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FIELD COMPARISON OF AGE OF AIR MEASUREMENT TECHNIQUES

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SUMMARY

The measurement of the local mean age of air at various locations in a room is useful to verify the efficiency of the ventilation system and to assess the main air streams and the dead zones. Several methods, using tracer gas, can be used to measure the age of air. This paper presents a comparison of these methods, including a study of the possible advantages and inconveniences.

Simultaneous measurements were performed with two tracers in an auditorium with balanced ventilation and complete mixing, using step-up, step-down and pulse techniques. Another experiment in a test office room with displacement ventilation brought some more experience. Practical consequences of these field experiments are also reported.

Conclusions of this study are that a) good mixing of the tracer and the air to be marked is essential and is often a problem; b) step-up injection technique is best appropriate for rooms with pulsed air; c) pulse technique can also be used in these rooms but is more sensitive to concentration errors and d) step-down (or decay) technique should be reserved for rooms with significant infiltration. These conclusions are somewhat different than those published by other authors after similar studies.

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INTRODUCTION

Scope of the presentation

To ensure health, safety and comfort in buildings, an efficient ventilation strategy should provide an adequate supply of fresh air to the building occupants to dilute airborne contaminates to acceptable concentrations. Since it can be assumed that the older the air is, the greater is its contaminate concentration, knowledge of the residence time or age of air is of great importance. From these quantities, various associated expressions of efficiency or effectiveness can be calculated.

Several tracer gas techniques can be used to measure the age of air. This contribution intends to provide some guidance in selecting one of these techniques when preparing an experiment in particular conditions. For that purpose, a theoretical study is proposed first, then experience gained from simultaneous field experiments performed with the various techniques is presented.

Definition of the age of air

The quantities defined below are explained in greater detail in the literature [1, 2, 3] and are only briefly described here. The particles of fresh air coming from outside or from the ventilation system arrive at a given location r in a room after a time $\tau(r)$ which will vary from one particle to the other. τ is called the residence time of the particle in the room, or its age, as if it were born when entering the room. Since there is a large number of air particles, we may define a probability density $f_r(\tau)$ that the age of particles arriving at a given location is between τ and $\tau+d\tau$ and a probability $F_r(\tau)$ that this age is higher than τ. The following relationships always hold between these two functions:

$$\frac{dF_r}{d\tau} = f_r(\tau) \qquad \text{and} \qquad \int_{\tau_r}^{\infty} f_r(t)\,dt = F_r(\tau) \qquad (1)$$

The **local mean age of air** at a point r, $\bar{\tau}_r$, is defined by the average age of all the air particles arriving at that point:

$$\bar{\tau}_r = \int_0^\infty \tau f_r(\tau)\, d\tau \tag{2}$$

The **room mean age of air** $\langle\tau\rangle$ is defined by the space average of the local mean ages of the air particles in the room:

$$\langle\tau\rangle = \frac{1}{V}\int_V \bar{\tau}_r\, dV \tag{3}$$

where V is the volume of the room.

Measurement method for the age of the air

The basic principle is to mark the air to be traced with a gas (the tracer gas), according to a known schedule, and to follow the concentration of that tracer gas at the location of interest. This technique is based on the assumption that the tracer gas behaves the same as the air: no adsorption, same buoyancy. It can be readily understood that if the air is marked at the inlet by a short pulse of tracer gas, and if the tracer molecules follow the air molecules, they will arrive at a given location at the same time as the air molecules. In fact, the pulse technique is not the only one and the probability functions (1) and the local mean ages (2) can be measured by recording the time history of the net tracer concentration, $C_r(t)$, at any point, r, by either of three strategies as follows:

- **step down**: uniform concentration of tracer is achieved at the beginning of the test, when the injection is stopped,
- **step-up**: the tracer is injected at air inlet, at a constant rate from the starting time throughout the test,
- **pulse**: a short pulse of tracer is released in the air inlet at the starting time.

