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A new method for air exchange efficiency assessment including natural and mixed mode ventilation

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1. Introduction

Ventilation effectiveness is defined through a set of physical parameters and indexes able to characterize the intrinsic performances of a ventilation system. According to Mundt [1], ventilation effectiveness includes indices representing the ability of a ventilation system to provide and distribute fresh air in occupied/breathing zones (air exchange efficiency and local air change index) and indices representing the ability to remove pollutants from confined spaces (contaminant removals effectiveness and local air quality index). Since these indices are based on ages for air renewal and pollutant residence time, it is very important to assess ventilation effectiveness considering not only ventilation rates, but also ages describing ventilated space conditions. Several authors and standards propose definitions, calculations, and experimental procedures to assess ages and indices [1–4]. Among ventilation effectiveness parameters, mean age of air at a point (τp) expresses the time spent by a number of air particles from their entrance to a given point in a ventilated space. The local mean age of air of different points can be averaged on the ventilated zone to express the room mean age of air (ÆτR). Another important parameter is the nominal time constant (τn), which represents the shortest time for the air exchange in a room.

Air exchange indices express the ability of the ventilation system to renew confined air by fresh air; they are defined either for a given point in the ventilated space (local air exchange index εax) or globally, for the whole ventilated zone (air exchange efficiency εx). Air exchange indices are function of the nominal time constant (τn) and the mean age of air (τp and τR respectively) [1].

For the whole room, the air exchange efficiency is:

εx = \frac{τn}{2(τR)} \cdot 100 [%]

In order to assess the air exchange efficiency of a ventilation system, the mean age of air at a point (τp) can be measured using the tracer gas decay method according to ISO 16000-8, 2007 [5] and ASHRAE 129, 2002 [6]. The mean age of the ventilated space can be referred to tracer concentrations at the exhaust [7], or calculated by the average of the local ages measured in several points,

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ABSTRACT

The COVID-19 health crisis highlighted the correlation between air exchange efficiency and virus airborne transmission. Air exchange efficiency is a performance index able to characterize ventilation effectiveness in buildings. Some standards, such as ASHRAE 129, clearly define assessment procedures of air exchange efficiency for mechanical ventilation, adopting tracer gas techniques. However, standardized procedures are based on measurements at the exhaust and cannot be adopted for natural and mixed mode ventilation strategies. In the ’80s, Sandberg suggested that tracer gas decay technique enables to measure simultaneously the nominal time constant (through air change rate measurements) and the mean age of air in several points of the ventilated zone. This paper aims to present practical issues and uncertainty analysis related to the implementation of this approach, in a new commissioning protocol. For this purpose, we compare the new procedure, based on Sandberg’s observation, with the ASHRAE 129 protocol for mechanical ventilation. Results coming from field campaigns show that the difference between air exchange efficiency values obtained using ASHRAE 129 protocol (51.8%) and the new procedure (47.4%) are usually negligible in low airflow rate, considering an average uncertainty of ± 7.0%. Results show that the procedure is robust and that it is technically possible to implement it to natural and mixed-mode ventilation.
neglecting the exhaust [6]. According to the ASHRAE 129 [6], the nominal time constant ($\tau_n$) is considered as the age of air at the exhaust, and measured the tracer gas decay method.

In 2020, the COVID 19 health crisis highlighted the influence of building ventilation on virus airborne transmission [8–9]. In new constructions, new requirements have to be considered in design phase of both HVAC and building system. Ventilation strategies in existing buildings have to be investigated through new commissioning protocols, and improved.

In this context, standardized approaches should be used to characterize mechanical as well as natural and mixed-mode ventilation. However, standardized methods, which consider exhaust as a reference, present significant problems. In fact, since the measurements of the nominal time constant are at the exhaust, they can only be done in presence of an exhaust. Thus, those procedures cannot be directly adopted in naturally ventilated spaces. Especially for single side ventilation, the opening is crossed by air flow due both to infiltration (working as a “supply”) and exfiltration (working as an “exhaust”). Thus, it is not possible to define the exhaust. Moreover, by measuring the nominal time constant at the exhaust, air exfiltration through the envelope cracks and spatial distribution of fresh air in the room are neglected.

In order to bridge this knowledge and technical gap, the paper presents a new procedure, based on the tracer gas decay technique (also known as step down method). Tracer gas techniques (step-up, step down, and pulse methods) are largely used for ventilation effectiveness analysis. Among these methods we selected the decay or step down technique. The latter is the only technique allowing to simultaneously measure the nominal time constant and the mean age of air in the ventilated zone. Despite the possibility of assessing air change rate (and so the nominal time constant in the ventilated zone), the pulse injection technique cannot be used to measure the local mean age and the room mean age: the small concentration need for pulse technique does not allow to have a homogenous mix of pollutant in occupied space. Moreover, the pulse injection is used in steady-state condition so it is not adapted for natural ventilation strategies characterized by transient. As for the step-up technique, it is used with tracer gas injection in the supply, and, in natural ventilation, (as for the exhaust), the supply cannot be defined [1].

