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VENTILATION MEASUREMENTS IN LARGE PREMISES

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ABSTRACT

The local mean age of air is now generally accepted as a suitable indirect indicator of air quality. Measurements in large buildings, however constitute a great problem, because it is extremely difficult to achieve the uniform tracer concentration, necessary when using ordinary tracer gas techniques. An alternative technique - **the homogeneous emission technique** - is suggested. In this case, the space is sub-divided into smaller zones, in each of which the emission rate of tracer gas is proportional to the zone-volume. The local mean age of air in each zone can be evaluated from the steady state concentrations of tracer gas.

The present paper reports the findings from an experimental demonstration of this technique. A passive tracer gas method has been used to measure the local mean ages at approximately 50 locations in a 380 m^3 laboratory hall. It is demonstrated that the passive tracer gas technique is a useful tool for obtaining the local mean age of air and the air exchange efficiency.

The theoretical and practical limitations of the new technique are discussed in the paper, with special attention to large buldings, where other methods fail, due to the difficulty in achieving a uniform mixing of tracer gas.

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INTRODUCTION

Ventilation measurements are usually carried out, using different tracer gas techniques. The most popular types of technique are the decay technique, the constant concentration technique and the constant emission technique. Sometimes, the buildup and the pulse techniques are also used. Depending on the type of building to be investigated and the type of information requested, there are a number of modifications in the practical use of the different techniques. The underlying principle of all these methods is to tag the air in the building (or a zone within the building) to a uniform concentration of tracer gas and study either the time evolution of concentration (decay, buildup and pulse techniques) or the steady state concentration (constant concentration and constant emission techniques). In the constant concentration technique the tracer emission rate is adjusted to achieve a target steady state concentration. The most severe practical limitation of these methods is the difficulty in achieving a uniform concentration in the building or the zone to be investigated. This problem is especially pronounced in leaky buildings, large buildings, or in buildings with many rooms. (See for example Raatschen & Walker [1]).

In the present paper we suggest an alternative tracer gas technique for ventilation measurements, which we tentatively call "**the homogeneous emission technique**". The underlying theory for this technique has been described by Sandberg [2]. To the authors knowledge, the technique has not been used in practice before. The development of the passive tracer gas method has now made this technique practically feasible. The possibility of utilizing the passive tracer gas technique in this context was shortly mentioned by Stymne and Säteri [3].

THEORETICAL BACKGROUND OF THE HOMOGENEOUS EMISSION TRACER GAS TECHNIQUE

It can be shown [2] that the local steady state concentration of a tracer is directly proportional to the local mean age of air if the tracer emission rate per volume is constant in all of the ventilated system. This means that if the tracer is homogeneously emitted in space, the local mean age can be monitored at each point, just by recording the steady state concentration.

$$\bar{\tau}_p = c_p/(\dot{m}/V) \tag{1}$$

where c_p denotes the steady state concentration at a point p, $\dot{m}/V$ is the tracer emission strength per unit volume and $\bar{\tau}_p$ is the local mean age of air at the point p.

Correspondance between stationary and transient tracer gas techniques

The local mean age of air is usually determined by applying the well known decay method, starting with a uniform initial concentration. At the desired point in space the decay of the concentration is recorded. The area under the decay curve is calculated from the concentration readings. The local mean age of air is calculated as the quotient of the area and the initial concentration.

$$\textit{Local mean age of air} = \frac{\textit{Area under the decay curve}}{\textit{Initial concentration}} \tag{2}$$

The decay technique is a *transient* technique, where the time evolution of the concentration is recorded.

In the homogeneous emission technique the gas is emitted at a constant rate at many evenly distributed points. The attained *stationary* concentration is recorded. The basis of the homogeneous emission technique for determining the local mean age of air is the correspondence between the following quantities (the arrows indicate the analogy).

