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Review of tracer gas-based methods for the characterization of natural ventilation performance: comparative analysis of their accuracy

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Abstract

Natural ventilation systems, taking advantage of natural driving forces, help to reconcile energy efficient buildings with a good Indoor Air Quality (IAQ). Its efficiency depends on several factors including climatic regions, seasons, building configurations, and surrounding characteristics. Building regulations often prescribe minimum airflow, which promotes the implementation of mechanical ventilation systems in new constructions. Their performance is invariant and easily verifiable making them convenient. Increasing incentives towards building energy sobriety encourage the use of natural or hybrid ventilation systems in new buildings. However, the lack of a measurement protocol often prevent from justifying that those systems verify air change requirements. It partially explains their weak implementation in new constructions. The purpose of this paper consists in establishing a literature review concerning the measurement of natural airflows. The literature review allowed identifying tracer gas methods, including also occupant-generated CO₂ methods, as being widely used methods to assess natural ventilation. Tracer gas methods allow the measurement of natural airflows, as well as indicators related to air distribution, without interfering with the flow pattern. After describing those methods, this paper discusses their suitability towards the measurement of natural airflows. They either rely on assumptions whose violation impact their accuracy, or practical limitations prevent from in-situ measuring. For instance, some methods, which are widely used in natural ventilation, assume steady airflows during the

measurement. Some innovative protocols, also based on tracer gas principles are also reported. Some insights are given towards an increase of the reliability of tracer gas methods.

Keywords:

Tracer gas methods, Occupant-generated CO₂ methods, Natural airflow measurement

1. Introduction

1 The building sector is the most energy consuming sector of European countries, with a
2 share of 40% of the final energy consumption [1]. Natural ventilation systems, taking advantage
3 of natural driving forces, allow reconciling energy efficient buildings with an acceptable Indoor
4 Air Quality (IAQ). Energy gains allowed by natural ventilation systems come from savings
5 associated with fan consumption, as well as night free-cooling. Schulze and Eicker [2]
6 compared the simulated energy consumption of a 1150 m² office building passively cooled and
7 ventilated, with the energy consumption of the same building with an air conditioner and
8 mechanical ventilation. The simulation is conducted in three different places: Istanbul,
9 Stuttgart, and Turin. Estimated energy gains related to fan consumption are about 4
10 kWh/m²/year while using single-sided natural ventilation instead of mechanical ones. Cooling
11 gains occurring with night free cooling was estimated between 13 kWh/m²/year in Stuttgart
12 and 44 kWh/m²/year in Istanbul [2]. Gratia et al. [3] simulated an office building in Belgium to
13 estimate energy gains allowed by free-cooling. They found a reduction of cooling needs up to
14 40% during a sunny summer day [3].

15 In France, building regulations impose permanent airflow rates inside buildings to maintain a
16 good IAQ. In view of the variable performance of natural ventilation systems, french regulations
17 indirectly promote the use of mechanical ventilation systems in new buildings. Moreover, a
18 standardized protocol named PROMEVENT [4] has improved the reliability of the evaluation
19 procedure of their performance, which eases the verification of required airflows. Direct airflow
20 or pressure measurements at the outlet allow assessing the ability of a mechanical system to
21 deliver standard-required fresh air.

22 In Europe, the implementation of natural ventilation in new buildings is challenging. Specific
23 performance-based procedures are required, intending to prove that the system actually leads
24 to airflow rates prescribed by regulations [5]. These performance-based procedures are often
25 realised thanks to network modelling, which complicates significantly the design stage [6].
26 Standardised pressure coefficients, and averaged wind speeds used in such models can lead
27 to significant discrepancies [7], [8]. Furthermore, the lack of measurement protocol suited to
28 the assessment of natural airflows prevent from verifying the predicted airflow at the building
29 commissioning. It justifies the weak implementation of natural ventilation in new construction.
30 Designers have several obstacles to overcome.

31 The particularity of natural ventilation is that modelling and measurement methods have to be
32 jointly considered to assess its performance. The knowledge on natural ventilation
33 performance suffers from the weak reliability in both modelling and measurement methods.
34 The following background section will first introduce challenges in measuring natural ventilation
35 airflows, and then, present an overview of modelling methods used in natural ventilation, while
36 questioning their reliability.

1.1. Background

1.1.1. Measuring natural airflows, a challenging task

1 Natural airflows are driven by low pressure differences, induced by the wind and by the
2 inside/outside temperature difference. Low pressures involved in natural airflows, prevent from
3 directly measuring airflow rates with instruments used to characterize mechanical airflows.
4 Under natural conditions, the airflow meter could interfere with the unstable flow pattern, which
5 would result in a non-reliable measurement. Some studies investigated the flow crossing
6 windows thanks to thermal anemometers [9], or pressure transducers [10], [11]. These
7 techniques assume the velocity field to be uniform along the cross section of the window, and
8 cannot account for the flow close to edges, which can lead to significant uncertainties [10].
9 Variable driving forces lead to another issue compared with mechanical ventilation systems:
10 the measurement method must record the variation or at least, the mean airflow rate during a

11 given period. Etheridge [12] propose the period of 0.5 h as airflow rates are usually assumed
12 to be stationary over such a period. Those characteristics justify the lack of measurement
13 protocol characterizing the performance of natural ventilation systems.

14 Technical difficulties related to natural ventilation aforementioned are overcome by using
15 indirect methods based on the concentration of a tracer gas, called tracer gas methods. They
16 have the advantage not to interfere with the flow pattern. They also account for
17 infiltration/exfiltration flows, compared with conventional airflow-meters, which is more reliable
18 [10]. However, they rely on assumptions whose violation results in an increase of uncertainty.
19 Most critical assumptions are the homogeneity of the tracer gas in the enclosure and the
20 invariant nature of airflow rates during the measurement. The latter theoretically restricts the
21 number of suited tracer gas methods as a fluctuating wind would induce fluctuations of airflow
22 rates, but this requirement is often ignored. The fluctuation of wind-driven airflows is induced,
23 in part, by the fluctuation of surface pressure [13]. Its impact on natural airflows has been
24 investigated in some studies [11], [14]. The pressure coefficient is strongly influenced by the
25 wind direction, which is quite unstable [11]. Small variations ($<10^\circ$) in the wind direction can
26 lead to significant variations of the pressure coefficient (20 to 30 Pa) [11]. Park et al. [14]
27 propose a formula based on experiments, which allows computing unsteady airflows thanks to
28 the average airflow and the ratio of the difference of pressure coefficient between two
29 openings, by its standard deviation. In other words, the unsteady airflow can be calculated
30 thanks to the variation of pressure coefficients. As the pressure coefficient is likely to fluctuate
31 significantly, so is the Air Change per Hour (ACH), making the steady airflow assumption hardly
32 suitable for natural airflows.

33 Other measurement methods derived from tracer gas methods are occupant-generated CO₂
34 methods [15]. They often require to have access to the occupancy rate, as well as the emission
35 rate. The emission rate, depending on people and activities, introduces another uncertainty
36 source. Also, in most of methods, the occupancy should not vary during a long time. Each one

37 of these methods will first be described and then discussed in the following, regarding their
38 suitability to the assessment of natural ventilation's performance.

1.1.2. Overview of modelling methods, reciprocally linked to measurement methods

1 The other challenge regarding the performance assessment of natural ventilation
2 systems concerns their several dependencies including the building geometry, openings
3 configuration, and climatic conditions. Modelling methods are, thus, required to allow the
4 extrapolation of the global performance from measurements, as much as measurement
5 methods are needed to validate models. Modelling methods are not the subject of the present
6 paper, but they are briefly presented here, as they will serve the analysis of methods
7 uncertainty.

8 Three modelling methods are used to model natural airflows: empirical and analytical models,
9 network models, and Computational Fluid Dynamics (CFD) models. Empirical and analytical
10 models are used in standards to compute airflows [16]. They assume the homogeneity of each
11 state parameters inside the whole building. Airflows are computed thanks to pressure laws [7].
12 These models are the most straightforward ones but suffer from the high number of
13 assumptions required to close the system of equations, resulting in a poor reliability regarding
14 wind effects [17]. However, major work is done towards a better consideration of wind effects
15 involved in single-sided ventilation and cross ventilation, which would greatly participate in an
16 increase of their reliability [18]–[21]. Network models require computer software such as
17 COMIS [22], CONTAM, or MATHYS [21], and are based on the resolution of Bernoulli
18 equations. Zones are defined inside the building with homogeneous state parameters, and
19 transfers between zones rely on pressure laws. Zhai et al. [22] realised a review of main
20 network modelling programs, and they did not find significant differences between them as
21 physics principles are similar. As empirical and analytical models, they treat wind effects with
22 difficulty, mainly because of the use of standardized pressure coefficients and averaged wind

23 speeds and directions [7], [8]. Finally, CFD models are the most used in natural ventilation as,
24 being based on Navier-Stokes equations resolution, they account well for wind effects. To
25 reduce the computational cost, two methods exist. The computation of Navier-Stokes
26 equations can be averaged over a period, which is called Reynolds Averaged Navier Stokes
27 (RANS) methods. Otherwise, a coarser mesh can be defined to ignore smaller scales eddies,
28 and this method is called Large Eddy Simulation (LES) method. Van Hoff et al. [23] realised a
29 review and a comparison of those CFD models. They found that, compared with experimental
30 data from a reduced-scale experiment conducted in a wind tunnel, LES method performs better
31 than RANS methods, but the computational time increases with a factor of 80 to 100 [23].
32 Being the most sophisticated models, the computational cost remains significant, even when
33 RANS or LES methods are used. Also, the huge amount of assumptions made by the modeller
34 requires a field validation, which is trouble-wise for natural ventilation, as already explained.
35 The validation technique is different in every study, which prevent from reliably comparing
36 models. The validation may be done with the measurement of state parameters [24], with
37 Particle Imaging Velocimetry (PIV) [25], with comparison to other studies [26], and with tracer
38 gas [10].

1.2. Objectives

1 A wider knowledge on natural ventilation performance can come from an increase of
2 the reliability of the measurement protocols of natural airflows. Along with helping to calibrate
3 models, it would also allow the verification of airflows predicted by them.
4 This paper presents a literature review on the assessment of natural ventilation performance,
5 with a focus on the accuracy of natural airflows measurement methods. This literature review
6 intends to provide the basis to allow further work on developing a new protocol, or increasing
7 the reliability of existing ones, by characterizing their uncertainty under natural ventilation
8 conditions. The aim of the present paper is to identify the best-suited, and accurate methods,
9 as well as insights to increase their reliability. A reliable measurement protocol of natural
10 airflows would have several benefits:

- 11 - help the wider implementation of natural ventilation in new constructions, at least
- 12 partially with the development of hybrid ventilation technologies;
- 13 - help to calibrate natural ventilation models;
- 14 - help research projects that treat improvements of natural ventilation modelling by
- 15 homogenizing field validation procedures;
- 16 - help to reduce the performance gap of buildings between the one predicted at the
- 17 design stage, and the actual one. As natural ventilation's performance is poorly known,
- 18 the estimation of energy losses due to the renewal of air of naturally ventilated buildings
- 19 can lead to significant discrepancies, notably because of window opening by the
- 20 occupant, which is often considered as one of the main source of the gap [27], [28].