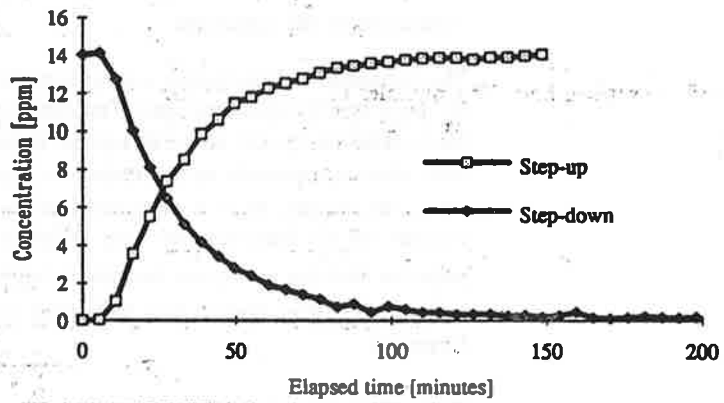

Figure 1: Variation of the concentration with time during measurements of the age of air, using step-up and step-down measurement techniques.

Figure 1 shows the variation of concentration during step-up and step-down measurements, while Figure 2 shows it for pulse measurement. These are real measurements performed in the auditorium mentioned at the end of this paper.

It is also possible to imagine other injection strategies like a rectangular or a triangular pulse, but we will limit this contribution to these three strategies, which are of common use. To interpret the recorded tracer gas concentrations and obtain the age of air, the background (or supply) concentration should first be subtracted from all measurements, and the elapsed time should be calculated by subtracting the starting time from all time values. The local mean age at a given measurement location is obtained by evaluating the expressions shown in Table 1. Note that the net concentration, C_r, is the difference between the concentration measured at location r and the concentration in the outdoor air.

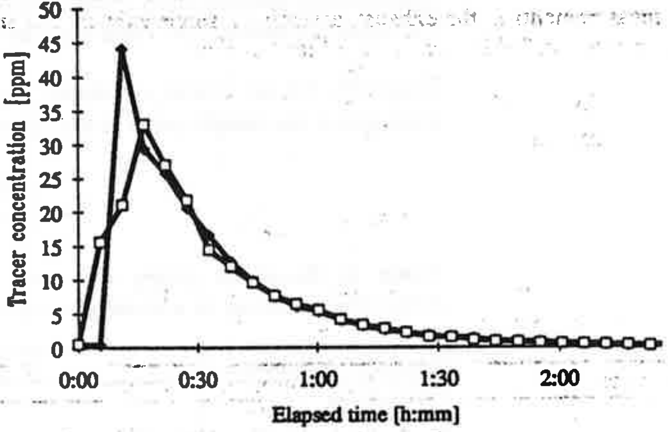

Figure 2: Concentration versus time during measurements of the age of air at two different locations, when using the pulse injection technique.

Table 1: Equations giving the probability distribution function of the age of air and the local mean age, from the measurement of the concentration history of a tracer gas, for various tracer injection strategies (From [1]).

Method for injection	Distribution at location r	Local mean age of air $\bar{\tau}_r$
Step down	$F(t)=\frac{C_r(t)}{C_r(0)}$	$\bar{\tau}_r=\frac{\mu_0(C_r)}{C_r(0)}$
Step-up	$F(t)=\frac{C_r(\infty)-C_r(t)}{C_r(\infty)}$	$\bar{\tau}_r=\frac{\mu_0[C_r(\infty)-C_r(t)]}{C_r(\infty)}$
Pulse	$f(t)=\frac{C_r(t)}{\mu_0(C_r)}$	$\bar{\tau}_r=\frac{\mu_1(C_r)}{\mu_0(C_r)}$

The various moments, μ_n, of the concentration are defined by:

$$\mu_n = \int_0^{\infty} t^n \, C_e(t) \, dt \tag{4}$$

If there is only one exhaust (and no exfiltration as well), the nominal time constant of the room, τ_n, which is the ratio of the room volume and the volumetric air flow rate, is equal to the mean age of air at the exhaust, $\overline{\tau}_e$, since at this location, the tracer gas is well mixed with the exhaust air:

$$\tau_n = \overline{\tau}_e \tag{5}$$

On the other hand, the room mean age of air, $<\tau>$, which is the average of the local mean ages of the air contained in the room, can also be deduced from tracer concentration measurements in the exhaust, assuming a single exhaust and steady state. The equations provided in Table 2 can be used for that purpose.