The aim of the paper is to demonstrate that is technically possible to assess air exchange efficiency index by adapting existing standardized procedures, that are formalized for mechanical ventilation, also in natural and mixed-mode ventilation strategies.

In order to verify its application, we compare the new procedure against the ASHRAE 129 protocol for mechanical ventilation strategy. In the paper, Section 2 focuses on the methodological framework. Section 3 presents the case study and the experimental campaign and the comparison between results, in particular air exchange efficiency values obtained using the two methods. Section 4 presents a discussion about results, while Section 5 is devoted to conclusions and perspectives.

2. Methodology

This section aims to present the new procedure. For the sake of completeness, the following paragraphs focus on both assessment method and uncertainty analysis used to characterize efficiency indices in mechanical ventilation. A summary of existing standardized methods compared to the new procedure is also reported.

2.1. Efficiency indices assessment

In order to extend the evaluation of air exchange efficiency to natural and mixed mode ventilation, the nominal time constant should to be estimated neglecting measurements at the exhaust. According to Sandberg [10] and Liddament [11], and the TN 34 [7], nominal time constant may also be defined as the ratio between the room volume and the fresh air flow. This means that the nominal time constant can be expressed as the inverse of the air change rate ($\lambda$):

$$\tau_n = \frac{1}{\lambda} [h]$$ (2)

The air change rates can be established measuring pollutants concentrations with the tracer gas decay method and using three different calculation techniques: i) two-points average; ii) linear regression; iii) nonlinear regression (multipoint decay) [12–13]. Since the air change rate ($\lambda$) is a function of concentration in several points in the room, considering Equation (2) it is possible to detach the assessment of the nominal time constant from measurements at the exhaust.

In this way, Equation (1) becomes:

$$\phi = \frac{1}{2\lambda} \cdot 100[\%]$$ (3)

The new procedure consists in considering the nominal time constant ($\tau_n$) as the inverse of the air change rate ($\lambda$), and the mean age of the ventilated space as the average of the local ages ($\langle \tau \rangle$). This allows to measure parameters in the room and to consider air change efficiency index independently of the ventilation strategy.

This approach requires the simultaneous measurement of air change together with local mean age of air, room mean age of air, and nominal time constant. Thus, we developed a new experimental protocol allowing to meet standards requirements for measurement and calculation of both air change rates [12–13], and local mean ages of air [5–6]. For this purpose, the tracer gas technique was selected. This technique allows to estimate ventilation effectiveness without blowing air or measuring the condition at the level of the exhaust and offers the possibility to compare the ASHRAE 129 method with the new one proposed in this study. Table 1 summarizes all these indices coupled with the calculation or measuring method and references. The same table reports indices and methods proposed by the new procedure.

2.2. Uncertainty analysis

One of the critical point during measuring the air change rate is the measurement accuracy. In fact, it depends on several parameters, including the way it is measured. Since tracer gas techniques consider the pollutant concentrations during the time, they are the most precise in terms of air change rate assessment. However, for these techniques, it is important to choose wisely how to implement the measure, particularly regarding the measuring time.

In this case, the measuring time is one of the most important parameter, since it affects the air change rate measure, its availability and the calculation/measure of ventilation effectiveness parameters and indices. In the new procedure, the aim is to perform the air change rate and local age of air simultaneously, therefore, the measurement period has been defined by the age of air measurement constraints.

Considering the decay technique, the age of air measurement needs at least a decay of 95% of the initial concentration, which is not the case for air change rate measurement. According to ASME 741, measuring times are recommended for each range of air change rate (Table 2).

Thus, there are no imposed limits for air change rate measuring process, but minimal durations that allow to minimize the occurring errors.
### Table 1
Summary of ventilation indices, calculation or measuring method and references.