2. Methodology

1 The analysis of measurement methods used for the characterization of natural ventilation
2 systems was based on forty-nine studies published between 1980 and 2018, and four
3 international standards from Europe and the United States. This sample of articles is non-
4 exhaustive and gathers mainly articles, and some books and reports. The comparative
5 analysis of the accuracy presented in section 4 requires to consider studies that compare
6 measurement methods to a reference, which is complicated in natural ventilation. For this
7 reason, the sample of articles also includes studies involving mechanical ventilation because
8 the reference value may be provided by airflow-meters in ducts for instance.

9 **Table 1** presents references used for the analysis. Studies are sorted regarding several
10 criteria. The third column (type of study) mentions whether the study basically uses
11 measurement methods, whether it tests its accuracy, or if the study is a review, or a theoretical
12 development. Then, the ventilation system is mentioned: natural, mechanical, or both. The
13 distinction is done if an article tackles the issue of conventional tracer gas method, or if it is
14 about occupant-generated CO₂ method. The measurement method is given in the following
15 column: decay, constant injection, constant concentration, or pulse for tracer gas methods;
16 and decay, build-up, or Transient Mass Balance Equation for occupant-generated CO₂

17 methods. The measured parameter is, then, specified because, as it will be described in
 18 section 3, tracer gas methods can be used for the measurement of the ACH, the age of air,
 19 and the effective volume of a room. Some articles compare measurement methods with
 20 models, it is mentioned in the second to last column. The reference method used for
 21 comparison in studies that test the accuracy of tracer gas or occupant-generated CO₂
 22 methods, is given in the last column. The accuracy testing could also be done by comparison
 23 with CFD models, which would be mentioned in the second to last column.

24 *Table 1 : non-exhaustive review of articles treating the measurement of natural ventilation performance*

Authors	Ref.	Type of study	Ventilation system	Tracer gas or Occupant CO ₂	Method	Measured parameter	Comparison with airflow model	Reference Measurement
<i>(Allab, 2017)</i>	[29]	Test	Both	TG	Dec	ACH; Age	-	hot wire
<i>(ASTM E741, 2017)</i>	[30]	Standard	Both-	TG	Dec ; CI; CC	ACH	-	-
<i>(ASTM D6245, 2012)</i>	[31]	Standard	Both-	Occ	TMBE ; Bui ; Dec	ACH	-	-
<i>(Batterman, 2017)</i>	[15]	Review	Nat	Occ	TMBE ; Dec ; Bui ; St	ACH	-	-
<i>(Bekö, 2010)</i>	[32]	Use	Nat	Occ	Bui ; St ; Dec	ACH	-	-
<i>(Bekö, 2016)</i>	[33]	Test	Nat	Occ; TG	Bui ; CI	ACH	-	CC
<i>(Blomsterberg, 1999)</i>	[34]	Use	Both	TG	CC ; CI	ACH	Net	-
<i>(Buratti, 2011)</i>	[35]	Test	Nat	TG	Dec	Age	CFD	-
<i>(Caciolo, 2011)</i>	[9]	Use	Nat	TG	Dec	ACH	Emp	-
<i>(Caciolo, 2013)</i>	[19]	Use	Nat	TG	Dec	ACH	Emp ; CFD	-
<i>(Dias Carrinho, 2015)</i>	[36]	Test	Nat	TG	Cyclic atm. CO ₂	ACH	-	Occ dec
<i>(Chao, 2004)</i>	[37]	Test	Both	TG	CC ; Dec	ACH	-	CC
<i>(Chu, 2015)</i>	[38]	Use	Nat	TG	Dec	ACH	-	Other studies
<i>(Coley, 2002)</i>	[39]	Test	Nat	Occ	TMBE	ACH	-	Dec
<i>(Cui, 2015)</i>	[40]	Test	Mech	TG	Dec	ACH	-	Air.-meter
<i>(Cui, 2015)</i>	[41]	Use	Nat	TG	Dec	ACH	Emp	-
<i>(Demmers, 2000)</i>	[42]	Test	Mech	TG	CI	ACH	CFD	Calibrated fan wheel
<i>(Duarte, 2018)</i>	[43]	Theory	Nat	Occ	TMBE Kalman filter	ACH	-	-
<i>(Dias Carrinho, 2015)</i>	[36]	Test	Nat	-	Cyclic atm. CO ₂	ACH	-	Occ dec

<i>(Etheridge, 2012)</i>	[12]	Theory	Nat	TG	Dec ; CI ; CC	ACH	-	-
<i>(Gough, 2018)</i>	[44]	Use	Nat	TG	Dec	ACH	Emp	-
<i>(Han, 2011)</i>	[45]	Theory	Mech	TG	Dec ; CI	Age	-	-
<i>(Hou, 2018)</i>	[46]	Use	Nat	Occ	Bui	ACH	-	-
<i>(ISO 12569, 2017)</i>	[47]	Standard	-	TG	Dec ; CI ; CC	ACH	-	-
<i>(ISO 16000-8, 2017)</i>	[48]	Standard	-	TG	Dec ; CI ; Pulse	Age	-	-
<i>(Koinakis, 2005)</i>	[49]	Use	Nat	TG	Dec	ACH	Net	-
<i>(Laussmann, 2011)</i>	[50]	Theory	-	TG	Dec ; CI ; CC	ACH	-	-
<i>(Lu, 2009)</i>	[51]	Test	Mech	Occ	Dec	ACH	-	Pressure
<i>(Lunden, 2012)</i>	[52]	Use	Nat	TG	CI	ACH	-	-
<i>(Macarulla, 2018)</i>	[53]	Test	Nat	Occ	Grey-box	ACH	-	-
<i>(Mikola, 2017)</i>	[54]	Use	Nat	Occ	Bui	ACH	-	-
<i>(Nikoloupoulos, 2012)</i>	[10]	Test	Nat	TG	Dec	ACH	CFD	-
<i>(Okuyama, 2011)</i>	[55]	Theory	Nat	TG	Dec	ACH	-	-
<i>(Penman, 1980)</i>	[56]	Use	Nat	Occ	TMBE	ACH	-	-
<i>(Riffat, 1993)</i>	[57]	Use	Nat	TG	Dec	Eff.Volume	-	-
<i>(Roulet, 1991)</i>	[58]	Theory	Mech	TG	Dec	Age	-	-
<i>(Roulet, 1991)</i>	[59]	Theory	-	TG	Dec ; CI ; CC	ACH; Age	-	-
<i>(Roulet, 2002)</i>	[60]	Test	Nat	Occ	Dec	ACH	-	Dec SF6
<i>(Sandberg, 1983)</i>	[61]	Theory	Mech	TG	CI ; Dec	Age	-	-
<i>(Sandberg, 1985)</i>	[62]	Test	Mech	TG	Dec ; CC	ACH; age	-	Air.-meter
<i>(Sandberg, 1989)</i>	[63]	Test	Mech	TG	CI ; CC	ACH	-	Air.-meter
<i>(Santamouris, 2008)</i>	[64]	Use	Nat	TG	Dec	ACH	-	-
<i>(Schibuola, 2016)</i>	[65]	Use	Nat	Occ	TMBE	ACH	-	-
<i>(Sherman, 1990)</i>	[66]	Theory	-	TG	Dec ; CI ; CC	ACH	-	-
<i>(Sherman, 2014)</i>	[67]	Test	Nat	TG	CI	ACH	-	-
<i>(Smith, 1988)</i>	[68]	Test	Nat	Occ	TMBE	ACH	-	-
<i>(Sutcliffe, 1990)</i>	[69]	Test	-	TG	Dec ; CI ; Pulse	Age	-	-
<i>(Turanjanin, 2014)</i>	[70]	Use	Nat	Occ	Dec	ACH	-	-
<i>(Turiel, 1980)</i>	[71]	Test	Nat	Occ	Dec	ACH	-	Dec ; Air.-meter
<i>(Van Buggenhout, 2006)</i>	[72]	Use	Mech	TG	CI	Age	Grey-box	CI
<i>(Van buggenhout, 2009)</i>	[73]	Test	Mech	TG	Dec	ACH	-	Air.-meter

25 *Mech = mechanical ; Nat = natural; TG = Tracer gas; Occ = Occupant-generated CO₂; Dec = Decay;*
26 *CC = Constant Concentration; CI = Constant Injection; TMBE = Transient mass balance equation; Bui*
27 *= Build-up; St= Steady-state; Cyclic atm. CO₂ = Cyclic atmospheric CO₂ variation; Air.-meter = Airflow-*
28 *meter; ACH = Air Change per Hour; Emp = Empirical; CFD = Computational Fluid Dynamic; Net.*
29 *=Network.*

30 Section 3 introduces conventional tracer gas methods as well as occupant-generated CO₂
31 tracer gas methods, and other innovative tracer gas-based methods. Their practical
32 advantages and drawbacks regarding the measurement of in-situ natural airflows are
33 mentioned. Beyond treating natural airflow measurement, the following section will present
34 how tracer gas methods allow measuring the age of air. Section 4 will stand for a compared
35 analysis, based on test studies mentioned in **table 1**, of the accuracy of methods presented in
36 3. As only tracer gas methods allow the measurement of the age of air, their accuracy towards
37 this indicator can not be tested. This is why the comparative analysis of the accuracy of tracer
38 gas methods presented in section 4 will only concern the measurement of the ACH.

3. Overview of tracer gas-based measurement methods

1 Tracer gas methods are widely used to characterize natural airflows. They have the double
2 advantage not to interfere with the flow pattern and to take into account infiltration and
3 exfiltration flows. Also, they account for the effective ventilation rather than the expected one
4 [10]. They may also be employed to measure the effective volume, in order to avoid
5 uncertainties induced when using the geometrical one [10]. Furniture lead to an overestimation
6 of the volume, whereas dead zones lead to the reverse. Tracer gas methods are based on the
7 concentration of a tracer gas. For most of them, they are suited to in-situ measurements but
8 could also be employed in small-scale studies using wind tunnels [38]. Three main ways of
9 injecting the gas within the zone are available: delivering it before the measurement, during
10 the measurement at a constant flow rate, or during the measurement at a variable flow rate
11 allowing to keep its concentration at a fixed target value. The first one, associated to tracer
12 decay methods, uses the decrease of the gas to obtain the mean ACH. The second one is

13 called the constant injection method and get the airflow from the rise in concentration or from
14 an equilibrium of the concentration occurring after, at least, 3 air changes. The last one is
15 called the constant concentration method and requires sophisticated servo-controlled air mass
16 flow controller looped to a target concentration.

17 Tracer gas methods are based on the zonal assumption including three requirements [66]:

- 18 - The tracer gas should be homogeneous in the entire zone;
- 19 - The zone should be isolated, with an exclusive exchange with the outdoor air;
- 20 - The outside air should be perfectly mixed within the zone.