Therefore, the air change efficiency, η_a, can be assessed directly by measuring the evolution of the concentration at the exhaust:

$$\eta_a = \frac{\tau_n}{2<\tau>} = \frac{\overline{\tau}_e}{2<\tau>} \tag{6}$$

Table 2: Equations giving the room mean age from the measurement of the concentration history of a tracer gas at the exhaust (From [1]).

Method for injection	Room mean age of air $<\tau>$
Step down	$<\tau> = \frac{\mu_1(C_e)}{\mu_0(C_e)} = \frac{\mu_1(C_e)}{\tau_n \, C_e(0)}$
Step-up	$<\tau> = \frac{\mu_1[C_e(\infty) - C_e(t)]}{\mu_0[C_e(\infty) - C_e(t)]}$
Pulse	$<\tau> = \frac{\mu_2(C_e)}{2\mu_1(C_e)} = \frac{1}{2\tau_n} \frac{\mu_2(C_e)}{\mu_0(C_e)}$

Interpretation

In practice, the various moments in the above formulae are calculated numerically, on the base of discrete recorded values of the concentration and time. The following section describes a simple way to calculate these moments, using the trapeze method, whose general formulation is:

$$\int_0^{t_N} f(t)\,dt \cong \sum_{j=0}^{N-1} \frac{f_j + f_{j+1}}{2} \Delta t \qquad (7)$$

where f_j is for $f(t_j)$ and Δt for $t_{j+1} - t_j$.

Assuming a linear variation of the concentration in each time step, we get, for the first moments defined in equation (4):

$$\mu_0 = \left[\frac{C_0 + C_N}{2} + \sum_{j=1}^{N-1} C_j\right] \Delta t + \varepsilon_0(N, \tau_d) \qquad (8)$$

$$\mu_1 = \left[\frac{1}{6} C_0 + \frac{3N-1}{6} C_N + \sum_{j=1}^{N-1} C_j j\right] \Delta t^2 + \varepsilon_1(N, \tau_d) \qquad (9)$$

$$\mu_2 = \left[\frac{1}{12} C_0 + \frac{6N^2 - 4N + 1}{12} C_N + \sum_{j=1}^{N-1} C_j \left(j^2 + \frac{1}{6}\right)\right] \Delta t^3 + \varepsilon_2(N, \tau_d) \qquad (10)$$

The number of measurements, N, could be large enough to ensure that the sum of the terms for $j > N$ are negligible, or, in other words, that C_N is very close to the steady state value. In this case, the remaining parts, $\varepsilon_n(N, \tau_d)$, are negligible. In practice, however, the measurement can be stopped before reaching the steady state. In this case, the tail in the integral of the moments is not measured and it should be estimated.

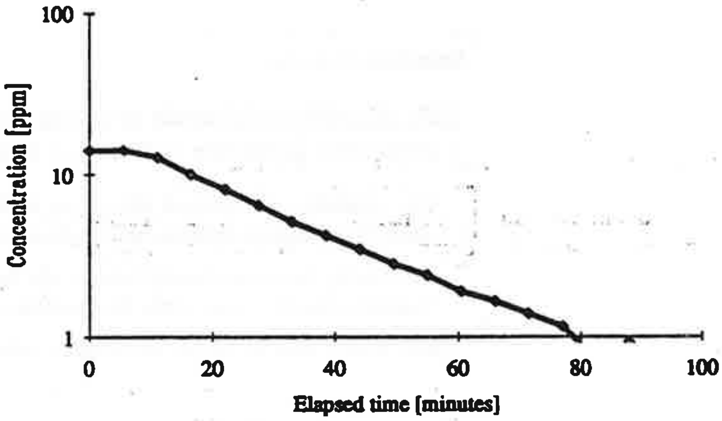

Figure 3: Logarithm of the concentration versus time in the step-down measurement shown in Figure 1. The decay of the concentration is close to an exponential after 20 minutes, that is a little less than the nominal time constant of the room.