Table 1 Correspondence between the decay method and the homogeneous emission method

Method	Controlled quantity	Measured quantity	Derived quantity
Decay method	Initial concentration	Area under the curve	Local mean age
	↓ ↑	↓ ↑	
Homogeneous emission	Homogeneous emission rate	Stationary concentration	Local mean age

The analogy displayed in table 1 can be proven in several ways. One possibility is to start from the time dependent mass conservation equation (Sandberg in ref. [4]). In mathematical parlance this is an application of the so called Duhamel's rule. Another possibility is to use the properties of the flow matrix, which appears in the multi-chamber theory [2]. The pertinant relationships in the multi-chamber theory are also given later in this paper.

The above relationship shows that, if the tracer is emitted homogeneously over the whole space and at a constant rate, then the local mean age can be calculated from equation (1) by recording the steady state concentration. In words this equation can be expressed as:

$$\textit{Local mean age of air} = \frac{\textit{Steady state concentration}}{\textit{Emission rate per unit volume}} \quad (3)$$

In practice it is of course not possible to emit a tracer perfectly homogeneously, but with the use of inexpensive passive tracer gas sources, it is possible to spread the tracer in many, fairly evenly distributed points, thus approximating a homogeneous emission.

Applications in multicell systems

In some cases, it is even possible to subdivide the building into a number of uniformly mixed cells. For example, in office buildings, each individual office room can often be treated as a uniformly mixed cell. In these cases the technique can be realized by choosing the emission rate of tracer gas proportional to the room volume of each cell, paying less attention to a homogeneous emission within each room.

In the multicell theory [2] the concentration distribution is formulated in matrix form:

$$\mathbf{C} = \mathbf{Q}^{-1}\dot{\mathbf{m}} \quad (4)$$

where $\mathbf{C}$ is a column vector describing the steady state concentrations in the different cells, $\mathbf{Q}^{-1}$ is the quadratic inverse flow matrix and $\dot{\mathbf{m}}$ is the column vector describing the tracer gas emission strengths in the cells.

The $\mathbf{C}$- and $\dot{\mathbf{m}}$-vectors for four cells are:

$$\mathbf{C} = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix} ; \quad \dot{\mathbf{m}} = \begin{bmatrix} \dot{m}_1 \\ \dot{m}_2 \\ \dot{m}_3 \\ \dot{m}_4 \end{bmatrix} \quad (5)$$

The τ-matrix can be expressed in terms of the inverse flow matrix and the diagonal volume matrix:

$$\boldsymbol{\tau} = \mathbf{Q}^{-1}\mathbf{V} \quad (6)$$

The mean age of air in cell i, $\bar{\tau}_i$, is equal to the sum of the elements of row i (row sum) in the τ-matrix. The mean age vector $\bar{\boldsymbol{\tau}}$ describes the mean age of air in all the different cells that constitute the building. The mean age vector is therefore obtained by multiplying the τ-matrix by the unit vector **1**.

$$\bar{\tau} = \tau \mathbf{1} \quad ; \text{where } \mathbf{1} \text{ is the unit vector} \quad \mathbf{1} = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \tag{7}$$

By combining (6) and (7) one obtaines the $\bar{\tau}$-vector in terms of the flow matrix and the cell volumes:

$$\bar{\tau} = \mathbf{Q}^{-1}(\mathbf{V}\,\mathbf{1}) \tag{8}$$

now, if the emission strength in each cell is proportional to the cell volume then

$$\dot{\mathbf{m}} = k \cdot (\mathbf{V}\,\mathbf{1}); \text{ where } k \text{ is a constant} \tag{9}$$

Substituting ($\mathbf{V}\,\mathbf{1}$) from (9) into (8) and utilizing (4) gives:

$$\mathbf{C} = \frac{1}{k}\bar{\tau} \quad \text{or equivalently} \quad \bar{\tau} = k \cdot \mathbf{C} \tag{10}$$

This means that the mean age of air is proportional to the steady state concentration in each uniformly mixed cell if the emission rate of tracer gas in each cell is proportional to the cell volume.

In this paper, we present an experimental demonstration of the homogeneous emission technique in a laboratory hall.