21 With the zonal assumption, the mass balance equation is applied to the tracer gas, considering
22 a single zone of volume V , in exclusive contact with the exterior [66]:

$$23 \quad V \frac{d(C(t))}{dt} + Q(t) * C(t) = E(t) \quad (1)$$

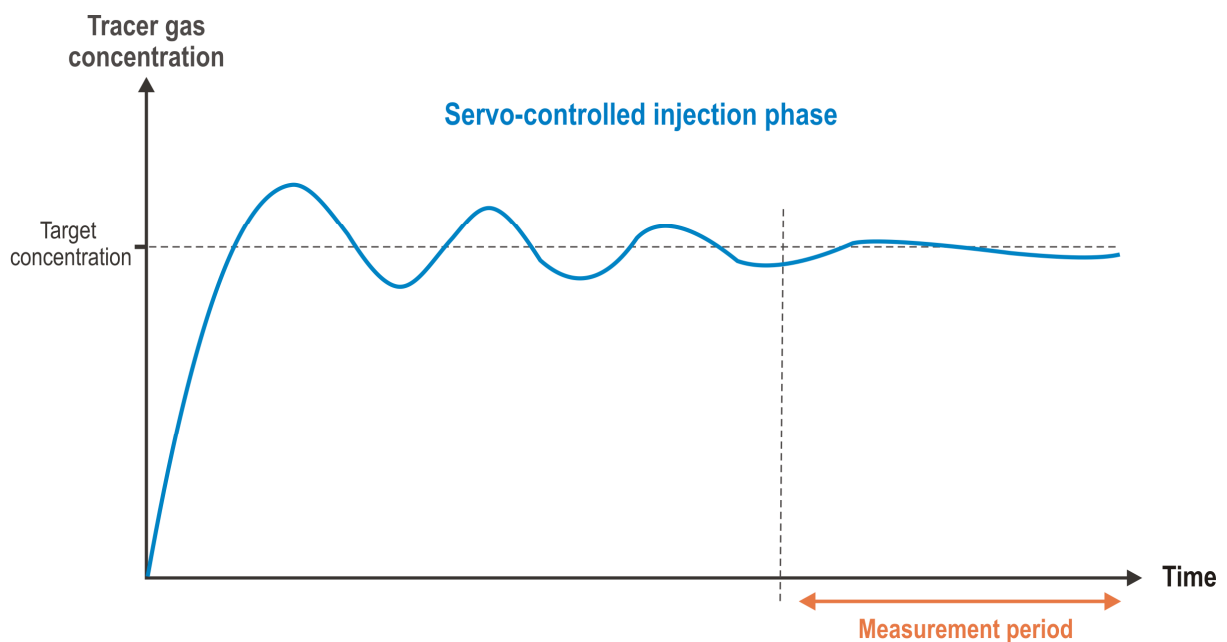
24 With V [m^3] the volume, $C(t)$ [m^3/m^3] the concentration, $Q(t)$ [$\text{m} \cdot \text{s}^{-1}$] the airflow and $E(t)$ [$\text{m}^3 \cdot \text{s}^{-1}$]
25 the emission rate.

26 Then, Sherman [66] proposed three techniques for analytically resolving *equation (1)*, with
27 their specific assumptions: the regression technique, the integral technique and the averaging
28 technique. Mathematical developments are available in [66]. The regression and the integral
29 techniques assume steady airflows during the time of analysis, whereas the averaging
30 technique tolerates variable airflows. We saw above a first source of distinction between
31 methods by ways of dosing the gas. The three resolution techniques result in another
32 distinction inducing sub-methods. Standards ISO 12569 [76] and ASTM E741 [77] describe
33 the application of each method and sub-method to measure airflow rates in a single zone.

3.1. Conventional tracer gas measurement

3.1.1. Constant concentration tracer gas ACH measurement

1 The constant concentration method may be considered as the reference tracer gas
 2 method. Its servo-controlled mass flow controller allows to describe the evolution of the ACH
 3 during the measurement thanks to the evolution of the emission rate of the tracer gas. This is
 4 the only tracer gas method able to account for a dynamic ACH. As the concentration is
 5 assumed to remain constant, the resolution of the mass balance equation is immediate, and
 6 the airflow is obtained by the ratio of the emission rate by the target concentration value. It can
 7 theoretically be computed instantaneously but according to the response time of the system,
 8 it is recommended to average the equation on successive periods [37]. Chao et al. [37]
 9 prescribe to start the injection hours before the beginning of the test to balance the system.
 10 This method requires sophisticated materials and trained staff. Its application is restrained to
 11 research projects [33], [34], [37]. It is often used to assess the accuracy of other tracer gas
 12 methods, considering the constant concentration method as the reference. **Figure 1** shows
 13 the principle of the constant concentration tracer gas method.



14

15 *Figure 1 : Schematic of the constant concentration tracer gas method*

16 3.1.2. Concentration decay tracer gas ACH measurement

1 The tracer decay method is the most used tracer gas methods thanks to its ease of
 2 implementation and to the small amount of tracer gas required. As aforementioned, the gas is

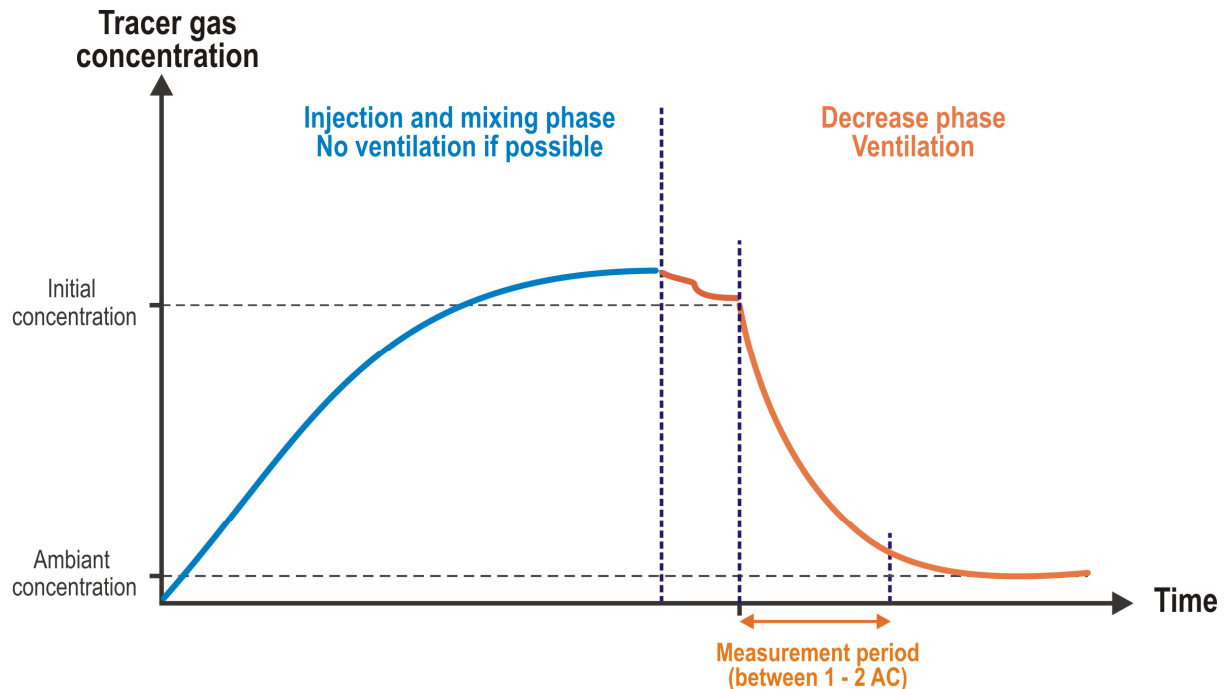
3 released before the measurement. When the concentration reaches its expected value, the
 4 injection is stopped. It is advised to use a mixing fan before the beginning of the measurement
 5 to ensure that the tracer gas concentration is homogeneous when the decay starts, which is a
 6 requirement of the standard ISO 12569 [47]. Then, the exponential decrease of the gas
 7 provides the mean ACH between the first and the last measurement points. The choice of the
 8 last measurement point is of a prime importance : the decrease of the gas has to be significant
 9 compared to the usual uncertainty of measurement instruments but the concentration of the
 10 tracer gas should not be too close to its ambient concentration [50]. It is prescribed to wait
 11 around 1 air change [47], [50]. **Figure 2** shows the principle of the decay method. Two
 12 analyses, or sub-methods, are then available, based on different resolutions of *equation (1)*:
 13 the two-points decay method and the multi-points decay method. The two-points decay method
 14 is based on the averaging technique and requires only two measurement points, which induces
 15 important uncertainties. On the contrary, the multi-points method represents a least-squares
 16 regression, allowing to significantly smooth measurement errors. Formulas are given in
 17 *equation (2-3)*:

$$18 \quad N_n = \frac{\sum t_i * \sum \ln(C_i) - n * \sum t_i * \ln(C_i)}{n * \sum t_i^2 - (\sum t_i)^2} \quad (2)$$

$$19 \quad N_2 = \frac{\ln(C_0) - \ln(C_f)}{\Delta T} \quad (3)$$

20 Sherman [66] gave the formula for the standard deviation of both methods, based on the error
 21 propagation law. Cui et al. [40] computed it with experimental data and found a difference of
 22 the standard deviation between both methods of about 6%. However, the least squares
 23 regression involved in the multi-points method implies steady airflows, which is hardly suited
 24 to natural ventilation, whereas the two-points method tolerates variable airflows. The result of
 25 the multi-points method under variable airflows would be biased. Nevertheless, the multi-points
 26 method is often preferred against the 2 points method, even to characterize fluctuating airflows
 27 [9], [10], [41], [44], [49], [64]. Two other sub-methods are possible: the pulse technique [74]
 28 and the step-down exhaust concentration method. Because these methods require an

29 identified inlet or outlet, they are not suited to all natural ventilation systems, namely cross
30 ventilation or single-sided ventilation, and will not be described here. Their application is
31 described in standard ISO 12569 [47].



32
33 Figure 2 : Schematic of the concentration decay tracer gas method

34

3.1.3. Constant injection tracer gas ACH measurement

1 The constant dosing method is also widely used but it requires an important amount of
2 tracer gas. The gas is dosed at a constant flow rate. The constant injection method requires
3 the tracer gas emission to be homogeneous within the enclosure. A mixing fan should be
4 avoided during the measurement, as it would affect the flow pattern under natural conditions.
5 Thus, several dosing points should be used, or if the inlet is clearly identified, the dosing point
6 should be placed near it. As for the concentration decay method, different analysis resulting
7 from different resolutions of *equation (1)* are possible. The integral technique leads to the
8 average concentration method and assumes steady airflows. If the airflow is variable, the
9 inverse concentration averaging method, based on the averaging technique, may be preferred.
10 *Equations (4 and 5)* give formulas of both methods. In both *equations (4 and 5)*, the
11 accumulation term may be neglected if enough time is waited. One may consider that after 3

12 air changes, the concentration have reached 95% of its equilibrium value [50]. The transient
 13 period occurring before may be discarded [47]. If the equilibrium concentration is steady, i.e in
 14 case of steady airflow, *equation (6)* may be employed.