| Index                        | Calculation/measuring method                                                                 | References                                      |
|------------------------------|------------------------------------------------------------------------------------------------|------------------------------------------------|
| **Air change rate ($i$) [h$^{-1}$]** | Two-points average: $\tau = \frac{i - \frac{i}{1 - \frac{i}{1}}}{\ln \left(\frac{C_i}{C_{in}}\right)}$ Linear regression: $C(t) = C_0 e^{-kt}$ Nonlinear regression (multipoint decay): $\lambda = \sum_{i=1}^{n} \frac{C_i - C_{in}}{C_{ini} - C_{in}}$ | ASTM E741, 2006 [12]; ISO 12569, 2012 [13] ASTM E741, 2006 [12]; ISO 12569, 2012 [13] ASTM E741, 2006 [12]; ISO 12569, 2012 [13] |
| **Nominal time constant ($t_n$) [h]** | Age of the air at the extraction: $t_n = \sum_{i=1}^{n} \frac{C_i - C_{in}}{C_{ini} - C_{in}}$ The inverse of the air change rate: $\frac{1}{i}$ | ASHRAE 129 [6] New procedure, according to Sandberg, 1983 [10] Liddament, 1996 [11] and AIVC TN34, 1991 [7] |
| **Mean age of air at a point ($\tau_{avg}$) [h]** | Linear regression and transitory (exponential and non-exponential part of the decay curb): $\tau_p = \frac{1}{C_{ini} \ln C_p}$ Average of concentrations: $\tau_p = \frac{1}{\sum_{i=1}^{n} C_i}$ | ISO 16000-8, 2007 [5] ASHRAE 129, 2002 [6] |
| **Zone mean age of air ($\tau$) [h]** | Average on age of air at 5 points in the ventilated space (neglecting the extraction): $\tau = \frac{C_p}{C_{ini}}$ Average on age of air at 6 points considering ventilated space and extraction: $\tau = \frac{C_p}{C_{ini} + Q_m}$ | ASHRAE 129, 2002 [6] AIVC TN34, 1991 [7] New procedure |
| **Air change efficiency at a point ($\eta_p$) [%]** | $\eta_p = \frac{100}{\tau_{avg}}$ | Munding [1] |
| **Zone air change efficiency ($\eta$) [%]** | $\eta = \frac{100}{\tau}$ | ASHRAE 129, 2002 [6] |

The summed tracer gas concentration in function of time [ppm]: $\sum_{t=i}^{N} C(t)$ = relative concentration in regression [ppm]: $C_p$ = air change rate in regression [h$^{-1}$]: $\tau$ = time [h]: $\eta$ = air change rate for measurement [h]: $C_i$ = gas concentration of the measurement i [ppm]: $N$ = number of measurement points [-]; $Q_m$ = air flow rate at the extraction m [m$^3$/h]: $\tau_{avg}$ = mean age of air at the extraction m [h] $Q$ = air flow rate [m$^3$/h]: $V$ = ventilated volume [m$^3$]; $C_p$ = pollutant average concentration in the zone [ppm].

### Table 2
Minimal durations recommended by ASM E741 for the air change rate measuring.

| Air change rate [h$^{-1}$] | Minimal durations [h] |
|----------------------------|-----------------------|
| 0.25                       | 4.00                  |
| 0.50                       | 2.00                  |
| 1.00                       | 1.00                  |
| 2.00                       | 0.50                  |
| 4.00                       | 0.25                  |

Nonetheless, it is important to specify that the minimal values fixed by standards are based on Sherman results during uncertainties analyses [14]. Sherman defined minimal durations for air change rate measure through the decay method based on measurement errors (Table 3).

These values come from the exponential uncertainty formula described by Sherman in the following equation:

$$\delta_\eta = \sqrt{1 + \frac{2\eta^2}{T}} \cdot \frac{\Delta C}{C_{ini}}$$

(4)

Where: $\eta$ = air change rate [h$^{-1}$]; $T$ = measuring period [h]; $C_{ini}$ = initial tracer gas concentration [ppm]; $C_{final}$ = tracer gas concentration [ppm].

However, Sherman also propose an applicable evolution when it is possible to estimate the uncertainty at the beginning and at the end of the decay process, with the following equation:

$$\delta_\eta^2 = \frac{1}{T^2} \left( \frac{\Delta C_{ini}^2}{C_{ini}} + \frac{\Delta C_{final}^2}{C_{final}} \right)$$

(5)

The second equation is used in the new procedure presented in this paper, in order to minimize the errors and to avoid the negative effects of the measuring time.

All the tests are carried out between 140 ppm (concentration at the beginning of the decay) and 3 ppm (concentration at the end of the decay). While the initial concentration is chosen to assure enough room to decay, the final concentration is established in order to respect the uncertainty measuring criterion of 5% (relative uncertainty) recommended by ASTM E741 standard.

The relative concentration uncertainties are then estimated, according to the ASTM E741 method, during blower door tests. Considering the best tests about the concentration fluctuation, we estimate the relative concentration uncertainties at 140 ppm and 3 ppm, to be respectively 0.37% and 4.02%.