Experimental

Description of the laboratory hall

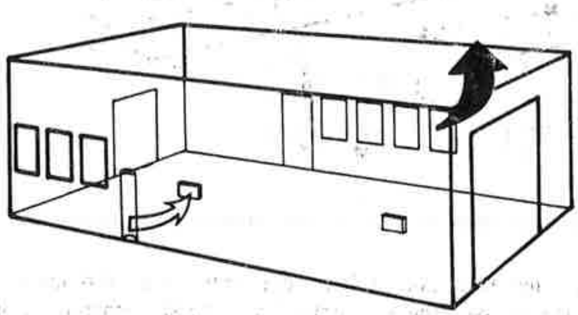


Fig. 1. Sketch of the laboratory hall. The filled arrow indicates the position of the air extract, while the unfilled arrow indicates the air supply at the low velocity supply unit. The two boxes on the floor on the centerline of the room denote the positions of air convectors used in the displacement mode of ventilation

The volume of the laboratory hall (fig. 1), chosen for the experiment is approximately 380 m^3, with the dimensions 13.2 m x 7 m x 4 m (LxBxH). One short-wall is an interior wall, while the other three are exterior walls. The exterior short-wall contains a large garage-port and is thus less insulated than the other exterior walls. The laboratory hall has its own balanced ventilation system. Two different modes of ventilation were investigated - firstly the normal mode of *mixed ventilation* and secondly *displacement ventilation*. The same air supply and extract devices were used in both cases. Ventilation air was supplied with a low velocity supply unit at floor level, while the extract air was withdrawn approximately 0.7 m below the ceiling close to the exterior short wall (see fig. 1). No return air is used.

Figure 2 shows how the total volume was divided into 48 subvolumes each with the dimensions 3.3 m x 1.75 m x 1.33 m (lxbxh). A passive tracer gas source was centrally positioned in each such subvolume, using a string suspended from the ceiling, each string holding three sources. Air was sampled using passive charcoal sampling tubes positioned in the corners of each sub-volume. Thus, 100 samplers were distributed in the laboratory hall - most of them attached to strings suspended from the ceiling and some attached close to the wall-surfaces. Integrating diffusive sampling was continued for a week in both experiments.

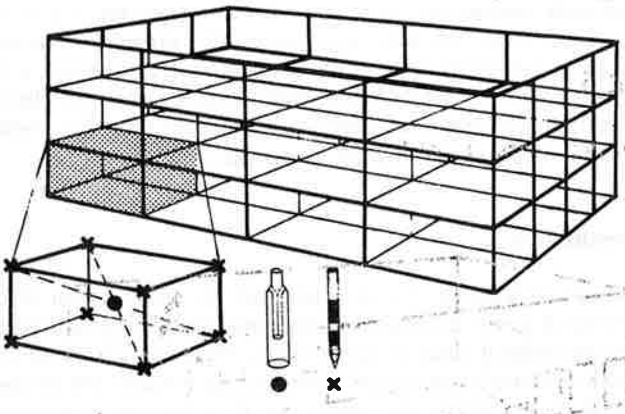


Fig. 2. Illustration of the subdivision of the room into 48 sub-volumes. As shown in the insert, each sub-volume is supplied with passive charcoal samplers (x) in its eight corners and a centrally positioned passive tracer gas source (•)

Tracer gas technique

The passive tracer gas technique used has been described by Stymne and Eliasson [5]. However, the passive tracer gas sources have been modified since then. The tracer gas sources used in this experiment consist of capillary tubes (0.2 mm inner diameter, 25 mm long) connected to small containers with liquid hexafluorobenzene (perfluorobenzene or PB for short). This new type of emitter (fig. 2) shows a high degree of reproducibility of emission rate between tubes. The emission rate at 21°C is equal to $26 \cdot 10^{-6} \pm 1 \cdot 10^{-6}$ g/h.