15

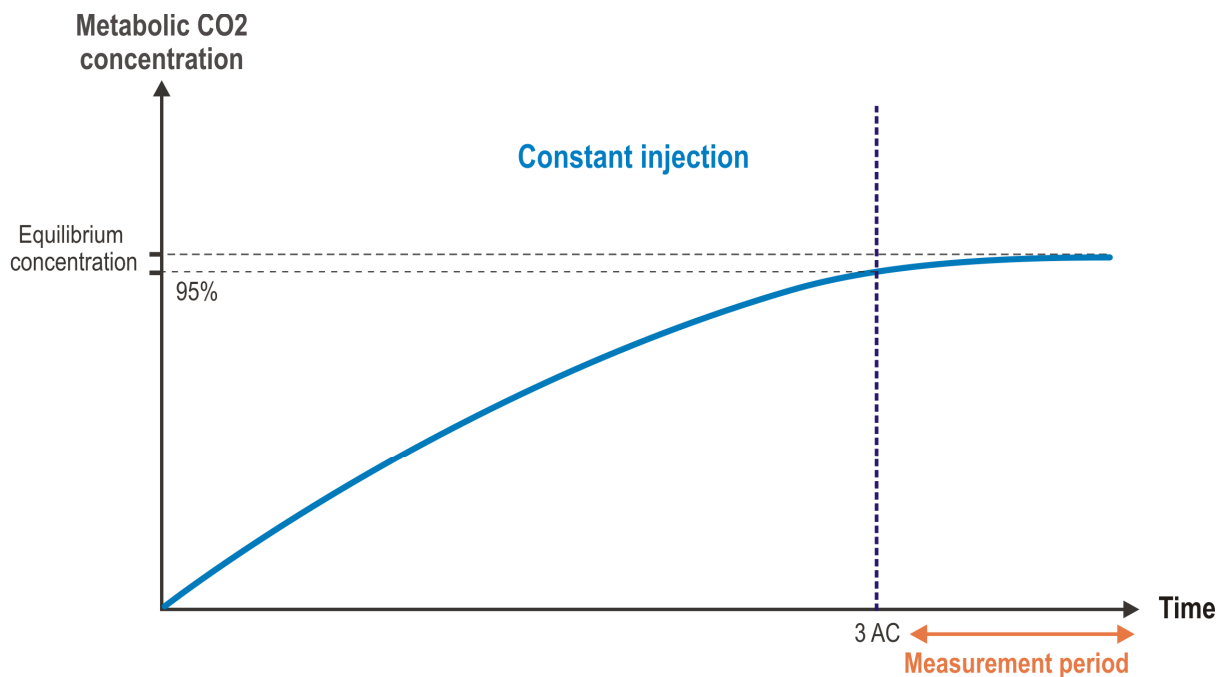
$$16 \quad Q_{avg.C^{\circ}} = \frac{E \cdot \Delta T}{\int_{t_0}^{t_f} C \cdot dt} - \frac{V}{\Delta T} \left[\frac{C_f - C_0}{\bar{C}} \right] \quad (4)$$

$$17 \quad \overline{Q_{inv.C^{\circ}}} = \frac{E}{\Delta T} \cdot \int_{t_0}^t \frac{dt}{C} + \frac{V}{\Delta T} \cdot \ln\left(\frac{C_0}{C_f}\right) \quad (5)$$

$$18 \quad Q_{steady} = \frac{E}{C(\infty)} \quad (6)$$

19 With ΔT [s] the time interval between the first and the last measurement point, C_0 [m^3/m^3] and
 20 C_f [m^3/m^3] the initial and final concentrations.

21 **Figure 3** shows the theoretical evolution of the concentration for the constant dosing method.
 22 A passive method is derived from the constant injection method. It is referred as the Constant
 23 Injection Long-Term Sampling (CILTS) method. A liquid is evaporated at a relatively constant
 24 rate through a controlling membrane. They are also commonly called “PFT” methods as gases
 25 used are PerFreons Tracer gases. The sampling technique may also be passive with
 26 absorption tubes, or active with sampling bags. This method allows to measure the mean
 27 airflow rate during months in occupied houses. It was widely used in the literature [33], [34],
 28 [75].



29

30 *Figure 3 : Schematic of the constant dosing tracer gas method, with constant airflow*

3.1.4. Tracer gas measurement of the age of air

1 The zonal assumption, mentioned in section 3, specifies that the gas should be
 2 homogeneous in the entire zone, and that the mixing of the fresh air with the old air should be
 3 perfect [66]. This section shows that, with multiple sensors, tracer gas methods allow taking
 4 advantage from the imperfect mixing of the air by assessing the air distribution.

5 Several studies [11], [59], [61], [71], [81] emphasize the necessity to consider the notion of the
 6 age of air to assess the performance of a ventilation system. It accounts for the distribution of
 7 the fresh air within an enclosure, describing the eventual incomplete mixing that is likely to
 8 occur in real buildings. The notion of the age of air can be local and global. The local mean
 9 age of air represents the average time spent by the air inside the room when it reaches a point
 10 of the space. The global mean age of air is the average time spent by the air inside the
 11 enclosure, i.e. the spatial average of all the local mean age of air. The age of air combined
 12 with the airflow rate, provides the ventilation efficiency indicator [61].

13 Tracer gas methods are the only measurement methods able to assess local ages of air, as
 14 well as the global age of air, which represents a great advantage compared to conventional

15 airflow meters. Standard ISO 16000-8 [48] describes the application of tracer gas methods for
16 the measurement of the age of air. The constant injection, the pulse method, as well as the
17 concentration decay can be used. The pulse method is similar to the decay method but the
18 amount of gas dosed is very small, and the measurement begins at the beginning of the
19 injection. The principle behind the measurement of the age of air is to mark the air before it
20 enters in the enclosure, by injecting the gas in the inlet. Roulet & Vandaele [59] gave formulas
21 to compute the age of air from each method mentioned above. The decay method can be
22 employed without the injection in the inlet, but by ensuring the homogeneity of the tracer gas
23 before the measurement in the space, making it the only method suited to the measurement
24 of the age of air in naturally ventilated spaces [29], [35]. The measurement of the concentration
25 at different locations gives information on local mean ages of air. Buratti et al. [35] compared
26 results of the local age of air measured by the decay method with CFD results, and found a
27 difference within 10% between both methods, which shows its accuracy. Sandberg and
28 Sjöberg [61] compared pulse method with decay method and found differences between 5 and
29 33%. Pulse method is likely to be less accurate than the decay method. This notion is very
30 sensitive to the flow pattern, so Jung et al. [76] proposed a method of cyclic step-up/step-down
31 injections to ensure the stability of the measured age of air.

32 Then, three possibilities to get the global age of air:

- 33 - Averaging all local ages of air, which supposes to have several sampling points;
- 34 - Mapping the age of air thanks to limited measurement points thanks to the method
35 developed by Roulet in Ref. [59], which is based on the development in Taylor series;
- 36 - Measuring the concentration at the outlet, supposing that all the air is evacuated at the
37 measured outlet. This method is less suited to natural ventilation.

38 Finally, for measurement methods that require to dose the gas at the inlet, Han et al. [45]
39 proposed a method to deal with multiple inlets or outlets. It is mainly suited to mechanical
40 ventilation systems.

3.2. Occupant-generated CO₂ tracer gas methods

1 Occupant-generated CO₂ methods are very interesting because they do not require the
2 injection of any tracer gas, taking advantage of a gas directly produced by occupants. Turiel
3 and Rudy [71] were among the firsts to identify the potential of occupant-generated CO₂.
4 Batterman [15] recently presented a review of existing occupant-generated CO₂ methods.
5 They are also described by the American standards ASTM D6245 [31]. Batterman [15]
6 identified four main methods relying on principles of tracer gas methods seen above: the
7 concentration decay, the build-up method, the steady-state method, and the Transient Mass
8 Balance Equation method. The main problem arising from these methods is the uncertainty in
9 the estimation of the emission rate, which depends on each occupant, occupancy, activity and
10 gender. The approximation, which is often made concerning emission rates, introduces
11 significant errors. Persily and de Jonge [77] proposed an update of the emission rate formula,
12 which had not been revised since 1980. They included, among other parameters, the influence
13 of the gender and of the age. In this respect, it has been proven that the old formula
14 overestimated the emission rate by 15% for males and by 25% for females [78].

3.2.1. Concentration decay

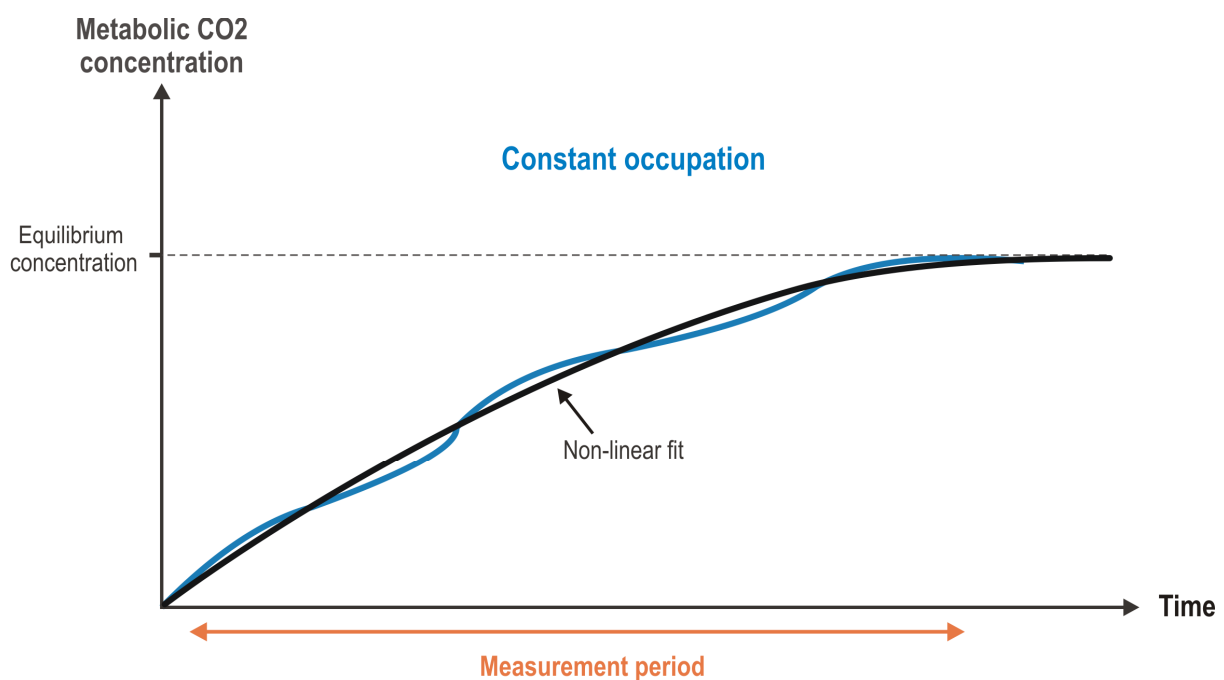
1 The occupant concentration decay is based on the same principle as the tracer decay
2 method showed on **figure 2**. The measurement begins when occupants leave the studied
3 zone. It has the advantage to be independent from the emission rate. However, it requires a
4 significant rise in CO₂ levels in the enclosure. Thus, this method is often used in classrooms
5 or offices [51], [60], [70], [71]. The occupancy in those buildings are particularly suited for this
6 method as periods of strong occupancy are followed by the simultaneous departure of
7 occupants, during breaks or at the end of the day. The increase of CO₂ must be in the order of
8 several hundreds in order to be higher enough than typical CO₂ measurement errors [15]. Lu
9 et al. [51] proposed a method based on the Maximum Likelihood Estimation (MLE) supposed
10 to be more powerful than regression techniques such as the least-squares regression.
11 However, the MLE does not allow variable airflow.