As shown in Figure 3, this tail is, in most cases, exponential. Therefore, for time larger than $t_N = N\Delta t$, it can be assumed that:

$$C(t > t_N) = C_N \exp\left(\frac{-t+t_N}{\tau_d}\right) \tag{11}$$

where τ_d is a time constant determined by a fit on the last measurements, in the exponential part. The time required for reaching an exponential decay depends not only on the nominal time constant of the room, but also on the ventilation system. In case of complete mixing and at steady state, the decay will be exponential from the beginning of the test. In case of perfect displacement ventilation, the decay will be very sharp after a time equal to the age of air and the concentration might be negligible before presenting an exponential decay.

When equation 11 is valid, the remaining part, $\varepsilon_n(N, \tau_d)$, can be calculated analytically:

$$\varepsilon_n(N, \tau_d) = \int_{t_N}^{\infty} t^n C_N \exp -\left(\frac{t-t_N}{\tau_d}\right) \, dt \tag{12}$$

and we obtain the following expressions, which can be used in equations 8, 9 and 10:

$$\begin{aligned} \varepsilon_0 &= C_N \tau_d \\ \varepsilon_1 &= C_N \tau_d (t_N + \tau_d) \\ \varepsilon_2 &= C_N \tau_d \left(\tau_d^2 + (t_N + \tau_d)^2\right) \end{aligned} \tag{13}$$

Selection Criteria

Some selection criteria should be used in order to select the method (step-up, step-down or pulse) most appropriate to the case to be measured. These criteria are of two kind:

- Practicability: the method should be usable on the particular room to be measured, with its ventilation system, and compatible with the tracer gas analyzer
- Sensitivity to experimental errors: the method and its corresponding interpretation formula should not multiply the experimental errors by a large factor.

These criteria will be further developed below.

PRACTICABILITY OF THE METHODS

Practicability with respect to the room and its ventilation system

Step-up and pulse methods use tracer gas to mark the fresh air, and therefore, the tracer gas should be injected in the fresh air. This can easily be performed when one or few inlet ducts are the only paths for fresh air. In this case the tracer is injected in these inlet ducts. Care should be taken, however, to have a good mixing of the tracer with the fresh air before this mix enters the room. In particular when there are several inlets, they should all have the same tracer gas concentration.

When there is a large amount of infiltration, or when there are too many inlets, or even when the controlled inlets are directly connected to the outdoor air without any duct allowing for mixing, these methods are not practical. In this case, only the step-down technique can be used. This technique uses the tracer gas to mark the air in the room, and the fresh air is identified by its purity: it dilutes the tracer. The main problem with this technique is that it requires a perfect mixing of the tracer gas at the starting time. If the mixing is not perfect, errors result from net migration of tracer gas from high concentration to low concentration zones.

Mixing can readily be achieved in small to medium sized rooms by the use of multiple injection and strong mixing fans. If the ventilation can be stopped, some time can be managed for allowing the tracer gas to mix perfectly with the air contained in the room, even when the room is large. Concentration measurements can be performed at various locations to ensure proper mixing. When this is achieved, at time $t = 0$, the mixing fans are stopped and the ventilation system is started while continuing the concentration measurements.

However, mixing with fans, as well as stopping and starting the ventilation perturbes the air flow pattern within the room, hence also the pattern of the age of air. The measured age(s) will then not be the age(s) which could be realised without these perturbations. For these reasons, the step down method should not be recommended in any case. Since this method is the only one able to measure the age of air in rooms with multiple air inlets or cracks directly connected to outdoor air, accurate resutls cannot be obtained in such rooms.

Practicability with respect to the analyzer

The concentration histories are usually measured by analyzing air samples taken at time intervals, Δt, scanning the various locations of interest. To minimize the discretization errors, that is to allow a linear interpolation between measurements, this time interval should be small compared to the time required to change the tracer concentration by a significant amount. However, the upper limit of the measurement time interval depends also on the ventilation system. In case of complete mixing (and in steady state), the tracer concentration changes exponentially, with a time constant equal to the nominal time constant of the room. In this case, a recommended value could be a fraction of the nominal time constant, e.g. $\Delta t < 0.2\ \tau_n$.

On the contrary, in case of perfect displacement ventilation, the concentration can present a sudden, large change after a time interval which depends on the location of the measurement and is directly related to the age of air. A good accuracy in measuring this time is hence required, and the measurement interval should be small compared to the age of air.