The emitters were suspended a few days before the samplers were positioned. The sampling tubes were de-capped shortly before positioning them. After a week the samplers were removed, capped and analysed for the amount of adsorbed tracer using gas chromatography.

The passive tracer gas technique has been demonstrated by Stymne *et. al.* [6] to be useful for measuring the time averaged tracer concentration distribution in great detail.

Mixing ventilation

In the mixing ventilation mode, the supply air was adjusted to a temperature of appr. 22°C. A slight over-temperature of the supply air compared to the room air temperature will create an upward buoyant jet. At a short distance from the supply device at the floor level this jet is turned into a vertical plume. The plume flow generates by entrainment an opposite downward flow in the ambient by entrainment, creating in this manner air recirculation in the whole room. Additional heat was supplied to the room via radiators along the exterior wall opposite the supply unit. The average outdoor temperature was slightly below zero during the period.

Displacement ventilation

In contrast to mixing ventilation, one tries to avoid the recirculation of contaminated air in a room ventilated by the displacement principle. This can be achieved only where the contaminants are emitted close to heat sources. Heat sources set up their own vertical air movements, which transport the contaminants towards the ceiling. While the air flow pattern is controlled by the supply air flow in mixing ventilation, the air flow pattern is now instead controlled by the plume flows from the heat sources. Recirculation of the contaminated air in the upper part of the room back to the occupied zone is hindered by creating a density (temperature) stratification. This temperature stratification must be maintained by feeding the room with cool ventilation air at the floor level. Thus, the prerequisites for displacement ventilation to be successful are that the majority of the contaminants eminate from heat sources and that there is an overall cooling demand in the room.

In this experiment the room was set up for displacement ventilation by positioning two 750 W electrically heated convectors in the room, one in each half of the laboratory hall. The supply air temperature was adjusted to 17°C.

The positioning of tracer gas sources and samplers was identical to that in the case of mixing ventilation (fig. 2). Additionally, the supply and extract air temperatures were recorded along with the room air temperatures at four levels in the middle of the room. To simulate contaminants released from the heat sources, a tracer gas of a second type - perfluoromethylbenzene (PMB) was emitted at the floor level close to the convectors.

Results

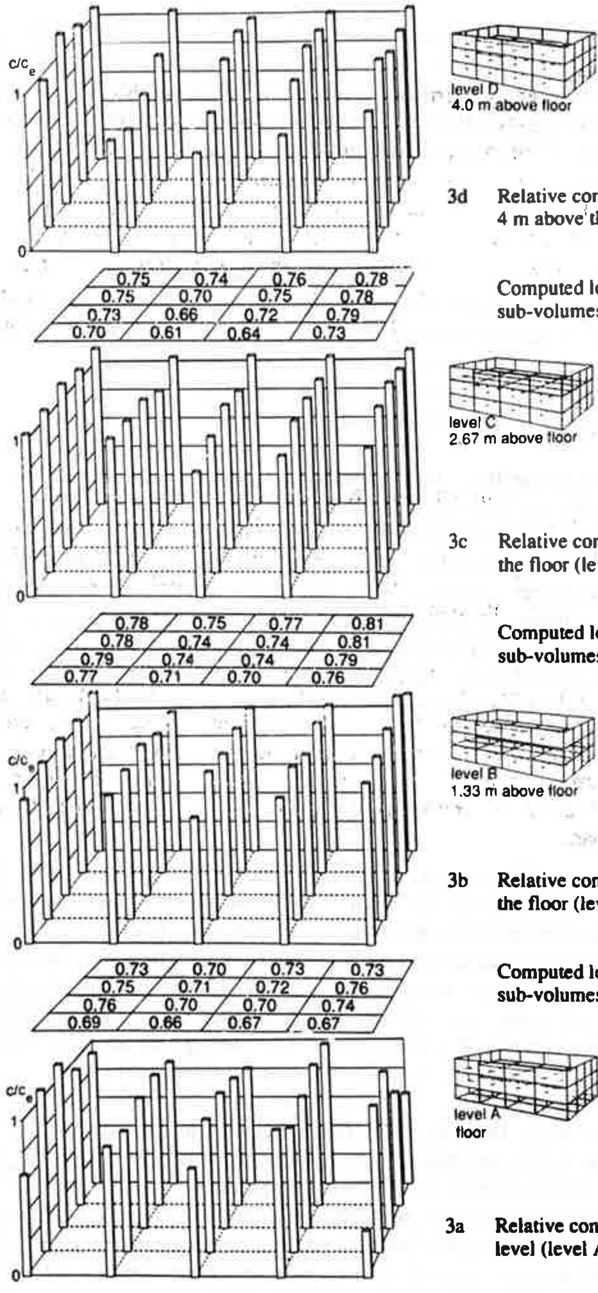
The results of the analysis are primarily obtained as time averages of concentration at the sampling points. It is shown that the concentrations differ little from point to point in the case of mixing ventilation. For the displacement mode of ventilation, however, there are substantial differences between different locations. The result is displayed in graphical form and discussed below.