Besides the measuring uncertainty, the one due to the tracer gas mixing is calculated and added to the total uncertainty. The mixing uncertainty is estimated depending on the gap between the maximal values and the minimal air change rate, according to the method proposed by Caciolo [15]:

$$\frac{\partial \lambda}{\lambda} = \frac{\lambda_{max} - \lambda_{min}}{2\lambda}$$

(6)

The total uncertainty is then calculated depending on both the measuring and the mixing uncertainty, with the following equation:

$$\frac{\partial \lambda}{\lambda} = \sqrt{\left(\frac{\partial \lambda}{\lambda}\right)_{measure}^2 + \left(\frac{\partial \lambda}{\lambda}\right)_{mix}^2}$$

(7)

According to ISO 16000-8, uncertainty for mean age of air at a point is calculated considering the (relative) standard deviations of determination of the integrated area and the initial concentration:

$$s^2 = s_{area}^2 + s_{00}^2$$

(8)

Where $s_{area}^2$ is the variance in calculating the true integral from $t = t_0$ to $t = t_{ Extraction}$; and $s_{00}^2$ is the variance in estimating the initial concentration.
Table 3  Uncertainties of air change rate measures depending on air change rates and measuring periods for one decay gas technique by average [14].

| \( \frac{d \lambda}{\lambda} / \% \) | T  | \( \lambda / h^{-1} \) |
|---------------------------------|----|-----------------|
| 0.25                            | 0.433 (177%) | 0.446 (93%) |
| 0.5                             | 0.193 (395%) | 0.193 (395%) |
| 1                               | 0.078 (31%)  | 0.153 (31%) |
| 2                               | 0.093 (37%)  | 0.683 (137%) |

The relative uncertainty \( s_{\text{area}} \) of the integrated area can be estimated from the absolute uncertainties \( s_{\text{in}} \) and \( s_{\text{ex}} \), which belong to the numerically integrated part and the extrapolated part, respectively [5].

\[
s_{\text{area}} = \sqrt{s_{\text{in}}^2 + s_{\text{ex}}^2} / (A_{\text{in}} + A_{\text{ex}}) \tag{9}
\]

Where \( A_{\text{in}} \) is the integrated area and \( A_{\text{ex}} \) is the interpolated area, as considered in ISO 16000-8.

\( s_{\text{area}} \) is the relative uncertainty at the initial concentration. It depends not only on the analysis of uncertainty, but also on possible spatial variations within and between zones due to inability to achieve a homogeneous initial concentration in the whole ventilated system [5]. Since for the ASHRAE 129 the nominal time constant is considered as the age of air at the extraction, the uncertainty is calculated in the same way.

Uncertainty for the air exchange efficiency is then considered as the cumulative uncertainty of the parameters considered for its calculation (Equations (1) and (3)).

Table 4 summarize uncertainty calculation methods from literature and standards, with the ones used in the new procedure. Even if all the cited standardized protocols and methods have been tested, in this paper we focus on air change rate given by an average calculation considering standards ASTM 2006 and ISO 2012 and room mean age of air considering measurements in 6 points for the new procedure and 5 points for the ASHRAE 129 method. Fig. 1 presents a flow chart of the methodology.

For further analyses concerning comparison between parameters assessment with the new procedure and TN 34 method, see Allab [18].

3. Experimental measurements

The experimental part of this research relates to two measurement campaigns carried out during the summer period in a classroom of the ESTP (Ecole Spécialisée des Travaux Publics du Bâtiment et de l’Industrie) in Paris. The room L21 is at the second floor of the Laplace building and it has two external walls, respectively facing North and West, whereas the other external walls border respectively with another classroom and a corridor. The room is a false ceiling but, it is not in communication with the nearby rooms, thereby ensuring the monozonal hypothesis. The HVAC system consists of two heating radiators and two air vents powered by and air handling unit, with a nominal flow rate of 2015 m³/h and 1715 m³/h recirculation.

Auxiliary measures were deployed in order to characterize room and environmental conditions. Together with geometrical measurements, effective volume and envelope airtightness measurements were conducted using tracer gas, according to ASTM E741 [12] and blower door tests following ISO 9972 [17–18]. Outdoor and indoor conditions were monitored using respectively data from a local weather station and an indoor microclimate station [19–20].

The experimental campaigns were realized in August and September respectively at “high” and “low airflow rate” regimes of the ventilation system, which correspond to an average of 11.90 m³/h per person and 6.20 m³/h per person respectively (assuming 35 users for the classroom). The air flow rate was calculated as a result of the air change rate assessment. Measurements for decay method were realized using a multipoint sampler and doser (INNOVA 1303) with a photoacoustic infrared absorption spectrometry (Innova 1412). SF6 gas was selected as tracer gas, starting with an initial concentration of 140 ppm. Even if SF6 is a potent greenhouse gas with a high global warming potential, its usage as tracer gas provides a more reliable result: CO₂ has...
a non-zero outdoor concentration and measurements can also be affected by the presence of users in other adjacent spaces of the building, this is also confirmed by Almeida [21]. SF6 is not present in the ambient air so a smaller emission can be easier traced with also a shorter test duration: each test took between 4 h and 8 h to reach 3 ppm (depending on the air flow rate regime).