With intermediate cases, the maximum allowed measurement interval also depends on the method used. Step-up and decay methods basically result in smoother concentration changes than the pulse method, which will always present a peak in concentration.

All these arguments result in the requirement that the gas analyser, together with the sampling device, should be able to perform measurements at time intervals shorter than the maximum allowed time interval. If the measurement time is a limiting factor, either fewer measurement points should be selected, or the step-up or step-down methods should be preferred to the pulse method.

SENSITIVITY TO ERRORS

Sources of errors

Errors may result from many sources, which are listed and explained below.

Tracer gas mixing: the tracer should be well mixed with the air to be marked. If it is not the case, changes in tracer gas concentration which are not related to the age of air will be observed, which will nevertheless be interpreted as resulting from air movements. This induces uncontrollable errors and bias in results. It is therefore important to control that good mixing is achieved where it should be. In the step-down method, the tracer gas concentration should be measured at several places within the room, and the experiment should not start as long as significant differences are measured. For step-up and pulse method, the tracer should be injected, preferably at several locations simultaneously, in a section of the duct far upstream of the inlet grids. Simultaneous tracer gas concentration measurements at different inlet grids allows one to control that all the grids blow air with the same tracer concentration. With the step-up method, this measurement also provides the final concentration, $C(\infty)$.

Concentration measurements: errors in concentration measurements have direct effects on the errors in the results. The errors in the results can be calculated when the errors in the concentration are known. This error analysis is performed below.

Timing: each method requires integration between the beginning of the experiment and an infinite time. The beginning of the experiment is the time when the signal is given with the tracer injection: Starting this injection in the pulse and step-up method, and stopping it in the step-down method. The measurements of the concentration should be timed accurately in relation to this starting time.

Reference concentration: As already stated, the concentrations which should be taken into account when interpreting the measurements are net concentrations, that is the difference between the concentrations measured at the location of interest and in the outdoor air. Errors in estimating the reference concentration are adding to the errors in the concentrations and hence directly influence the results.

For step-down and pulse measurements, the outdoor concentration can be measured before injecting any tracer, or at the end of the test, when the tracer gas is totally diluted. It can also be measured during the test with a second analyzer or a scanning valve. This could be more accurate but may lengthen the time interval between measurements.

For step-up measurements, the reference concentration is the concentration reached at the end of the test, when the measured air is completely changed by new air. This seems to be a disadvantage but it should be noted that this final concentration is immediately reached in the inlet duct, where the tracer is fully mixed with the fresh air. Hence, this concentration can be monitored during the test, thus controlling if there is really a steady flow rate. Since outdoor concentration is also required here, one more analyzer or the scanning of one more point is required, and this may also slow the measurement schedule.

Finite number of measurement, and numerical integration: The numerical integration can be accurate when the time interval between measurements, Δt, is small enough. If not, a bias is introduced by the integration. This can be partly compensated by using the Simpson technique or any more sophisticated numerical integration method instead of the trapeze method.

Error analysis

This analysis intends to provide some guidance on how the measurement errors are propagated through the interpretation formula to the results. The general equation used below assumes that the results of measurements, x_i, are randomly distributed around an average value with a gaussian distribution, the standard deviation being $\sigma(x_i)$. The estimate σ_y, of the errors on the results, $y(x_i)$, when the errors on the measurements are independent of each other is then:

$$\sigma^2(y) = \sum_i \left[\frac{\partial y}{\partial x_i}\right]^2 \sigma^2(x_i) \tag{14}$$

Therefore, using the equations shown in Table 1 and 2, we obtain, for the step-up or step-down methods:

$$\frac{\sigma^2(\bar{\tau})}{\tau^2} = \frac{\sigma^2(\mu_0)}{{\mu_0}^2} + \frac{\sigma^2(C)}{{C_{ref}}^2} \tag{15}$$

$$\frac{\sigma^2(\langle\tau\rangle)}{\langle\tau\rangle^2} = \frac{\sigma^2(\mu_1)}{{\mu_1}^2} + \frac{\sigma^2(\mu_0)}{{\mu_0}^2} \tag{16}$$

where C_{ref} is for C_0 in the step down technique and C_∞ for the step-up technique. It should be mentioned here that the error of the concentration, $\sigma(C)$, should include the error on the reference concentration too. It could hence be estimated at $\sqrt{2}$ times the error of single concentration measurement.