To be strictly connected to the local mean age of air, the emission should have been homogeneous. In this case, we have used a rather large distance between sources. This means that there are spatial variations of the concentration, which do not necessarily depend on differences in the local mean ages of air, but merely are due to the different distances from the tracer sources. With localized, instead of diffuse sources, there will of course be a larger concentration close to a source, than at some distance from it. In order to minimize the local effects from sources, the sampling was performed at the corners of the subvolumes, mentioned before (fig. 2). Furthermore, we have chosen to present the local mean ages from the average concentrations of all eight corners of a subvolume.

Mixing ventilation

The results for mixing ventilation are graphically displayed in fig. 3a-3d for the measuring points at four levels above the floor. The vertical axis shows the concentrations relative to the concentration in the extract. Consequentially, it also shows the ratio between the local mean age of air and the nominal time constant (τ_n) The computed mean ages of air in the subvolumes between the displayed levels are inserted between the bar charts. The local mean ages of air are computed from the average tracer concentration in all eight corners of a subvolume. The average of all local mean ages $\langle\bar{\tau}\rangle$ was found to be 0.73 h, while the nominal time constant τ_n was 0.77 h.

As expected the results show that the local mean ages of air are quite close to the nominal time constant in every subvolume. The air exchange efficiency $\varepsilon_a = \tau_n/(2\langle\bar{\tau}\rangle)$ was found to be 53%. This is typical for a mixing ventilation system. We have shown that there are no short-circuit regions or stagnant zones in the room. As one also could have expected, there is a slightly lower local mean age in the neighbourhood of the supply terminal. Especially striking is the fact the lowest mean age of air is found at the ceiling level above the supply terminal. This observation can easily be explained by the upward movement of the supply air due to its over-temperature.



3d Relative concentrations the roof level 4 m above the floor (level D)

Computed local mean ages of air in the sub-volumes between level C and D

3c Relative concentrations 2.67 m above the floor (level C)

Computed local mean ages of air in the sub-volumes between level B and C

3b Relative concentrations 1.33 m above the floor (level B)

Computed local mean ages of air in the sub-volumes between level A and B

3a Relative concentrations at the floor level (level A)

Fig. 3. **Mixing ventilation.** Bar graphs showing the time averaged (1 week) concentrations in all sampler positions, relative to the concentration found in the extract. The local mean ages of air (in hours) in the sub-volumes between the levels are written between the diagrams

