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Experimental characterization of the impact of unsteady airflows on tracer gas measurement

Gabriel Remion^{1,2,*}, Bassam Moujalled¹, Mohamed El Mankibi²

¹ Cerema Centre-Est, Equipe BPE, 46 rue Saint-Theobald, 38080 L'isle d'Abeau, FRANCE

² ENTPE, Univeristy of Lyon, 3 rue Maurice Audin, 69120, Vaulx-en-velin, France

* gabriel.remion@entpe.fr

Abstract. Natural ventilation induces several issues when trying to measure airflows. Low pressure differences that drive natural airflows are very sensitive. A small pressure drop introduced by an airflow-meter would significantly affect the flow pattern. Furthermore, for window aired buildings or rooms, the implementation of a protocol to characterize the flow through a window is practically hard to implement and often poorly reliable. For these reasons, tracer gas methods are widely used to measure natural airflows. They do not interfere with the flow path, as they do not require any other instruments than concentration sensors. The principle is to inject a tracer gas inside a chamber and to observe the evolution of the concentration of the tracer gas. The knowledge of the emission rate of the gas, as well as its concentration evolution allows describing the airflow.

Unfortunately, tracer gas methods are highly sensitive to the measurement noise, which is likely to be significant for concentration sensors. Most used methods, in the literature, use regression techniques to reduce the measurement noise. However, the regression implies steady airflows during the measurement, which should theoretically discard natural airflows. For lack of better methods, these techniques are often used in natural conditions, regardless of the variation of airflows. The present paper experimentally assess the impact of variable airflows on the accuracy of most common tracer gas methods, namely the constant injection and the concentration decay methods. The experiment was implemented in a laboratory cell, taking advantage of a controllable extract fan to simulate natural airflows, while allowing the direct measurement of the airflow in the extract duct. This value provides the reference value for the comparison of tracer gas methods results. Insights are also given, using signal-processing techniques to improve the reliability of tracer gas methods under variable airflows.

1. Introduction

Measuring natural ventilation performance is a challenging task. The plurality of openings, the diversity of natural ventilation systems and the intrusive nature of flow meters prevent from directly measuring their performance. Indirect methods, called “tracer gas methods” are commonly used to characterize the performance of ventilation systems, because they provide an estimation of the Air Change Rate (ACR) without interfering with the flow pattern. ACR is well suited for characterizing ventilation performance as it gives an indication on the capacity to remove a pollutant [1]. These methods rely on the analysis of the evolution of the tracer gas concentration. There are three main types of tracer gas methods: the constant injection, the concentration decay, and the constant concentration methods. The constant injection and the constant concentration methods both consist in dosing the gas continuously during the measurement. The distinction between them is that the latter is closed-loop to a concentration value enabled by an automated mass flow controller, whereas the first releases the gas at a constant flow. The concentration decay method requires the injection of the gas before the measurement, and the evolution of the concentration of the gas provides the ACR. Descriptions of methods were realized by Roulet & Vandaele and are subjects to international standards such as ISO 12569, or ASTM E741 [2]–[4].



Tracer gas methods are, however, characterized by important sources of uncertainty, which can be measurement uncertainty, or model uncertainty. They are very sensitive to the measurement noise. The most used method, i.e. the multi-points decay method [5]–[8], uses a regression to smooth the measurement uncertainty, but the regression requires steady airflows. The wide use of the multi-points method is explained by a good agreement of implementation requirements with natural ventilation specificities, and a rather good accuracy under steady airflows. The aim of the experiment, presented here, is to compare the accuracy of the multi-points decay method under variable airflows, to the accuracy of other tracer gas methods that theoretically tolerate variable airflows, namely the 2 points decay method, and the inverse concentration constant dosing method. The 2 points decay method is supposed to be less accurate under steady airflows, which explains its lower use in the literature. The inverse constant dosing method is practically less easy to implement in natural ventilated rooms, because it requires several dosing points of the gas. Furthermore, direct losses of the gas through the outlet may lead to large uncertainties [9].

2. Methods

2.1. Experimental setup

The test was conducted in an experimental cell of 2.45m width, 3.17m length and 2.65m height, leading to a volume of 20.6 m³. The infiltration rate has been estimated at 0.14 Vol/h using the tracer gas decay method. It was taken into account in the computation of the standard deviation due to measurement errors. The laboratory cell is featured with a controllable fan, allowing to simulate airflow variation profiles. An airflow-meter, which is installed in the extract duct connecting the fan to the room, provides the reference value of the airflow rate. Laussmann & Helm have proved the suitability of CO₂ by comparing tracer gas results from CO₂ and SF₆ [10]. We chose CO₂ as a tracer gas during the experiment, considering that no internal sources were to take into account. 5 stand-alone CO₂ sensors with an accuracy of 3% +/- 50 ppm, based on the Infrared Absorption technology, were used inside the enclosure. These sensors are averaged to inhibit the negative effect of inhomogeneous tracer gas. The acquisition frequency was set to 11 seconds (the highest allowed by these sensors). Each experiment has been repeated three times to strengthen the reliability of results.