For the 14 tests, 6 measurement points for gas concentration were considered: 5 in the ventilated space and 1 at the exhaust, (Fig. 2). In order to cover the room surfaces as best as possible, the spatial distribution of the points was established according to the method proposed by Roulet [7] and Awbi [22]. Following the geometrical model, the four points at the corners (from point 2 to 5 in the Fig. 2) were placed at 1.5 m from walls, ceiling and floor. In order to represent the breathing zone, the point in the center of the room (point 6) was placed at 1.1 m from the floor. The last point (Point 1) was placed at the exhaust.

As shown in Fig. 2, one of the vents is for the supply of the air and the other is for the exhaust. The extraction vent is omnidirectional, while the supply blower directs the airflow towards the center of the room.

In order to compare results given by ASHRAE 129 method with the ones of the new procedure, an uncertainty analysis was developed for all the quantities and for the air change efficiency index. The experimental protocol is further described in Allab [16], while uncertainty was established as already presented in Section 2.

4. Results

In this section the paper focuses on indices and errors measured and calculated for mechanical ventilation strategies.

Results in Tables 5 and 6 for high and low flow rate regime respectively, focus on average values of air change rate, age of the air and nominal time constant, measured and calculated according to the ASHRAE 129 method (A) as well as the new procedure (NP). Results are reported with uncertainties calculated as presented in section 3.

Tables 7 and 8 show the air exchange efficiency for high and low flow rate regime calculated according to the ASHRAE 129 method (A) as well as the new procedure (NP). Results are reported with uncertainties calculated as presented in section 3.

Results for air change rate uncertainty are achievable only by assuring to start and to finish the concentration decay homogeneously, according to ASTM E741, with the consequences of obtaining relatively weak errors. The uncertainty due to the gas mixing can increase for a calculation on all the test points. In this case, a concentration gap among the measuring points can generate important errors, especially when it comes to ventilation.
Table 6
Average results and errors for low flow rate regime for air change rate ($k$, age of the air ($\tau$)), nominal time constant ($\tau_m$), measured and calculated according to the ASHRAE 129 method (A) and new procedure (NP).

| Test | $k$ [h/$C_0$] | $\tau_m$ [h] | $\tau_A$ [h] | $\tau_{m,NP}$ [h] | $\tau_{A,NP}$ [h] | $\delta_{\tau_{A,NP}/\tau_{A}}$ [%] |
|------|----------------|--------------|-------------|------------------|------------------|-----------------------------|
| MV7  | 0.99 ±0.8%     | 1.10 ±6.8%  | 1.09 ±6.8% | 1.01 ±1.15       | 1.15 ±3.0%       | ±3.0%                      |
| MV8  | 0.90 ±0.8%     | 1.15 ±6.8%  | 1.14 ±6.8% | 1.11 ±1.17       | 1.17 ±2.9%       | ±2.9%                      |
| MV9  | 0.90 ±0.8%     | 1.08 ±6.8%  | 1.08 ±6.8% | 1.11 ±1.06       | 1.06 ±3.0%       | ±3.0%                      |
| MV10 | 0.92 ±0.8%     | 1.03 ±6.8%  | 1.03 ±6.8% | 1.09 ±1.04       | 1.04 ±2.5%       | ±2.5%                      |
| MV11 | 0.90 ±0.8%     | 1.09 ±5.6%  | 1.10 ±6.6% | 1.11 ±1.09       | 1.09 ±3.0%       | ±3.0%                      |
| MV12 | 0.90 ±0.7%     | 1.10 ±6.6%  | 1.10 ±6.6% | 1.11 ±1.20       | 1.20 ±3.0%       | ±3.0%                      |
| MV13 | 0.90 ±1.2%     | 1.17 ±6.7%  | 1.16 ±6.7% | 1.11 ±1.20       | 1.20 ±3.0%       | ±3.0%                      |
| MV14 | 0.90 ±1.1%     | 1.10 ±6.8%  | 1.08 ±6.8% | 1.04 ±1.16       | 1.16 ±3.0%       | ±3.0%                      |

Table 7
Average results and errors for high flow rate regime for air exchange efficiency ($e_a$), measured and calculated according to the ASHRAE 129 method (A) and new procedure (NP).

| Test | $e_{A}[\%]$ | $\delta_{e_{A}}$ | $e_{A,ASHRAE}[\%]$ | $\delta_{e_{A,ASHRAE}}$ |
|------|--------------|------------------|----------------------|--------------------------|
| MV1  | 44.3 ±6.6%   | ±6.6%            | 52.2 ±7.2%           | ±7.2%                    |
| MV2  | 46.1 ±8.1%   | ±8.1%            | 53.3 ±8.7%           | ±8.7%                    |
| MV3  | 44.0 ±6.5%   | ±6.5%            | 54.0 ±7.1%           | ±7.1%                    |
| MV4  | 46.1 ±7.0%   | ±7.0%            | 50.6 ±7.7%           | ±7.7%                    |
| MV5  | 46.6 ±7.1%   | ±7.1%            | 51.4 ±7.7%           | ±7.7%                    |
| MV6  | 47.7 ±7.5%   | ±7.5%            | 54.0 ±8.1%           | ±8.1%                    |