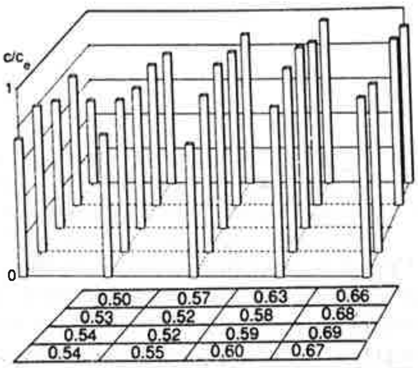
Displacement ventilation

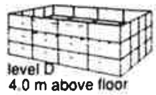
There is a completely different pattern of local mean ages with this mode of ventilation. The diagrams in fig. 4a-4d show that there is a pronounced lower age of air in the lower part of the room compared to the upper part. This difference is much more pronounced in that half of the room in which the supply unit is situated. In the part of the room where the large badly insulated door is situated the result shows a mixed region which indicates recirculation of air beween the upper and the lower part of the room. This mixing is created by the downward convection currents at the wall and the upward convection at the closest heat source. The computed air exchange efficiency was 69%. This should be compared to the theoretical limit of 100% for piston flow and 50% for ideal mixing.

Dispersion of contaminants

The dispersion pattern of contaminants emitted close to heat sources in the displacement mode of ventilation has also been investigated by positioning a second type of tracer source at the floor level close to the convectors. The result is displayed in fig. 5a-5d. The bars show the concentration of this contaminant at every measuring point, relative to the concentration found in the extract.

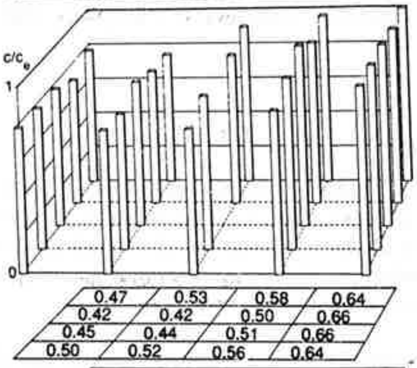
The result shows that there are substantially lower concentrations at the floor level than further up in the room. Especially low concentrations are found at the locations of the air convectors, where ventilation air is fed to the convectors. At the 1.3 m level, however, there are high concentrations above the convectors, due to the transportation of contaminants in the plume flows. Similarily as seen in fig. 4 it is obvious that there is a more pronounced displacement zone in the left part of the room, compared to the right part.

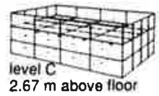




4d Relative concentrations at the roof level 4 m above the floor (level D)

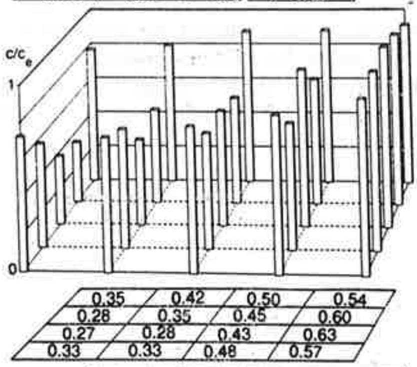
Computed local mean ages of air in the sub-volumes between level C and D

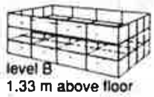




4c Relative concentrations 2.67 m above the floor (level C)

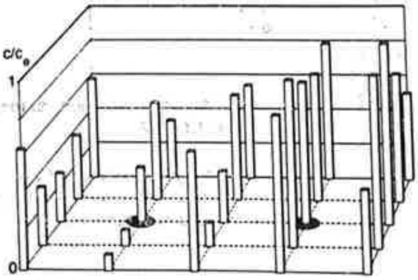
Computed local mean ages of air in the sub-volumes between level B and C

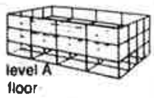




4b Relative concentrations 1.33 m above the floor (level B)

Computed local mean ages of air in the sub-volumes between level A and B

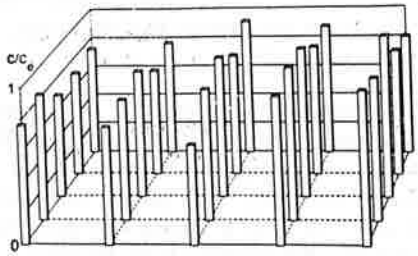


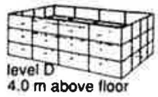


4a Relative concentrations at the floor level (level A)