For the pulse technique, the equivalent equations are:

$$\frac{\sigma^2(\bar{\tau})}{\bar{\tau}^2} = \frac{\sigma^2(\mu_1)}{\mu_1^2} + \frac{\sigma^2(\mu_0)}{\mu_0^2} \tag{17}$$

$$\frac{\sigma^2(\langle\tau\rangle)}{\langle\tau\rangle^2} = \frac{\sigma^2(\mu_2)}{\mu_2^2} + \frac{\sigma^2(\mu_1)}{\mu_1^2} \tag{18}$$

Assuming an error in the concentration, $\sigma(C)$, which is independent of time, and errors in time $\sigma(t)$ and in the final decay rate, $\sigma(\tau_d)$, the errors in the various moments can be calculated, assuming that integration runs from 0 to $t_N = N\Delta t$ and that the remaining parts are calculated for $t > t_N$ using equation (11). Moreover, in equations (19) to (21), it is assumed that the number of measurements is large enough (e.g. more than 10) and only the largest power of N or t_N is kept in the sums.

$$\sigma^2(\mu_0) = (t_N \Delta t + \tau_d^2)\,\sigma^2(C) + [C_0 + C_N]^2\,\sigma^2(t) + C_N^2\,\sigma^2(\tau_d) \tag{19}$$

$$\begin{aligned}\sigma^2(\mu_1) = {} & \left[\frac{t_N^3\,\Delta t}{3} + \tau_d^2(t_N + \tau_d)^2\right]\sigma^2(C) \\ & + t_N^2 C_N^2\,\sigma^2(t) + C_N^2(t_N + 2\,\tau_d)^2\,\sigma^2(\tau_d)\end{aligned} \tag{20}$$

$$\begin{aligned}\sigma^2(\mu_2) = {} & \left[\frac{t_N^5\,\Delta t}{5} + \tau_d^2[\tau_d^2 + (t_N + \tau_d)^2]^2\right]\sigma^2(C) \\ & + t_N^4 C_N^2\,\sigma^2(t) + C_N^2 t_N^2[t_N + 4\,\tau_d]^2\sigma^2(\tau_d)\end{aligned} \tag{21}$$

Calculations of orders of magnitudes of these errors with usual values show that the larger is the order of the moment, the larger the error is. Therefore, error on the room mean age is larger that the error on the local age and the pulse technique induces larger errors than the two other techniques.

Errors in the concentrations have the largest influence. Errors in starting time may be important only in the step-down and step-up methods. Care should also be taken in determining the tail parts, ε_i, according equations (13). Errors in the time constant τ_d may have a large influence and this parameter, if used, should be determined with the best possible accuracy. A recommended technique is a least square fit on the logarithms of the last M concentrations, providing that $M\Delta t \cong \tau_d$ and that this part of the decay is exponential *[3]*.

EXPERIMENTS

The age of air was measured at 10 locations within an auditorium and at the air exhaust, in order to obtain a coarse map of the age. The mapping technique [3, 4] and the results of this experiment [5] are reported elsewhere. For the special purpose of method comparison presented in this paper, simultaneous measurements were performed using two tracer gases with step-up, step-down and pulse techniques.

The auditorium is a room of about 440 m^3 volume, with balanced ventilation. Exhaust grilles are all in the ceiling, while air is pulsed at each table and along a row in the ceiling, above the first rank of seats (Figure 4).