3.2.2. Steady-state method

1 The steady-state method is the steady constant injection method presented in **figure**
2 **3**. The occupancy and the airflow rate should not change during the measurement, which has
3 to last at least three air changes. This represents a significant obstacle to the method as the
4 equilibrium is very hard to achieve [15]. As a consequence, no pertinent studies were found
5 using this method, because the following Build-up method is often preferred in the case of a
6 constant occupation.

3.2.3. Build-up method

1 The build-up method can also be considered as a constant injection method. However,
2 it uses the transient increase of the CO₂ concentration and not the steady-state as the
3 conventional constant injection method. Therefore, the measurement requires less time than
4 the steady-state method. A non-linear regression is required, often performed thanks to
5 numerical solvers. This method is most often used to assess the ventilation of bedrooms [32],
6 [33], [46], [54]. The airflow rate should not change. **Figure 4** presents the build-up method.
7 The non-linear regression is represented with the dark line.

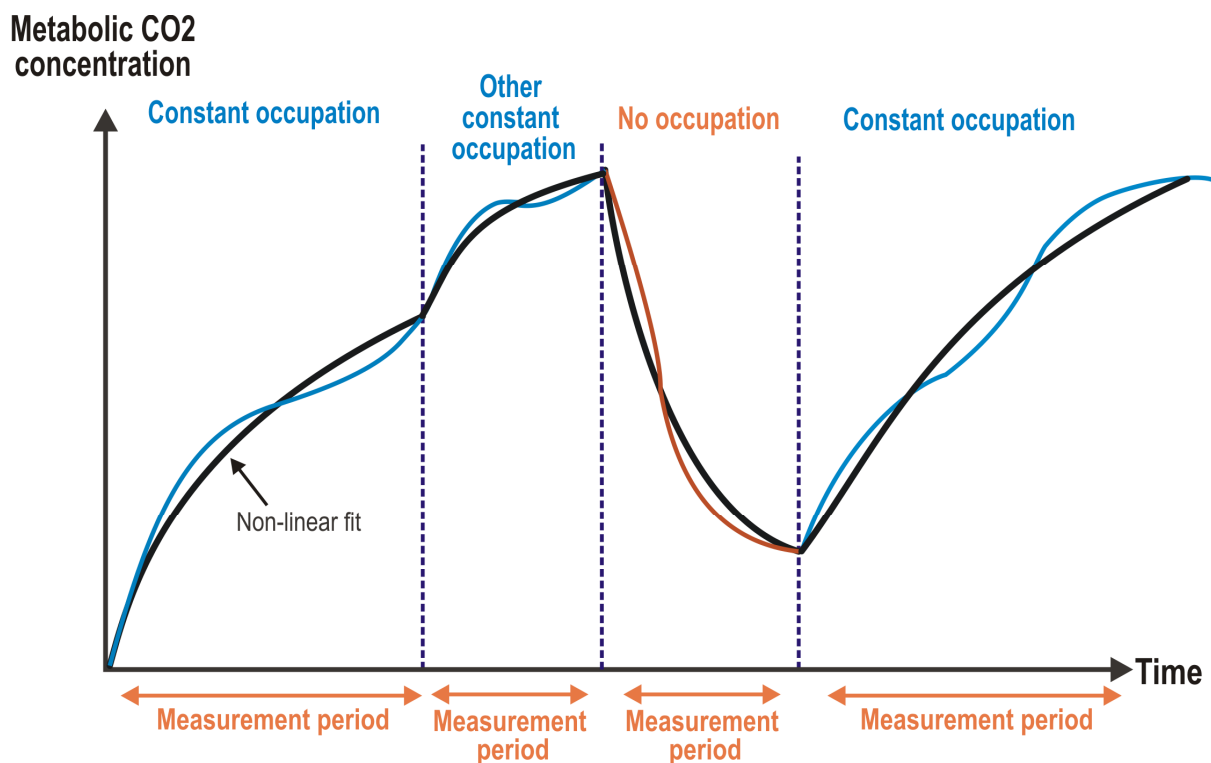


8

9 *Figure 4 : Schematic of the occupant-generated CO₂ build-up method with constant airflow*

3.2.4. Transient Mass Balance Equation method (TMBE)

1 The Transient Mass Balance Equation uses computer programs performing a non-
2 linear fit. The occupancy can change but must be recorded as it represents an input of the
3 model. The emission rate as well as the airflow rate is deduced from the model. This method
4 is particularly suited to assess the ventilation performance of schools, because of the
5 intermittent periods between strong occupancy and breaks [39], [56], [65], [68], [79]. The main
6 advantage of this method is the flexibility towards the occupancy, as long as it is recorded [15],
7 [79]. The airflow rate should be constant during the fitting. If the occupancy or the ventilation
8 rate are likely to change, the regression has to be split on successive periods, in which both
9 are assumed to be constant. This flexibility makes it the most convenient occupant-generated
10 CO₂ method, as suggested by Batterman [15]. **Figure 5** shows the successive non-linear fit
11 implied in the TMBE method.



12

13 *Figure 5 : Schematic of the occupant-generated CO₂ TMBE method with constant airflow*

14

3.3. Innovative tracer gas-based methods

1 A few innovative methods were found through the literature review. There are yet no
2 feedback on these methods but it appears consistent to mention them in the present paper.
3 Dias Carrinho et al. [36] developed a method taking advantage of the cyclic variation of
4 atmospheric CO₂ concentration to obtain the ACH. The outdoor concentration should normally
5 be constant for the resolution of *equation (1)*, but they resolved it in the frequency domain to
6 allow its fluctuation. Okuyama and Onishi [55] also used the frequency domain to propose an
7 innovative method. The injection of the gas was sinusoidal, and they observe the response of
8 the system in the frequency domain. The sinusoidal injection requires controlling a mass flow
9 controller, which is difficult for in-situ measurements.

10 Grey box modelling methods were also tested to assess ventilation rates or the age of air [53],
11 [72]. Grey box modelling are stochastic data (black box) coupled with deterministic equations
12 (white box). Stochastic data are measurements of the concentration of the gas, and
13 deterministic equations are analytical expressions as *equation (1)*. The ventilation rate should
14 not change during the modelling time.

15 Recently, Duarte et al. [43] proposed using Kalman filtering to resolve the TMBE approach.
16 Kalman filtering is said to be the best compromise to reduce the effect of measurement noise,
17 while keeping the ability to track the dynamic of the system [80]. It appears very convenient for
18 natural ventilation systems as the filter adapts itself to measurement noise, and can account
19 for a dynamic ventilation rate [43].

20 The resolution of the mass balance equation in the frequency domain and the use of dynamic
21 signal processing filters, by allowing dynamic ACH, are encouraging for a better experimental
22 characterization of natural airflows.

4. Accuracy of natural airflow measurement methods

4.1. Accuracy of conventional tracer gas methods

1 The main difficulty of studies testing the accuracy of natural ventilation measurement
2 methods is the trouble to have a reference value for comparison. Methods are either compared

3 to the constant concentration method [33], [37], or to models, which can be empirical [9], [19],
4 [41], [44], network [8], [34], [49] or CFD [10], [35], [41]. Empirical models have more
5 uncertainties than tracer gas methods so they cannot account for the reference. Correlations
6 between tracer decay and empirical methods often give poor results [8], [42], [44]. Network
7 models may be reliable for simple geometries but standardized constant pressure coefficients
8 and mean wind characteristics may lead to large deviations for complex buildings [8], [34].
9 Blomsterberg et al. [34] found a deviation of 20% for an apartment, between the constant
10 concentration method and the network model. CFD models could be reliable, but the huge
11 amount of assumptions realised by the modeller requires a field validation, which is difficult in
12 natural ventilation. Some studies found good correlations between CFD models and tracer
13 decay measurements [10], [35]. However, in those studies, the tracer gas methods is often
14 considered as the CFD validation technique. Therefore, the CFD is not considered as the
15 reference. It means that, in natural ventilation conditions, only the constant concentration
16 method is accurate enough to stand for the reference, enabling to test the accuracy of other
17 tracer gas techniques. Chao et al. [37] tested the decay technique in a naturally ventilated
18 open-space of an office building and found a difference between both methods of 10% with
19 opened windows and 16% with closed windows. Bekö et al. [33] tested the accuracy of the
20 Long Term Constant Injection Sampling method in a real house. The LTCIS method
21 overestimated by 150% the ACH. This is in accordance with the work realised by Sherman et
22 al. [67] based on field measurements implemented by Lunden et al. [52]. They estimated the
23 LTCIS uncertainty around 100% in in-situ buildings if the airflow rate was likely to fluctuate and
24 if passive sources of the gas were not thermally controlled [52], [67].

25 Tracer gas methods are further investigated thanks to mechanical ventilation, which allow
26 performing a direct measurement of the airflow rate in the extract duct as a reference.
27 However, it bypasses the effect of fluctuating airflow, which is likely to have an impact on some
28 tracer gas methods, as mentioned above. Allab [29] evidenced the impact of variable airflows
29 on the multi-points method by comparing its result to the one of the variable-airflow-tolerant 2

30 points method, in a classroom. Under steady airflows, he found a deviation between both
31 methods of 2%, whereas the deviation was about 7% under variable airflows. Following results
32 do not consider fluctuating airflows. The uncertainty of the constant concentration method was
33 tested twice by Sandberg et al. [62], [63] in an experimental building. It ranges from 1% to 6%
34 compared to an airflow-meter [62], [63]. With steady airflows, the most critical assumption of
35 tracer gas methods is the homogeneity of the tracer. It is common, even if theoretically untrue
36 [63], to average several sensors to minimize the influence of the inhomogeneity. Articles
37 questioned the best sampling position for decay methods [40], [73]. Van Buggenhout [73]
38 found a maximum deviation of 86% with the sensor situated near the inlet. Sensors near the
39 outlet give the best results. With this condition, results within 10% of the true value can be
40 expected for the multi-points decay method [40], [73]. The 2 points decay method showed
41 results within 15% [40]. It shows the importance of sampling locations, all the more so that the
42 inlet and the outlet are not always identifiable in natural ventilation. Sandberg and Blomqvist
43 [62] also found a deviation of the multi-points decay method of 11% in an experimental multi-
44 zone laboratory cell.

45 Regarding now the constant injection steady-state method, Demmers et al. [42] measured
46 deviations from -7 to 19% in an experimental cell. Sandberg and Stymne [63] found that, in the
47 case of the dosing of the gas in the exhaust room, which is always the case in a single-zone,
48 a direct loss of the gas could lead to deviations up to 100%.