2.2. Determination of airflow profiles

A mechanical ventilation system was used to reproduce airflows in accordance with airflows induced by natural conditions. We considered stack and cross ventilation. Stack ventilation was simulated by computing airflows from the formula characterizing the flow between two openings of different height (**equation 1**). The formula was filled with meteorological data measured by a local weather station in Lyon, France. Stack ventilation is mainly induced by buoyancy effects. In order to have significant fluctuations of airflow, we looked for a day with a significant temperature amplitude.

$$Q_{stack}(t) = C_d \cdot A_{eff} \cdot \sqrt{\frac{2 \cdot g \cdot \rho_{ext} \cdot H \cdot \frac{T_{ext} - T_{int}}{T_{int}}}{\rho_{int}}} \quad (1)$$

With C_d [] the discharge coefficient, A_{eff} [m²] the effective area, ρ_{ext} and ρ_{int} [kg.m⁻³] the external and the internal density of the air, H [m] is the height between two openings, T_{ext} and T_{int} [°C] the external and internal temperatures, g [m.s⁻²] the acceleration of gravity.

Airflows were then computed and two profiles were isolated, one in the morning leading to a monotonous decreasing profile [75 to 50 m³.h⁻¹ in 2 hours], and one in the afternoon, leading to a monotonous increasing profile [50 to 65 m³.h⁻¹ in 2 hours]. It corresponds to temperature fluctuations of 4°C in 2 hours. Those particular profiles were selected because it allows to have more than 5 air renewals in 2 hours (which is important for the constant dosing method) and because their mean values are similar.

To simulate a flow consistent with cross-ventilation, we used data from a study conducted by J. Lo et al. [11]. They investigated the flow crossing windows of a multi-zone building. We determined two profiles from those data, based on a different multiplier coefficient (0.3 and 0.7). The

coefficient 0.3 was chosen to set the mean airflow at the same level than the two aforementioned profiles. The coefficient 0.7 allows to test the impact on the accuracy of tracer gas methods of wider amplitude fluctuations, varying with higher speeds.

Finally, a stationary profile was set to the mean airflow value of the three first profiles mentioned above. Figure 1 shows airflows measured by the airflow meter, for each variation profile that have been used in the experiment.

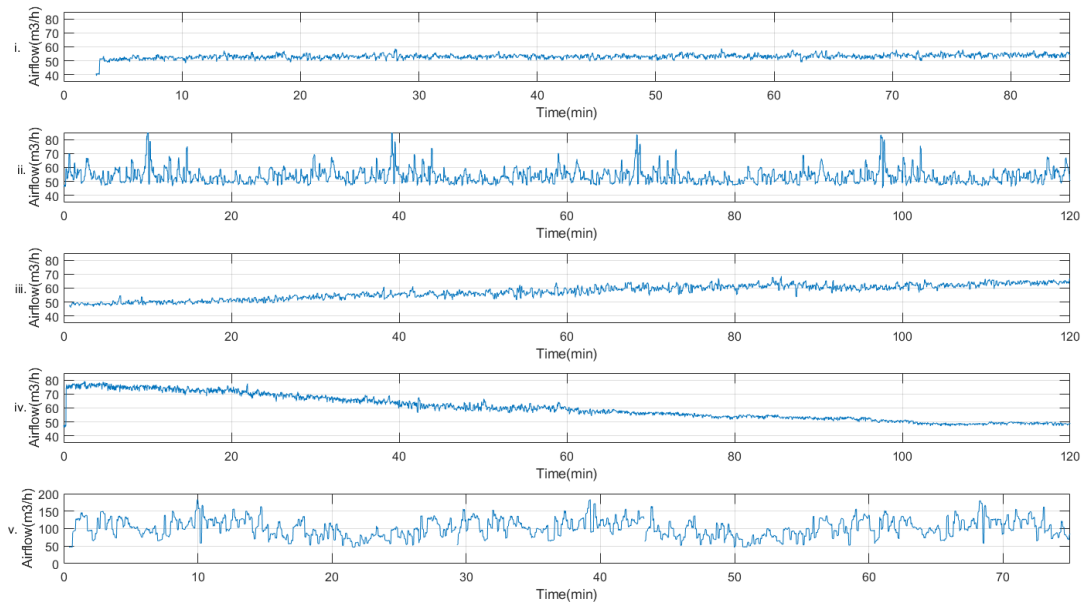


Figure 1. Airflow variation profiles: (i) stationary, (ii) cross, (iii) stack increasing (up), (iv) stack decreasing (down), (v) high cross (hicross)

2.3. Calculation of the ACR

Each tracer gas method ensues from the mass balance equation:

$$V \frac{d(C(t))}{dt} + Q(t) * C(t) = E(t) \quad (2)$$

With V [m^3] the volume, $C(t)$ [m^3/m^3] the concentration, $Q(t)$ [$\text{m}^3 \cdot \text{s}^{-1}$] the airflow and $E(t)$ [$\text{m}^3 \cdot \text{s}^{-1}$] the emission rate.