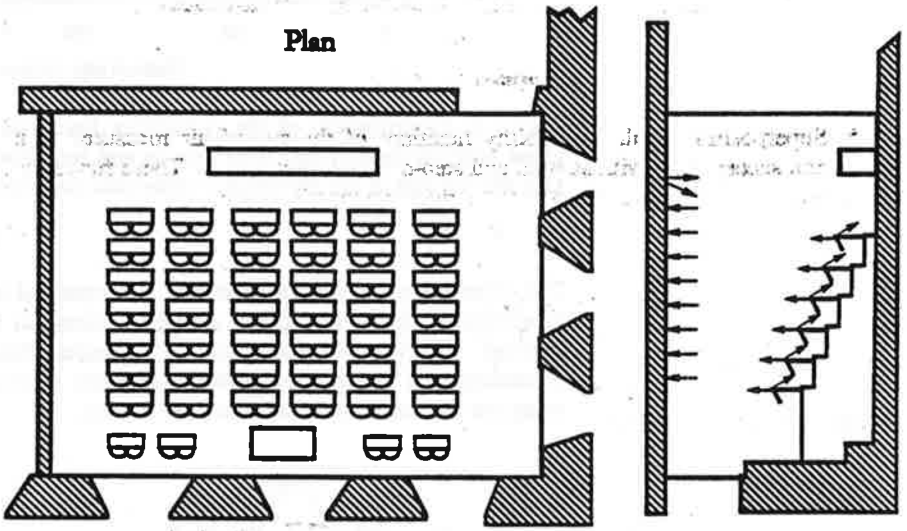

Figure 4: Auditorium in which measurements were performed.

A first result is shown in Figure 5, where the probability functions of the age of air at a particular location for two successive step-up and step-down experiments are shown superposed. The good agreement of these two curves results not only from steady state flow rate but also from a perfect mixing of the tracer gas with the air to be traced.

When mixing is not reached, the records of the concentration cannot be used to measure the age of air, as shown on Figure 6. In this case, the tracer was nevertheless injected at 10 l/minute during 15 minutes, upwind a large oscillating fan, 30 cm diameter, whose jet was directed successively in every direction in the auditorium. Moreover, a blanket was moved actively to improve the mixing. It is obvious that, despite these classical precautions, good mixing was not achieved at the beginning of the test, since the concentration at this location continues to grow while the tracer gas injection was cut.

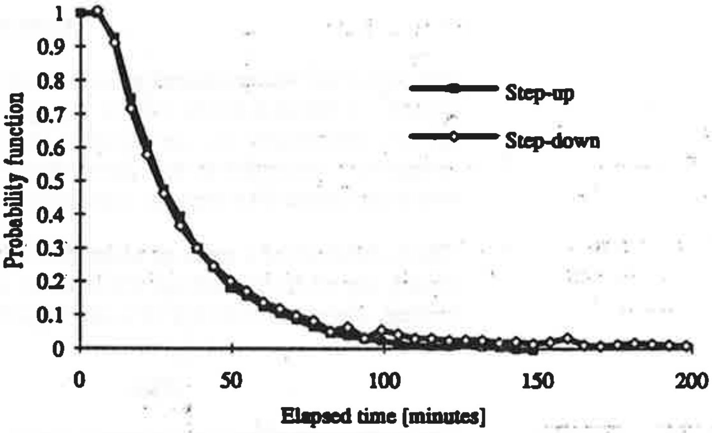

Figure 5: Superposition of the probability functions of the age of air measured at a given location successively with step-up and step-down measurements. These functions give the fraction of the air which is older than the corresponding time.

The other curve, showing a good mix, was obtained after a step-up. By the end of both experiments, there is a slight difference between the probability functions, hence between relative concentrations. This results from the choice of the reference concentrations, which were in both cases the average of the last ten measurements, when the concentrations stabilize close to zero.

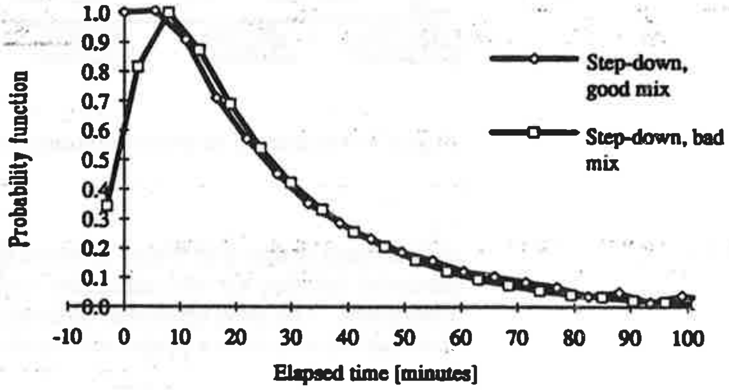

Figure 6: Example showing the result of mixing problems at the beginning of a step-down measurement. This also shows the effect of slight differences in reference concentration by the end of the measurement, after 50 minutes.