49 The accuracy of each method is reported on **table 2**, as well as practical considerations.
50 References mentioned in the last column are studies used to characterize the accuracy. As
51 stated before, the distinction has to be made whether the accuracy is estimated under
52 mechanical ventilation, or under in-situ natural ventilation conditions. Accuracy values inside
53 brackets, in **table 2**, refer to the second estimation. We can see from the table that the most
54 convenient conventional tracer gas method in terms of in-situ implementation would be the
55 concentration decay, as it requires the less time and cost with a relatively good accuracy
56 compared to other tracer gas methods, apart from the constant concentration method.

57 Accuracies under variable airflows of the unbiased two points method, and the biased multi-
58 points method are greater than 15%.

59 4.2. Accuracy of occupant-generated CO₂ tracer gas methods

1 Due to their occupancy specifications, decay, and Transient Mass Balance Equation
2 methods are often experimented in schools or offices [39], [56], [65], [68], [70], [71], [79],
3 whereas the build-up method exclusively concerns bedrooms [32], [33], [46], [54].

4 The accuracy of the build-up method was evaluated against the constant concentration tracer
5 gas methods [33]. Bekö et al. [32] found an overestimation up to 100% of the build-up method.
6 Hou et al. [46] reported that Stavova, in her thesis, estimated the accuracy of this method in
7 controlled conditions around 15%. Coley et al. [39] investigated the accuracy of the TMBE
8 method by comparison with the multi-points decay method. They found 15% deviations with
9 closed windows and 40% with opened windows. Finally the occupant-generated CO₂ decay
10 method was compared to SF₆ decays by Turiel et al. [72] and Roulet et al. [58] in schools .
11 Deviations between both decays were between 1 and 30%.

12 Smith et al. [68] proposed an uncertainty analysis of occupant-generated CO₂ methods. He
13 identified four uncertainty sources: (i) non-homogeneous mixing; (ii) variations in ventilation
14 rates; (iii) errors in measured CO₂; (iv) errors in the estimated CO₂ production. (ii) and (iii) are
15 common with tracer gas methods. (i) is more critical for occupant-generated CO₂ methods as
16 the dosing is not controlled. (iv) is proper to occupant-generated CO₂ methods. Thus,
17 occupant-generated CO₂ methods are likely to be more biased than conventional tracer gas
18 methods. This is observable in **table 2** where accuracies and practical considerations
19 concerning occupant-generated CO₂ methods are also reported. The occupant-generated CO₂
20 decay method has more uncertainties than the conventional decay method. The Build-up
21 method has no equivalent in conventional tracer gas methods but has an uncertainty ranging
22 from tracer gas-usual uncertainty to 100%. The TMBE method offers flexibility. Its accuracy
23 depends on the accurate choice of regression periods but seems promising. Precautions have

24 to be taken concerning accuracies of the TMBE and decay methods as they were estimated
25 against the conventional decay method, which already has a non-negligible uncertainty.

26 4.3. Accuracy of innovative tracer gas method

1 Among innovative tracer gas methods, the cyclic atmospheric CO₂ variation method
2 [36] has been compared to a reference, whereas the accuracy of the others was tested by
3 computing the standard deviation from the model used to reconstruct the ventilation rate [43],
4 [53], [55]. Therefore, apart from the cyclic atmospheric CO₂ variation method, estimations of
5 the accuracy that will follow do not account for uncertainties due to experimental constraints.
6 The cyclic atmospheric CO₂ variation method has been tested against the occupant-generated
7 CO₂ decay method. Results over six experiments were within 10% [36].
8 The grey box modelling method has been tested with CO₂ data measured in a classroom [53].
9 The uncertainty of CO₂ sensors is of 2%. The standard deviation of the ventilation rate has
10 been computed and represents 8%. The ventilation rate has not been compared to a reference.
11 The two following methods, namely the sinusoidal tracer gas injection [55], and the TMBE
12 Kalman filtering methods [43], were tested through a generation of synthetic time series of
13 concentration. Regarding the sinusoidal tracer gas injection method, Okuyama & Onishi [55],
14 considered a constant ventilation rate, and a sinusoidal tracer gas generation rate. The
15 standard deviation of the emission rate is set to 1.2%, and a standard deviation of the
16 concentration sensor of 0.5% is used. From the evolution of the concentration, they
17 recomputed the ventilation rate. They found a standard deviation of the ventilation rate based
18 on regression residuals of 5%. The standard deviation encompasses the actual deviation from
19 the ventilation rate used to generate the synthetic time series of the concentration.
20 Uncertainties due to in-homogeneity of the tracer gas, as well as due to a fluctuating airflow
21 are not included in this accuracy estimation.
22 For the TMBE Kalman filtering method, Duarte et al. [43] generated CO₂ time series by
23 considering variable ventilation, and occupancy rates. The occupancy scenario simulated a
24 classroom hosting students from different ages during the day (influencing the generation rate).

25 To generate time series, the standard deviation of the CO₂ sensor and the generation rate
 26 were set to respectively 50 ppm and 4%. The standard deviation of the reconstructed
 27 ventilation rate was computed and it was equal on average to 20%. Considering the 95%
 28 confidence interval, apart from a sudden change in the ventilation rate of 300%, which induces
 29 a little lag, there is a good fit of the reconstructed ventilation rate with the original one. The fit
 30 is even better when there is no internal sources of CO₂, which means during breaks.
 31 Accuracies and practical considerations of innovative methods have also been reported on
 32 **table 2**. Among innovative methods, the sinusoidal injection is practically non suited to in-situ
 33 measurement, because it requires sophisticated equipment. The TMBE Kalman filtering
 34 method, and the Cyclic atmospheric variation method, are interesting as they allow the
 35 description of a fluctuating airflow, without any dosing requirements. The accuracy of the
 36 second one is inferior than 10%, but it was estimated against the occupant decay method,
 37 which has already significant uncertainties (30%). The Kalman filter leads to an accuracy of
 38 20% with volunteer fluctuations of the ventilation rate and the metabolic emission rate. Its
 39 accuracy was altered by an important standard deviation of the emission rate of the gas, due
 40 to deviations in the estimation of the metabolic CO₂ generation. It would be interesting to test
 41 this method in real conditions, and to compare its accuracy to a reference method.

42 *Table 2: Comparison of natural airflow measurement methods*

Method	Sub-method	Fluctuating ACH	Measurement time	Cost	Accuracy	Ref. method for the accuracy	Other limits	References
Concentration decay	Multi-points	No	1 AC	-	< 10% (< 15%)	-Air.-meter -(CC)	- Volume < 500 m ³	[29], [37], [40], [62], [73]
	2 points	Yes	1 AC	-	< 15%	-Air.-meter		
Constant injection	Steady-state	No	3 AC	+	< 100%	-Air.-meter -Cal. fan wheel	- Important amount of TG	[42], [63]
	Inverse concentration	Yes	3 AC	+	NA	--	- The dosing of the gas should be homogeneous	
	Long term	Yes	Weeks, Months	--	(< 150%)	-(CC)		[33], [52], [67]
Constant concentration		Yes ¹	No requirement	++	< 6%	- Air.-meter	-Sophisticated material	[62], [63]

Occupant generated CO₂	Build-up	No	NA < 3 AC	--	<15% (< 100%)	-Air.-meter -(CC)	- No change in occupancy - Need emission rate	[15], [32], [46]
	Decay	No	1 AC	--	(< 30%)	-(Conv. Decay)	- Require a significant charge in CO ₂	[15], [60], [71]
	TMBE	Yes	No requirement	--	(< 40%)	-(Conv. Decay)	- Need the occupancy - Need the emission rate	[15], [39], [56]
Innovative tracer gas methods	Cyclic atm. Variation	Yes ¹	Days, Weeks	--	(< 10%)	-(Occ. decay)	-Need no occupancy	[36]
	Grey box	No	Days	--	< 8% ²	-	-Need the occupancy	[53]
	Sinusoidal injection	No	No requirement	++	< 5% ²	-Synthetic ventilation rate	-Sophisticated material	[55]
	TMBE Kalman filter	Yes ¹	No requirement	--	< 20% ²	-Synthetic ventilation rate	-No other limits	[43]

43

44 *The accuracy value inside brackets refers to in-situ natural ventilation conditions. ¹ the constant*
45 *concentration method does not only tolerate variable airflow but also account for its dynamic.² this*
46 *accuracy has been estimated from model residuals and not from experimental comparison. Cyclic atm.*
47 *Variation = Cyclic atmospheric CO₂ variation; Air.-meter = airflow-meter; CC = Constant concentration;*
48 *Cal. fan wheel = Calibrated fan wheel; Conv. Decay = Conventional tracer gas decay; Occ. decay =*
49 *Occupant-generated CO₂ decay.*

5. Discussion

1 Occupant-generated CO₂ methods are very interesting for certain types of studies. The
2 majority of articles treating these methods is restricted to schools, offices, or bedroom surveys.
3 Specifications related to the occupancy restrict their use. Moreover, airflows are assumed
4 constant, problematic in natural ventilation. Based on same principles than conventional tracer

5 gas methods, the impossibility to control adequately the dosing of the gas leads to larger
6 uncertainties than conventional tracer gas methods. However, it could be interesting to
7 transpose some techniques developed for occupant-generated CO₂ methods to conventional
8 tracer gas methods. For instance, the build-up method, taking advantage of the rise in CO₂
9 following an increase in the occupancy has no equivalent in conventional methods. It is an
10 interesting approach as it would require less time than the conventional constant injection
11 tracer gas measurement to obtain an ACH, and the constant flow would then be ensured and
12 known. The constant airflow assumption is still an issue.

13 Concerning tracer gas methods, the constant dosing strategy involves a complex
14 implementation. The dosing of the gas should be homogeneous, whereas a mixing fan should
15 be avoided for natural ventilation. It would affect the thermal stratification and lead to a non-
16 reliable result. Among constant dosing techniques, the CILTS was widely used because it can
17 be implemented by means of a passive evaporation of the gas. However, some studies showed
18 that the variation of the airflow rate and the dosing rate during the significant period of
19 measurement (months) leads to high uncertainties. Other methods implying a constant release
20 of the gas with a mass flow controller were less documented. Nevertheless, even if several
21 dosing points are implemented to ensure the homogeneous dosing of the gas, significant
22 deviations may occur because of direct losses of the gas through outlets. Decay methods are
23 the most suited to natural airflow in-situ measurements, because the homogeneity of the gas
24 can be ensured with a mixing fan before the beginning of the measurement. Their accuracies
25 is relatively good compared to other tracer gas methods. Most of the time, the multi-points
26 decay method is preferred, regardless of the constant assumption of the airflow. Its accuracy
27 is affected, compared to its estimation in studies testing the method under mechanical
28 ventilation. The impact of unsteady airflows on its accuracy was only tested once by Allab [29].
29 It would be interesting to further investigate whether the 2 points decay method should be
30 employed or not, regarding the amplitude of the variation of airflows. Decay methods are also
31 the only methods suited to the measurement of the age of air of a naturally ventilated building.

32 It means that the age of air and the ACH can be measured simultaneously, and the ventilation
33 efficiency indicator can be calculated, which is a significant asset.