Table 8
Average results and errors for low flow rate regime for air exchange efficiency ($e_a$), measured and calculated according to the ASHRAE 129 method (A) and new procedure (NP).

| Test | $e_{A}[\%]$ | $\delta_{e_{A}}$ | $e_{A,ASHRAE}[\%]$ | $\delta_{e_{A,ASHRAE}}$ |
|------|--------------|------------------|----------------------|--------------------------|
| MV7  | 45.6 ±6.9%   | ±6.9%            | 52.6 ±7.4%           | ±7.4%                    |
| MV8  | 48.6 ±6.8%   | ±6.8%            | 51.2 ±7.4%           | ±7.4%                    |
| MV9  | 51.5 ±6.8%   | ±6.8%            | 49.1 ±7.4%           | ±7.4%                    |
| MV10 | 52.8 ±6.9%   | ±6.9%            | 50.5 ±7.4%           | ±7.4%                    |
| MV11 | 51.1 ±5.6%   | ±5.6%            | 48.8 ±6.1%           | ±6.1%                    |
| MV12 | 50.6 ±6.6%   | ±6.6%            | 49.7 ±7.2%           | ±7.2%                    |
| MV13 | 47.6 ±6.8%   | ±6.8%            | 51.5 ±7.3%           | ±7.3%                    |
| MV14 | 47.5 ±6.9%   | ±6.9%            | 53.6 ±7.4%           | ±7.4%                    |

Fig. 3. Air exchange efficiency results for mechanical ventilation, in high flow rate (1–6) and low flow rate (7–14) regimes, for ASHRAE 129 and proposed method.

Fig. 4. Mean age of the air at point ($\tau_p$) for tests in high flow rate regime (from MV1 to MV6) in each point of the Fig. 2.

Table 9
Mean age of the air at point ($\tau_p$) for tests in high flow rate regime (from MV1 to MV6).

| Test | 1 – exhaust | 2 – SE | 3 – SW | 4 – NW | 5 – SW | 6 – centre |
|------|-------------|--------|--------|--------|--------|------------|
| t_r1 | 0.71 ±2.9%  | 0.71 ±2.9% | 0.68 ±2.9% | 0.67 ±3.0% | 0.68 ±3.0% | 0.68 ±3.0% |
| t_r2 | 0.68 ±5.0%  | 0.66 ±2.9% | 0.66 ±2.9% | 0.63 ±3.0% | 0.61 ±3.5% | 0.61 ±3.0% |
| t_r3 | 0.66 ±2.9%  | 0.66 ±2.9% | 0.66 ±2.9% | 0.63 ±2.9% | 0.60 ±3.2% | 0.60 ±3.2% |
| t_r4 | 0.62 ±2.9%  | 0.69 ±3.2% | 0.64 ±3.3% | 0.64 ±3.3% | 0.65 ±3.3% | 0.64 ±3.3% |
| t_r5 | 0.67 ±3.1%  | 0.68 ±3.1% | 0.65 ±3.1% | 0.64 ±3.2% | 0.65 ±3.2% | 0.64 ±3.2% |
| t_r6 | 0.67 ±3.2%  | 0.64 ±3.4% | 0.63 ±3.3% | 0.59 ±3.3% | 0.63 ±3.4% | 0.61 ±3.3% |
strategies with an air change efficiency index beyond or below 50%. This is one of the reason that supported the choice of using the average calculation method for determining the air change rate, besides the validity of the method for results not biased in case of unsteady effects.

Following the ASHRAE 129 air exchange efficiency has an average value of 51.8%, whereas the proposed method, which considers spatial calculation and the unwanted air leaks through cracks, reports a value of 47.4%. Considering an average uncertainty of ± 7.0% the gaps between the methods are non-significant in low flow rate tests.

Figure 3 shows air exchange efficiency results for mechanical ventilation using, from test MV1 to MV6, high flow rate ventilation and, from test MV7 to MV14, low flow rate ventilation.

Since tracer gas technics also allow to describe airflow distribution in the ventilated zone, the paper also presents results about local mean ages in the ventilated space of the case study. In this way, according to the definition of mean age of air, it is possible to highlight the time needed to renovate the air in a specific point of the room. Considering ages of air in all measurement points it is possible to estimate the uniformity of the air distribution and to highlight if air stagnation zones do exist.

With reference to Fig. 2, for each point (from 1 to 6), Tables 9 and 10 report the values of the local mean age of the air for each test respectively in high and low flow rate regime.

Figure 4 shows local mean ages of air for all the measurement point in mechanical ventilation using, from test MV1 to MV6, high flow rate ventilation and, from test MV7 to MV14, low flow rate ventilation.