Figure 7 shows the effects of a bad mixing in a step-up experiment performed in a room equipped with a displacement ventilation system. The tracer gas was injected at least 5 meter upwind the inlet grilles, and the ducts have several bends between the injection point and the grilles. Nevertheless, this experiment shows that the final concentrations at the exhaust grilles and in the lungs of a manikin sitting at 3 m. from the injection grilles are not the same. The dramatic difference between both ages can also readily be seen: the manikin inhales an air which is much younger than in the exhaust. This is not the case in the auditorium, where all the locations show similar ages.

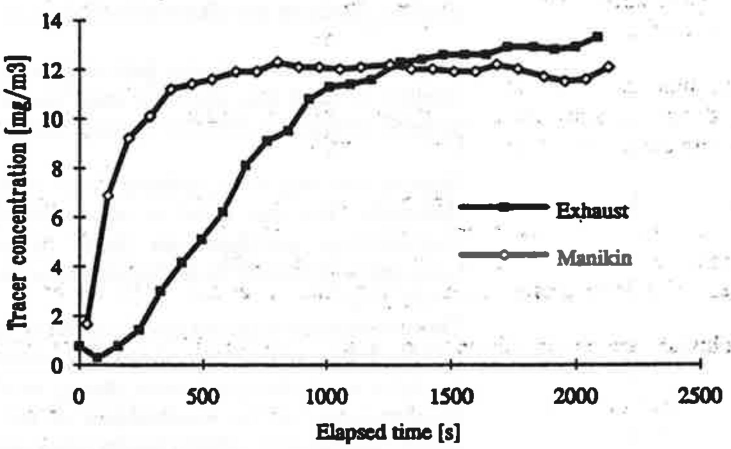

Figure 7: Concentration versus elapsed time in a step-up experiment, at two locations. A bad mixing of the tracer in the inlet duct results in different final concentrations.

CONCLUSIONS

From the above studies, the qualities of the various techniques can be deduced, and are shown in Table 3.

Table 3: Characteristics of the three measurement techniques with respect to practicability and insensitivity to errors. ++ is very good, -- is very bad.

	Qualification for:		
Characteristics or property	Step-down	Step-up	Pulse
Usable with infiltration	+	--	--
No perturbation of flow patterns	--	++	++
Can be used with slow analyzers	+	+	-
Fast technique, short experiment	-	-	+
Insensitivity to sources of errors:			
Bad tracer gas mixing	-	-	-
Errors on concentration	-	-	--
Errors on timing	-	-	+
Definition of the baseline	-	-	--
Numerical integration	+	+	-

As a summary, it is essential, with any technique, that special care is taken in a) mixing the tracer gas with the air to be marked; b) in accurate timing and c) in good concentration measurements.

Step-down technique is the only one which can be used when infiltration is significant. However, a good initial mixing is required, resulting in a large perturbation of the flow patterns, hence of the distribution of the age of air.

Step-up and pulse technique both require that all the fresh air is pulsed through a small number of ducts but, since the tracer should be mixed within these ducts, the air flow patterns within the measured space is not perturbed.

Step-up and step down techniques are more sensitive to timing errors than the pulse technique, but the latter is more sensitive to errors in concentration. Finally, concentration variations are faster in the pulse technique, hence concentration measurements should be performed more frequently, to avoid integration errors.

These conclusions are not exactly those of references [6] and [7], which are also quoted in [3]. These authors concluded that since the step-up method requires a long time period to reach the steady state, during which the air flow pattern may change, it is not recommended for the measurement of the room mean age, and that both pulse and decay methods give reliable results when used adequately.

The present opinion of the authors of this paper is that both step-up and step-down techniques require a long time period, and that the final concentration in the step-up technique can be assessed at any time during the experiment. Therefore, there is no special reason to reject the step-up technique. The pulse technique is not much shorter. The adequate use of the step-down technique results in changing the ages of air, and therefore cannot be recommended where another method can be used.

Therefore, we recommend to use the step-up technique whenever there are few inlet ducts in which the tracer can be injected. The pulse technique can also be used in this case if the analyzer is fast and accurate enough. The step-down technique should be reserved for cases with significant uncontrolled infiltration.

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