34 Innovative methods that have been identified seem promising, especially methods that allow
35 the measurement of a fluctuating airflow rate, namely the cyclic atmospheric CO₂ variation
36 method, and the TMBE Kalman filtering method. Both do not require any additional dosing of
37 a gas. However, the cyclic atmospheric CO₂ variation method implies that the building is
38 unoccupied, which can be difficult to obtain as the duration of the measurement should last
39 several days. Furthermore, the accuracy of the TMBE Kalman filtering method needs to be
40 further tested in experimental conditions, compared to a reference method.

41 High frequency measurement noise is critical for the accuracy of tracer gas methods. Some
42 sub-methods, such as the multi-points decay, the build-up or the TMBE methods for instance,
43 use regression techniques, which help to reduce its negative influence. The problem is that it
44 assumes steady airflows. The TMBE technique, contrary to other mentioned methods,
45 performs successive regressions on time intervals in which the airflow is assumed constant.
46 Measurement instruments allow now to have a nearly continuous acquisition. This procedure
47 could be applied to the multi-points tracer decay method by dividing the decrease in smaller
48 periods, in which airflows are more likely to be steady. The significant amount of
49 measurements available should ensure the accuracy. A good compromise has still to be found
50 for regression periods, to be long enough to sufficiently reduce measurement noise, while
51 being small enough compared to the dynamic of airflows; otherwise, the measurement would
52 be biased. Other authors prescribe using a low pass filter to get rid of measurement noise [55].
53 The issue is the same as airflows can be governed by high frequency stimuli. Kalman filtering
54 seems very promising as it adapts itself to the measurement noise, without hiding the dynamic
55 of the observed parameters [43]. It could be interesting to test it on other tracer gas methods
56 than the TMBE method, in which the emission rate of the gas is better described. Thus, work
57 on signal processing, and especially filtering could significantly improve the accuracy of tracer
58 gas methods for the characterization of natural airflows.

6. Conclusion

1 Measurement methods used in studies assessing natural ventilation performance were
2 described and analysed. Their suitability to in-situ assessment of natural ventilation was
3 questioned, and their accuracy was identified from existing studies. None of identified methods
4 in their current application are, both, accurate enough and suited to in-situ measurements.

5 Occupant-generated CO₂ methods have the advantage of not requiring any dosing materials,
6 but suffer from more sources of uncertainty than conventional tracer gas methods. Their
7 application is restricted to particular buildings or rooms. The Transient Mass Balance Equation
8 method associated with the Kalman filter seems encouraging for schools applications as the
9 filter allows the description of a dynamic airflow, while adapting to changes in occupation.

10 Among conventional tracer gas techniques, Constant dosing techniques are more difficult to
11 implement and direct losses of the gas can alter their accuracy. Decay methods are more
12 adapted to natural ventilation in-situ measurement, with an accuracy of 15%. Another asset of
13 decay methods is their ability to measure also the age of air in natural ventilation, which was
14 identified as an important indicator of the performance of a ventilation system. Their reliability
15 can be increased by clarifying the choice of the 2 points or the multi-points method regarding
16 the amplitude of fluctuation of the airflow.

17 Some techniques could be derived from occupant-generated CO₂ method to improve the
18 accuracy of conventional tracer gas methods. For instance, it could be interesting to split the
19 regression period of the widely used multi-points tracer decay method in smaller periods, which
20 is the technique implied on the Transient Mass Balance Equation method. It would reduce the
21 time lags of the assumed steady airflow, reducing bias associated with it, and a dynamic airflow
22 rate could be obtained. The period of successive regressions has to be subtly found in order
23 to smooth measurement errors while not deteriorating the dynamic of the system. Moreover,
24 the Kalman filter has been tested with an uncertainty in the emission rate of the gas. It could
25 be interesting to test it with a better-known emission rate, with conventional tracer gas methods

26 for instance, to bypass this important uncertainty source. The filter would have the ability to
27 track the dynamic airflow rate, while reducing the influence of measurement errors. Thus,
28 signal-processing improvements on the multi-points tracer gas decay method would certainly
29 lead to an increase of accuracy

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References

- [1] C. A. Balaras, A. G. Gaglia, E. Georgopoulou, S. Mirasgedis, Y. Sarafidis, and D. P. Lalas, 'European residential buildings and empirical assessment of the Hellenic building stock, energy consumption, emissions and potential energy savings', *Build. Environ.*, vol. 42, no. 3, pp. 1298–1314, Mar. 2007.
- [2] T. Schulze and U. Eicker, 'Controlled natural ventilation for energy efficient buildings', *Energy Build.*, vol. 56, pp. 221–232, Jan. 2013.
- [3] E. Gratia, I. Bruyère, and A. De Herde, 'How to use natural ventilation to cool narrow office buildings', *Build. Environ.*, vol. 39, no. 10, pp. 1157–1170, Oct. 2004.
- [4] Laure Mouradian, I. Carré, F. R. Carrié, A. Bailly, V. Leprince, and G. Perez, 'Projet PROMEVENT - Rapport bibliographique : Etat des lieux des protocoles et du matériel utilisés pour caractériser les débits de ventilation', Rapport bibliographique, 2017.
- [5] G. Guyot, M. H. Sherman, and I. S. Walker, 'Smart ventilation energy and indoor air quality performance in residential buildings: A review', *Energy Build.*, vol. 165, pp. 416–430, Apr. 2018.
- [6] B. Chenari, J. Dias Carrilho, and M. Gameiro da Silva, 'Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review', *Renew. Sustain. Energy Rev.*, vol. 59, pp. 1426–1447, Jun. 2016.
- [7] S. Wullens, 'Étude numérique de la ventilation naturelle, mise en oeuvre d'un modèle fin dans une simulation de thermique du bâtiment', Université Grenoble Alpes, 2015.
- [8] A. Belleri, R. Lollini, and S. M. Dutton, 'Natural ventilation design: An analysis of predicted and measured performance', *Build. Environ.*, vol. 81, pp. 123–138, Nov. 2014.
- [9] M. Caciolo, P. Stabat, and D. Marchio, 'Full scale experimental study of single-sided ventilation: Analysis of stack and wind effects', *Energy Build.*, vol. 43, no. 7, pp. 1765–1773, Jul. 2011.
- [10] N. Nikolopoulos, A. Nikolopoulos, T. S. Larsen, and K.-S. P. Nikas, 'Experimental and numerical investigation of the tracer gas methodology in the case of a naturally cross-ventilated building', *Build. Environ.*, vol. 56, no. Supplement C, pp. 379–388, Oct. 2012.
- [11] L. J. Lo and A. Novoselac, 'Cross ventilation with small openings: Measurements in a multi-zone test building', *Build. Environ.*, vol. 57, pp. 377–386, Nov. 2012.
- [12] D. Etheridge, *Natural Ventilation of Building, Theory, Measurement, and Design*. Wiley, 2012.
- [13] M. P. Straw, C. J. Baker, and A. P. Robertson, 'Experimental measurements and computations of the wind-induced ventilation of a cubic structure', *J. Wind Eng. Ind. Aerodyn.*, vol. 88, no. 2–3, pp. 213–230, Dec. 2000.

- [14] J. S. Park, 'Long-term field measurement on effects of wind speed and directional fluctuation on wind-driven cross ventilation in a mock-up building', *Build. Environ.*, vol. 62, pp. 1–8, Apr. 2013.
- [15] S. Batterman, 'Review and Extension of CO₂-Based Methods to Determine Ventilation Rates with Application to School Classrooms', *Int. J. Environ. Res. Public Health*, vol. 14, no. 12, p. 145, Feb. 2017.
- [16] AFNOR, *NF EN 16798-7 : Performance énergétique des bâtiments — Ventilation des bâtiments — Partie 7 : Méthodes de calcul pour la détermination des débits d'air dans les bâtiments y compris les infiltrations (Modules M5-5)*. 2017, p. 68.
- [17] S. Omrani, V. Garcia-Hansen, B. Capra, and R. Drogemuller, 'Natural ventilation in multi-storey buildings: Design process and review of evaluation tools', *Build. Environ.*, vol. 116, pp. 182–194, May 2017.
- [18] T. S. Larsen, 'Natural ventilation driven by wind and temperature difference', Videnbasen for Aalborg UniversitetVBN, Aalborg UniversitetAalborg University, Det Teknisk-Naturvidenskabelige FakultetThe Faculty of Engineering and Science, Sektionen for Architectural EngineeringDivision of Architectural Engineering, 2006.
- [19] M. Caciolo, S. Cui, P. Stabat, and D. Marchio, 'Development of a new correlation for single-sided natural ventilation adapted to leeward conditions', *Energy Build.*, vol. 60, pp. 372–382, May 2013.
- [20] T. S. Larsen, C. Plesner, V. Leprince, F. R. Carrié, and A. K. Bejder, 'Calculation methods for single-sided natural ventilation: Now and ahead', *Energy Build.*, vol. 177, pp. 279–289, Oct. 2018.
- [21] G. Carrilho da Graça, 'A technical note on simplified modeling of turbulent mixing in wind-driven single sided ventilation', *Build. Environ.*, vol. 131, pp. 12–15, Mar. 2018.
- [22] Z. (John) Zhai, M. E. Mankibi, and A. Zoubir, 'Review of Natural Ventilation Models', *Energy Procedia*, vol. 78, pp. 2700–2705, Nov. 2015.
- [23] T. van Hooff, B. Blocken, and Y. Tominaga, 'On the accuracy of CFD simulations of cross-ventilation flows for a generic isolated building: Comparison of RANS, LES and experiments', *Build. Environ.*, vol. 114, pp. 148–165, Mar. 2017.
- [24] G. Elshafei, A. Negm, M. Bady, M. Suzuki, and M. G. Ibrahim, 'Numerical and experimental investigations of the impacts of window parameters on indoor natural ventilation in a residential building', *Energy Build.*, vol. 141, pp. 321–332, Apr. 2017.
- [25] M. Z. I. Bangalee, J. J. Miao, S. Y. Lin, and J. H. Yang, 'Flow visualization, PIV measurement and CFD calculation for fluid-driven natural cross-ventilation in a scale model', *Energy Build.*, vol. 66, pp. 306–314, Nov. 2013.
- [26] N. Ikegaya, C. Hirose, A. Hagishima, and J. Tanimoto, 'Effect of turbulent flow on wall pressure coefficients of block arrays within urban boundary layer', *Build. Environ.*, vol. 100, no. Supplement C, pp. 28–39, May 2016.
- [27] P. X. W. Zou, X. Xu, J. Sanjayan, and J. Wang, 'Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives', *Energy Build.*, vol. 178, pp. 165–181, Nov. 2018.
- [28] C. Demanuele, T. Twedell, and M. Davies, 'Bridging the gap between predicted and actual energy performance in schools.pdf', presented at the World Renewable Energy Congress XI, Abu Dhabi, 2010.
- [29] Y. Allab, 'Evaluation expérimentale des performances des systèmes de ventilation dans le bâtiment: efficacité de ventilation et confort thermique', PhD Thesis, Paris, ENSAM, 2017.
- [30] ASTM, *ASTM E741 - 17 : Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution*, vol. ASTM E741. 2017.
- [31] ASTM, *ASTM D6245 - 12 : Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation*. 2012.
- [32] G. Bekö, T. Lund, F. Nors, J. Toftum, and G. Clausen, 'Ventilation rates in the bedrooms of 500 Danish children', *Build. Environ.*, vol. 45, no. 10, pp. 2289–2295, Oct. 2010.