Table 10
Mean age of the air at point (tₚ) for tests in low flow rate regime (from MV7 to MV14) in each point of the Fig. 2.

| Test | 1 – exhaust | 2 – SE | 3 – SW | 4 – NW | 5 – SW | 6 – centre |
|------|-------------|--------|--------|--------|--------|------------|
| MV7  | 1.15 ±3.0%  | 1.08 ±3.0% | 1.09 ±3.0% | 1.03 ±3.0% | 1.03 ±3.1% | 1.03 ±3.1% |
| MV8  | 1.17 ±3.0%  | 1.16 ±3.0% | 1.13 ±3.0% | 1.16 ±3.0% | 1.12 ±3.1% | 1.14 ±3.1% |
| MV9  | 1.06 ±2.9%  | 1.14 ±3.0% | 1.07 ±3.0% | 1.05 ±3.0% | 1.07 ±3.0% | 1.07 ±3.1% |
| MV10 | 1.04 ±2.9%  | 1.00 ±3.1% | 1.01 ±3.0% | 1.00 ±3.0% | 1.08 ±3.1% | 1.06 ±3.1% |
| MV11 | 1.07 ±2.5%  | 1.14 ±2.5% | 1.09 ±2.5% | 1.09 ±2.5% | 1.08 ±2.5% | 1.08 ±2.5% |
| MV12 | 1.09 ±2.9%  | 1.07 ±2.9% | 1.08 ±3.0% | 1.14 ±3.0% | 1.17 ±3.0% | 1.09 ±3.0% |
| MV13 | 1.20 ±3.0%  | 1.20 ±3.0% | 1.22 ±2.9% | 1.14 ±3.0% | 1.07 ±3.0% | 1.19 ±3.0% |
| MV14 | 1.16 ±3.0%  | 1.12 ±3.0% | 1.14 ±3.0% | 1.04 ±3.1% | 1.04 ±3.1% | 1.07 ±3.0% |

5. Discussion

Air change rates (λ) for the first series of tests (high flow rate) range from 1.64 h⁻¹ to 1.78 h⁻¹ (Table 5). These variations may be explained by the envelope airtightness influence, which can interfere with the air exchanges and the quality of air flow control (PID optimization). Considering uncertainties (between ± 0.7% and ± 0.9%), these variations are quite low. For low flow rate tests (Table 6), air change rates range from the 0.90 h⁻¹ to 0.99 h⁻¹ with an average of 0.92 h⁻¹, not showing a significant difference considering uncertainties (on average ± 1.0%). Since air change rate uncertainty considers both the measuring and the mixing contributions, measurement times and the initial concentration of the gas have a substantial influence.

Measured values of the air change rates lead to an average of 11.90 m³/h.person and 6.20 m³/h.person for the high flow rate and low flow rate regimes respectively. These air flow rates are below French and European requirements. By referring to the EN 16798 [23] recommendations for fresh air flow requirements per occupant, these values are widely below the thresholds defined for existing buildings: by considering an average occupation of 35 students though, the ventilation flow rates would correspond to 20 m³/h.person for existing buildings (category III) and 35 m³/h.person for new or renovated buildings (category II).

The nominal time constant (tₚₑₑ) measured in the ventilated zone with the new procedure is about 0.60 h for the high regime and 1.09 h for the low one (Tables 5 and 6). Regarding the extraction measures (tₑₑₑₑ), the nominal time constant value (0.68 h and 1.15 h) can be biased by the fact that the air is short-circuited prob-
ably through the airtightness cracks. Furthermore, the nominal time constant measured in the ventilated zone can be unreliable in case of heterogeneous areas not taken into account by the chosen measurement points. Considering the relative uncertainties based on the nominal time constant, the gaps are non-significant.

The analysis based on the extraction can be biased because of the unwanted leaks that jeopardize the ventilation effectiveness results. The air permeability of the envelope plays an important role since the room presents a lower airtightness than the one established by the French standard. This is confirmed by blower door tests. The envelope air permeability expressed as the infiltration rate at 4 Pa referred to heat loss surfaces \( Q_{4Pa,surf} \), has an average value of 2.26 m\(^3\)/h.m\(^2\), that is higher than the threshold of French thermal regulation of 2005 (1.7 m\(^3\)/h.m\(^2\)). The air changes per hour, expressed as the infiltration rate at 50 Pa referred to the heated volume \( n_{50} \), has an average value of 6.79 h\(^{-1}\), while the threshold for PassivHaus label is 0.6 h\(^{-1}\). The hypothesis of the influence of envelope permeability can also be confirmed by analyzing the gaps occurred according to the ventilation flow rate. Since the classroom is maintained at an overpressure, it is probable that the envelope airtightness is more influential for higher ventilation regimes. Air change rate passing through the envelope cracks is also estimated by tracer gas in natural pressure measurements giving values between 0.04 h\(^{-1}\) and 0.07 h\(^{-1}\) [16].