This paragraph will not present the theoretical development leading to formulas of each method that are tested on the experiment. However, techniques used to analytically solve **equation 2** will induce practical limitations, which is why they are mentioned here. Sherman propose three techniques to solve **equation 2** : the averaging technique, the integral technique, and the regression technique [12]. The first two techniques have no restrictions on the airflow during the experiment, whereas the regression assumes a stationary airflow during the measurement. We will test two concentration decay methods, often called the 2 points and the multi-points methods, and one constant dosing method, called the inverse concentration method. Two of the tested methods are based on the averaging technique, namely the 2 points decay method and the inverse concentration constant dosing method. The multi-points decay method is based on the regression technique, which justifies the assumption about stationary airflows.

Among decay methods, the multi-points method is often preferred over the 2 points method as the regression allows to considerably smooth measurement errors (under stationary conditions). Cui et al. compared their standard deviation and found higher uncertainty of 6% for the 2 points method [13]. We will examine results of the 2 points and the multi-points method under variable airflows. In spite of its more complex implementation requirements, the inverse concentration constant dosing strategy was also tested because of its tolerance towards variable airflows.

3. Results

3.1. Accuracy of decay methods under variable airflows

The accuracy of both decay methods was characterized by analysing the deviation between the airflow calculated from decay methods, and the airflow measured by the calibrated airflow-meter, between 1 and 2 air changes (AC). This period is chosen because the standard ISO 12569 prescribes to wait at least 1 air change, but not too long, as the tracer gas concentration should not be too close to its ambient value [3]. We computed the median value of the standard deviation due to measurement noise over this period from formulas given by Cui et al., for the 2 points and the multi-points methods [13]. They are reported in Figure 2 through dash lines. Figure 2 shows boxplots of experimental deviations of airflows between 1 and 2 air changes (AC), for the multi-points and the 2 points methods. Despite the three times repetition of each experiment, only one experiment by profile is shown, in order to ease up the observation (the standard deviation between each repetition is inferior than the standard deviation due to the measurement noise, which allows us to do so).

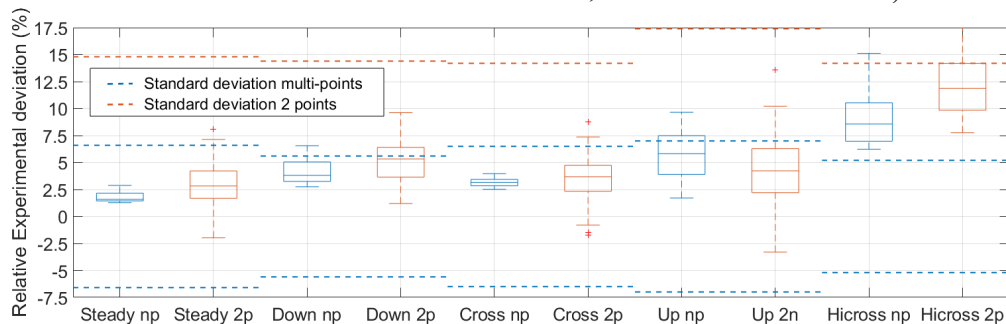


Figure 2. Boxplots of the experimental deviation between the measured and the calculated airflows for the 2 points and the multi-points methods, during the period of 1 to 2 air changes.

Regarding the multi-points method, apart from the highly varying profile, we can see from Figure 2 that standard deviations encompass medians of experimental relative deviations ranging from 1.6% (0.9 m³/h) for the steady profile to 5.8% (3.2 m³/h) for the increasing profile. The highly varying profile leads to a median value of the experimental deviation of 8.6% (8.8 m³/h), 3 points above the calculated standard deviation.

Concerning now the 2 points method (boxes in orange) each median values are within the standard deviation, as we could expect because this method allows variable airflows. However, deviations between the 2 points and the multi-points method are below 3.3%, whereas the standard deviation is almost 10% greater. This may be explained by the fact that 5 sensors are averaged, which is likely to smooth the measurement noise.