- [33] G. Bekö *et al.*, 'Diurnal and seasonal variation in air exchange rates and interzonal airflows measured by active and passive tracer gas in homes', *Build. Environ.*, vol. 104, pp. 178–187, Aug. 2016.
- [34] Å. Blomsterberg, T. Carlsson, C. Svensson, and J. Kronvall, 'Air flows in dwellings—simulations and measurements', *Energy Build.*, vol. 30, no. 1, pp. 87–95, 1999.
- [35] C. Buratti, R. Mariani, and E. Moretti, 'Mean age of air in a naturally ventilated office: Experimental data and simulations', *Energy Build.*, vol. 43, no. 8, pp. 2021–2027, Aug. 2011.
- [36] J. Dias Carrilho, M. Mateus, S. Batterman, and M. Gameiro da Silva, 'Air exchange rates from atmospheric CO₂ daily cycle', *Energy Build.*, vol. 92, pp. 188–194, Apr. 2015.
- [37] C. Y. Chao, M. P. Wan, and A. K. Law, 'Ventilation performance measurement using constant concentration dosing strategy', *Build. Environ.*, vol. 39, no. 11, pp. 1277–1288, Nov. 2004.
- [38] C.-R. Chu, Y.-H. Chiu, Y.-T. Tsai, and S.-L. Wu, 'Wind-driven natural ventilation for buildings with two openings on the same external wall', *Energy Build.*, vol. 108, pp. 365–372, Dec. 2015.
- [39] D. A. Coley and A. Beisteiner, 'Carbon Dioxide Levels and Ventilation Rates in Schools', *Int. J. Vent.*, vol. 1, no. 1, pp. 45–52, Jun. 2002.
- [40] S. Cui, M. Cohen, P. Stabat, and D. Marchio, 'CO₂ tracer gas concentration decay method for measuring air change rate', *Build. Environ.*, vol. 84, no. Supplement C, pp. 162–169, Jan. 2015.
- [41] S. Cui, R. Issoglio, J. Koffi, M. Mankibi, P. Stabat, and D. Marchio, 'Performance evaluation of natural ventilation through windows with horizontal a blade shutter', *ISIAQ Conf. Indoor Air 2014*, p. 9, 2015.
- [42] T. G. M. Demmers, L. R. Burgess, V. R. Phillips, J. A. Clark, and C. M. Wathes, 'Assessment of Techniques for Measuring the Ventilation Rate, using an Experimental Building Section', *J. Agric. Eng. Res.*, vol. 76, no. 1, pp. 71–81, May 2000.
- [43] R. Duarte, M. Glória Gomes, and A. Moret Rodrigues, 'Estimating ventilation rates in a window-aired room using Kalman filtering and considering uncertain measurements of occupancy and CO₂ concentration', *Build. Environ.*, vol. 143, pp. 691–700, Oct. 2018.
- [44] H. L. Gough *et al.*, 'Field measurement of natural ventilation rate in an idealised full-scale building located in a staggered urban array: Comparison between tracer gas and pressure-based methods', *Build. Environ.*, vol. 137, pp. 246–256, Jun. 2018.
- [45] H. Han, C.-Y. Shin, I.-B. Lee, and K.-S. Kwon, 'Tracer gas experiment for local mean ages of air from individual supply inlets in a space with multiple inlets', *Build. Environ.*, vol. 46, no. 12, pp. 2462–2471, Dec. 2011.
- [46] J. Hou *et al.*, 'Air change rates at night in northeast Chinese homes', *Build. Environ.*, vol. 132, pp. 273–281, Mar. 2018.
- [47] AFNOR, *NF EN ISO 12569 : Performance thermique des bâtiments et des matériaux - Détermination du débit d'air spécifique dans les bâtiments - Méthode de dilution de gaz traceurs*. 2017.
- [48] AFNOR, *NF ISO 16000-8 : Air intérieur Partie 8 : Détermination des âges moyens locaux de l'air dans des bâtiments pour caractériser les conditions de ventilation*. 2012.
- [49] C. J. Koinakis, 'The effect of the use of openings on interzonal air flows in buildings: an experimental and simulation approach', *Energy Build.*, vol. 37, no. 8, pp. 813–823, Aug. 2005.
- [50] D. Laussmann and D. Helm, 'Air change measurements using tracer gases: Methods and results. Significance of air change for indoor air quality', in *Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality*, InTech, 2011.
- [51] T. Lu, A. Knuutila, M. Viljanen, and X. Lu, 'A novel methodology for estimating space air change rates and occupant CO₂ generation rates from measurements in mechanically-ventilated buildings', *Build. Environ.*, vol. 45, no. 5, pp. 1161–1172, May 2010.

- [52] M. Lunden *et al.*, 'Experiments to evaluate and implement passive tracer gas methods to measure ventilation rates in homes', Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States), 2012.
- [53] M. Macarulla, M. Casals, N. Forcada, M. Gangoells, and A. Giretti, 'Estimation of a room ventilation air change rate using a stochastic grey-box modelling approach', *Measurement*, Apr. 2018.
- [54] A. Mikola, T. Kalamees, and T.-A. Köiv, 'Performance of ventilation in Estonian apartment buildings', *Energy Procedia*, vol. 132, pp. 963–968, Oct. 2017.
- [55] H. Okuyama and Y. Onishi, 'Uncertainty analysis and optimum concentration decay term for air exchange rate measurements: Estimation methods for effective volume and infiltration rate', *Build. Environ.*, vol. 49, no. Supplement C, pp. 182–192, Mar. 2012.
- [56] J. M. Penman, 'An experimental determination of ventilation rate in occupied rooms using atmospheric carbon dioxide concentration', *Build. Environ.*, vol. 15, no. 1, pp. 45–47, Jan. 1980.
- [57] S. B. Riffat and K. W. Cheong, 'Estimation of zone effective-volume using tracer-gas techniques', *Appl. Energy*, vol. 45, no. 4, pp. 327–334, 1993.
- [58] C.-A. Roulet, R. Compagnon, and M. Jakob, 'A Simple Method Using Tracer Gas to Identify the Main Airflow and Contaminant Paths within a Room', *Indoor Air*, vol. 1, no. 3, pp. 311–322, Sep. 1991.
- [59] C.-A. Roulet and L. Vandaele, 'Air flow patterns within buildings measurement techniques', AIVC, AIVC Technical Note 34, 1991.
- [60] R. Claude-Alain and F. Foradini, 'Simple and Cheap Air Change Rate Measurement Using CO₂ Concentration Decays', *Int. J. Vent.*, vol. 1, no. 1, pp. 39–44, Jun. 2002.
- [61] M. Sandberg and M. Sjöberg, 'The use of moments for assessing air quality in ventilated rooms', *Build. Environ.*, vol. 18, no. 4, pp. 181–197, Jan. 1983.
- [62] M. Sandberg and C. Blomqvist, 'A quantitative estimate of the accuracy of tracer gas methods for the determination of the ventilation flow rate in buildings', *Build. Environ.*, vol. 25, no. 4, pp. 139–150, 1985.
- [63] M. Sandberg and H. Stymne, 'The constant tracer flow technique', *Build. Environ.*, vol. 24, no. 3, pp. 209–219, Jan. 1989.
- [64] M. Santamouris *et al.*, 'Experimental investigation of the air flow and indoor carbon dioxide concentration in classrooms with intermittent natural ventilation', *Energy Build.*, vol. 40, no. 10, pp. 1833–1843, Jan. 2008.
- [65] L. Schibuola, M. Scarpa, and C. Tambani, 'Natural Ventilation Level Assessment in a School Building by CO₂ Concentration Measures', *Energy Procedia*, vol. 101, pp. 257–264, Nov. 2016.
- [66] M. Sherman, 'Tracer-Gas Technique For Measuring Ventilation in a Single Zone', *Build. Environ.*, vol. 25, no. 4, pp. 365–374, 1990.
- [67] M. H. Sherman, I. S. Walker, and M. M. Lunden, 'Uncertainties in air exchange using continuous-injection, long-term sampling tracer-gas methods', *Int. J. Vent.*, vol. 13, no. 1, pp. 13–28, 2014.
- [68] P. N. Smith, 'Determination of Ventilation Rates in Occupied Buildings from Metabolic CO₂ Concentrations and Production Rates', *Build. Environ.*, vol. 23, no. 2, pp. 95–102, 1988.
- [69] H. Sutcliffe, 'A guide to air change efficiency', *AIVC*, p. 48, 1990.
- [70] V. Turanjanin, B. Vučićević, M. Jovanović, N. Mirkov, and I. Lazović, 'Indoor CO₂ measurements in Serbian schools and ventilation rate calculation', *Energy*, vol. 77, pp. 290–296, Dec. 2014.
- [71] I. Turiel, 'Occupant-generated CO₂ as an indicator of ventilation rate', 1980.
- [72] S. Van Buggenhout *et al.*, 'Data-based mechanistic modelling approach to determine the age of air in a ventilated space', *Build. Environ.*, vol. 41, no. 5, pp. 557–567, May 2006.
- [73] S. Van Buggenhout, A. Van Brecht, S. E. Özcan, E. Vranken, W. Van Malcot, and D. Berckmans, 'Influence of sampling positions on accuracy of tracer gas measurements in ventilated spaces', *Biosyst. Eng.*, vol. 104, no. 2, pp. 216–223, 2009.

- [74] L. A. Wallace, S. J. Emmerich, and C. Howard-Reed, 'Continuous measurements of air change rates in an occupied house for 1 year: The effect of temperature, wind, fans, and windows', *J. Expo. Anal. Environ. Epidemiol.*, pp. 296–306, 2002.
- [75] H. Okuyama, Y. Onishi, S. Tanabe, and S. Kashihara, 'Statistical data analysis method for multi-zonal airflow measurement using multiple kinds of perfluorocarbon tracer gas', *Build. Environ.*, vol. 44, no. 3, pp. 546–557, Mar. 2009.
- [76] A. Jung and M. Zeller, 'Analysis and testing of methods to determine indoor air quality and air change effectiveness', *Rhein.-Westfäl. Tech. Univ. Aachen Ger.*, 1994.
- [77] A. Persily and L. de Jonge, 'Carbon dioxide generation rates for building occupants', *Indoor Air*, vol. 27, no. 5, pp. 868–879, Sep. 2017.
- [78] M. Qi, L. Xiaofeng, L. Weschler, and J. Sundell, 'CO₂ generation rate in Chinese people', *Indoor Air*, vol. 24, no. 24, pp. 559–566, 2014.
- [79] D. L. Johnson, R. A. Lynch, E. L. Floyd, J. Wang, and J. N. Bartels, 'Indoor air quality in classrooms: Environmental measures and effective ventilation rate modeling in urban elementary schools', *Build. Environ.*, vol. 136, pp. 185–197, May 2018.
- [80] L. Ljung, *System Identification: Theory for User*. Prentice Hall, 1987.