Concerning the air exchange efficiency \( (e_a^2) \) the majority of results related to ASHRAE 129 method (51.8%) tends toward, according to Mundt [1], a fully mixed flow model \( (e_a^2 = 50\%) \). For the new procedure \( (e_a^2) \) results in high flow rate regime (47.4%) seem to be closer to a shorter-circuit flow model \( (e_a^2 < 50\%) \) (Table 7), while for the low flow rate regime (Fig. 2) they are similar to ASHRAE 129 method. This means that, for high flow rate regimes, the new procedure underestimates the air exchange efficiency compared to ASHRAE 129. In other words, results provided with the new procedure are more conservative than the standardized ones and preferable considering the risk of under-ventilation.

Spatial distribution of local mean ages is relatively homogenous for high flow rate ventilation (Table 9), with the presence of some dead zones (old age), especially in points 2 (close to the supply vent) (Fig. 2). On the contrary, point 4 shows younger ages, due to the unidirectional orientation of the air supply openings toward this zone. Age's distribution in low velocity regime (Table 10) is relatively more important comparing to the high one. In order to assess the ventilation efficiency in terms of spatial distribution of the air, one should consider the highest local mean age in the room. This information allows to evaluate the risk of airborne transmission via the possible exposure time. In our case study, for high flow rate regime, we should wait at least 42 min \( \pm 3.0\% \) (highest local mean age of air at point 2) to renovate the air everywhere in the room. While for the low flow rate the highest local mean age is more than an hour (73 min \( \pm 3.0\% \)).

6. Conclusions

This paper presented a new procedure to establish ventilation effectiveness indices. The new method is based on tracer gas decay technics and considers for the calculation of air exchange efficiency index: the nominal time constant as the inverse of the air change rate \( (\lambda) \), and the mean age of the ventilated space as the average of the local ages. Since these two parameters are assessed by referring to the ventilated space, it is possible to calculate the air exchange efficiency index independently of the ventilation strategy (mechanic, natural, mix mode).

To validate this hypothesis, we compared the new procedure against ASHRAE 129 method for mechanical ventilation in a classroom.

In the case study, for high flow rate regime, the proposed method gives an air exchange efficiency lower than the one estimated following the ASHRAE 129 method, showing a short-circuited ventilation. This means that a huge part of fresh air is extracted before diluting the exhaust air. Therefore, the new procedure is more conservative than ASHRAE 129 method and somehow preferable for a commissioning protocol. Moreover, the analysis of local mean ages of air in the ventilated space, allowed to describe the efficiency of the ventilation strategy in spatial air distribution.

The latest has a great importance considering influence of ventilation on the risk of airborne transmission of viruses like COVID-19, neglecting the position of the emission source [24]. The proposed method has physical and practical limits. Whereas, the ASHRAE 129 method allows measuring the air exchange efficiency considering the extraction, the new procedure needs a precise implementation on the ventilated volume. On the other hand, unlike the ASHRAE 129 method, the new one allows to consider the airtightness defects and it can be used regardless the ventilation strategy.

In order to generalize the procedure, more tests are needed enabling to consider other configurations: air flow rates, air flow pattern, indoor and outdoor climatic conditions (temperature, humidity, air flow rate, pressure, turbulence intensity), envelope air leakages, room configuration. Parametrical analysis about validated numerical models should be realized for enabling the study of a larger panel of configurations [25]. Further studies will also focus on robustness of the new procedure for natural and mixed mode ventilation strategies. More numerical studies and experimental campaigns are needed to assess air exchange efficiency considering their transient nature, the effect of the variability of boundary conditions and openings configurations [26–29].

In practice, the in-field measurements with the new procedure took between 4 and 8 h, without considering instrumentation time. Further studies are planned to compare the procedure with other easier and more used commissioning protocols. However, technical and technological improvements are needed to reduce measuring ages and indices without losing in accuracy.

However, results prove how effectiveness assessment requires a larger systemic vision, considering the interface between ventilation system and building envelope. Envelope permeability plays an important role and it is the main element that makes the difference between the two methods for the nominal time constant calculation. In fact, in the proposed procedure, nominal time constant measurements include airflow in both exhaust and air leakages, while in ASHRAE method only the exhaust is considered. However, more investigations and a larger number of samples are needed to validate this hypothesis.

The usage of this new procedure can be beneficial in several situations: i) in existing mechanically ventilated buildings in which the airtightness defects cannot be neglected; ii) in order to take into account the spatial air distribution in the ventilated zone; iii) in case of natural and mixed-mode ventilation strategies, where it is not possible to consider the exhaust. The literature still misses a standardized measurement and commissioning tool for natural and hybrid ventilation strategies, and the new methodology might represent its inception.

To conclude, new protocols are needed for indoor air quality (IAQ) commissioning in order to overcome limitations of standardized methods and to consider new challenges and user needs, and this new procedure represents a step further in this direction.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
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