3.2. Accuracy of constant dosing method under variable airflows

Constant dosing strategies require to have reached a nearly equilibrium concentration, which means that, at least, 3 AC have been waiting, representing 95% of the equilibrium value. The calculation was computed for each time step from 3 to 5 AC. We reported standard deviations due to the measurement noise calculated by the error propagation law on Figure 3. Figure 3 shows the boxplot of the deviation between the reference airflow and the calculated one from the inverse concentration method. It theoretically tolerates variable airflows. We can see from Figure 3 that each profile leads to a median deviation inferior than the standard deviation, except for the decreasing profile. The latter leads to deviations higher than 27.5% (14.8 m³/h), which is far from usual uncertainties. The highly varying profile leads to a median deviation almost equal to 0%, but its interquartile distance is nearly equal to 15% (15.4 m³/h). Otherwise, accuracies are in the order of magnitude of the accuracy of the multi-points decay method.

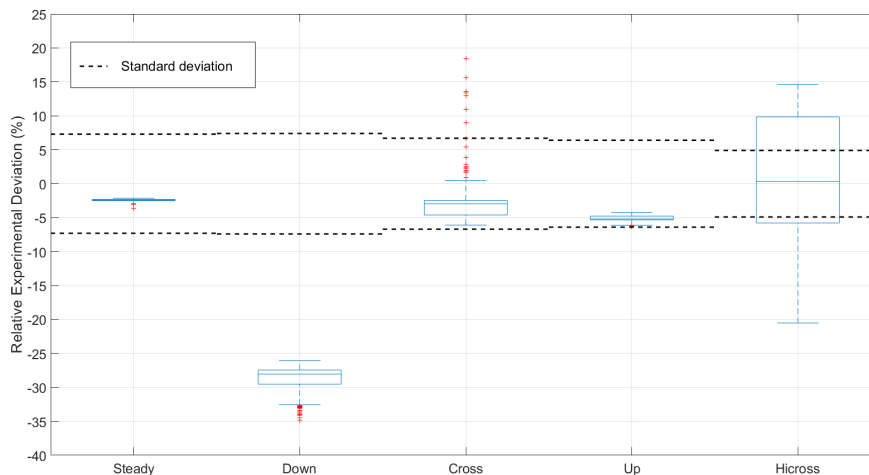


Figure 3. Boxplots of the experimental deviation between the measured and the calculated airflows for the inverse concentration constant dosing method, from 3 AC to the end

4. Discussion

The inverse concentration constant dosing method was tested because it tolerates variable airflows. It is more difficult to implement than decay methods as the dosing of the gas has to be homogeneous. In natural ventilation, a mixing fan should be avoided in order not to interfere with the flow pattern. Thus, the homogeneous dosing implies the implementation of several dosing points. The comparison of its accuracy with the accuracy of decay methods does not justify to choose this method instead of decay methods, to characterize natural variable airflows. Regarding the concentration decay method, the calculated standard deviation encompasses experimental deviations for almost every profile. Only the strongly varying profile leads to higher deviations, 3 points above the standard deviation. Also, the 2 points method leads to closer results from the multi-points method than suggested by the calculation of standard deviations, but are still more scattered.

Stack airflows were computed with a significant temperature variation of 4 °C in 2 hours. The cross ventilation airflow profile can be represented by a variation of standard deviation of +/-10% around the mean value of 2.7 Vol.h⁻¹ (55 m³.h⁻¹), with a maximum airflow of 83 m³.h⁻¹. Under those conditions, the variation of airflow does not lead to higher uncertainties than the measurement noise. The multi-points decay method can be used, despite the variation of airflow. However, we highlighted the influence of the speed of variation. The highly varying profile, representing airflows varying around 5 Vol.h⁻¹, (same variation than the cross ventilation profile in percentage, but two times higher in absolute) could be affecting the mixing of the air, and indirectly affecting the accuracy of the method. Even under those conditions, the 2 points method does not allow better results, as its standard deviation is significantly higher than the multi-points one. More work has to be done to test other levels of airflows, and other amplitudes of variation.

5. Conclusion

An experiment was conducted under laboratory conditions to compare the accuracy of 3 tracer gas methods under variable airflows. The multi-points decay method is the most used method in the literature, with a good accuracy, an ease of implementation, but an intolerance towards variable airflows. The two other methods tolerate variable airflows, but the 2 points decay method has significant measurement uncertainties, and the inverse concentration constant dosing method is difficult to implement in natural ventilation. It has been observed that variable airflows consistent with stack or cross ventilation airflows do not alter the accuracy of the multi-points decay method accuracy which is mainly governed by the measurement uncertainty. However, very high levels of airflows of 5 ACH varying about +/-10%, may lead to extra-uncertainties, probably caused by a weaker mixing of the fresh air with the old air. Deviations under these conditions, were about 10%. These conclusions

should be verified on in-situ conditions, with the additional homogeneity of the gas issue, which is known to have a significant impact on the accuracy of tracer gas methods.

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