a mild period of the shoulder season, the temperature gradient was low (maximum value around 3.8 °C), which helps justify this result.

(**a**)   (**b**)
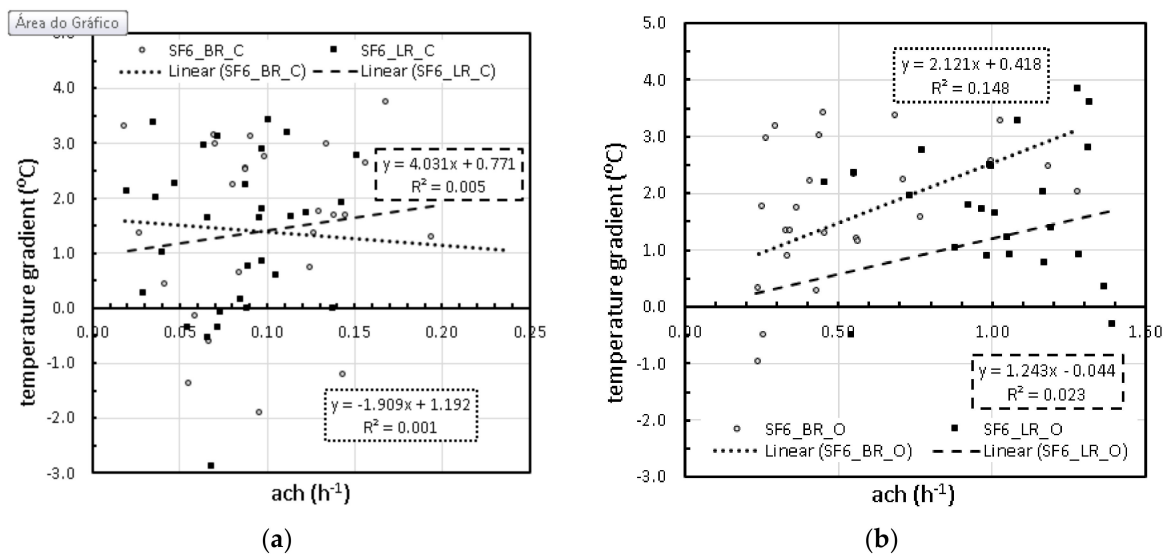
Figure 11. Air change rate versus indoor–outdoor temperature gradient: (**a**) Sulfur hexafluoride (SF_6)—door closed; (**b**) Sulfur hexafluoride (SF_6)—door open.

Despite this limitation of the sample, it was sought to identify the tests in which the effect of the temperature difference could be important. Thus, the tests in which this difference was higher than 3 °C were isolated. In order to give more robustness to this analysis by increasing the sample size, the measurements performed in the two compartments were combined, maintaining only the separation between the assemblies with the door open and the door closed. Figure 12 shows the results, where a trend for a linear correlation between the two variables can now be identified. The coefficient of determination, R^2, attained for the closed door measurements was 0.34 and for the open door scenario was 0.56. Previously published research also led to identical findings as linear correlations

between measurements of ventilation rate and temperature gradient were found but for temperature differences above 10 °C [12,40].
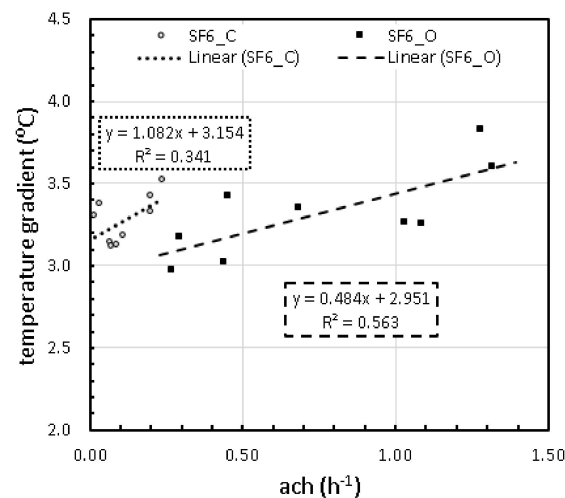
Figure 12. Air change rate versus indoor–outdoor temperature gradient: Sulfur hexafluoride (SF_6)—only temperature differences higher than 3 °C.

7. Conclusions

In naturally ventilated buildings, the air movement only depends on wind speed and indoor–outdoor temperature gradient (buoyancy forces). The time-dependency of these phenomena makes the accurate measurement of ventilation rates a rather complex task. In this paper, the variability in the measurement of ventilation rates using tracer gas and decay technique was evaluated and the following conclusions were drawn:

- If one intends to assess ventilation rates using tracer gas and the decay technique, one-time measurements are not enough. A large variability was found among the results with the coefficient of variation ranging from 20% (CO2_LR_C) to 64% (CO2_BR_O and SF6_BR_O). The variability was slightly higher in the BR, both for closed and open door scenarios, probably because it is located on the first floor. No large differences in variability were identified between open and closed door scenarios;
- Using occupant generated CO_2 as tracer gas requires guaranteeing that no users are inside the dwelling when the decay starts. The results showed large differences in the air change rate attained using CO_2 and SF_6 in the LR, for the open door scenario, when the occupants left the space but were in the upper floor. These results confirm the impact of occupancy as a source of cross-contamination issues;
- The effect of wind speed was confirmed as the main trigger mechanism in this case study in the mid-season period, where the indoor–outdoor temperature difference is not so significant;
- Concerning the indoor–outdoor temperature gradient, the low values found in the majority of the measurements constrained the conclusions. However, the results indicated that a minimum difference of 3 °C was required to observe the effect of the temperature;
- Additional research is required as the effect of the wind direction was not considered. Future works include increasing the sample size and establishing the importance of wind direction and indoor–outdoor temperature gradient. The new results will also allow extending and validating the key achievements of the present work.

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