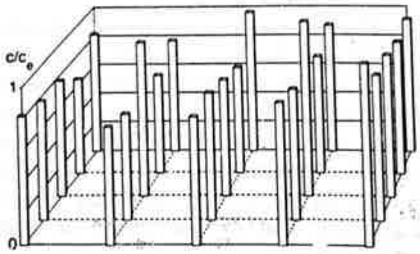
The shadowed ellipses show the positions of the two 750 W air convectors at the floor level

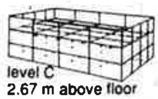
Fig. 4. **Displacement ventilation.** Bar graphs showing the time averaged (1 week) concentrations in all sampler positions, relative to the concentration found in the extract. The local mean ages of air (in hours) in the sub-volumes between the levels are written between the diagrams



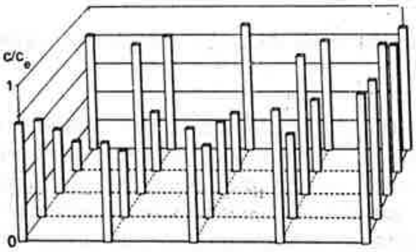


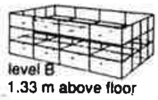
5d **Relative concentrations at the roof level 4 m above the floor (level D)**



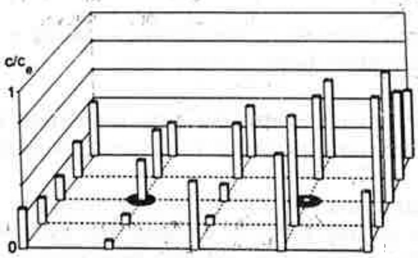


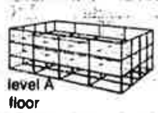
5c **Relative concentrations 2.67 m above the floor (level C)**





5b **Relative concentrations 1.33 m above the floor (level B).**





5a **Relative concentrations at the floor level (level A)**

The shadowed ellipses show the positions of the two 750 W air convectors at the floor level

Fig. 5. **Displacement ventilation**. Tracer gas emitted 7 cm above the floor level, close to the air convectors. The bar graphs show the time averaged (1 week) concentrations in all sampler positions, relative to the concentration found in the extract

Discussion

The aim of this paper was to show how the homogeneous tracer emission technique can be utilized to measure local mean ages of air. The paper also serves to demonstrate how this technique can be realized using passive tracer gas sources.

However, the demonstration should not be regarded as an example of a recommended mode of examination of ventilation in large premises. It would in most cases not be possible to distribute the tracer gas sources so evenly, without disturbing the activity going on for example in a factory hall. However, with proper experimental planning, we think it is possible, in most cases, to find a satisfactory distribution pattern of tracer gas sources, without interfering with the activities in the building.

A natural question is how far from each other, the sources might be positioned and still yield a satisfactory approximation of a homogeneous emission. It is possible to get a rough estimate of the permissible distance from the air velocity and the mean age of air. In order to level out the influence of local surces, the air present at a measuring point should have had the opportunity to spend its time close to several sources. For example; if the local mean age of air is 30 minutes and the average air velocity is 0.05 m/s, then the "air parcels" have on the average travelled 90 meters before striking the sampler. It is therefore probable that several meters of distance between emission sources can be tolerated in this case.

It should be noted that sampling should not be done close to a source, in order to avoid local high concentration.

Probably, the most attractive application of the homogeneous emission technique is in investigation of large buildings with many rooms. As mentioned before, each room can often be considered an uniformly mixed zone - a fact that simplifies the practical application. With the use of passive tracer gas sources - each room is supplied with the required number of sources to yield an emission strength proportional to the volume of the room.

Air sampling is performed after equilibration, either by active pumping during a few minutes or by performing passive diffusive sampling during several days.

In contrast to the constant concentration technique, where the total ventilation flow rate is obtained, the homogeneous emission technique yields the local mean age of air.

The mean age of air is an air quality indicator and can not be directly translated into total ventilation flow rate. However, if the mixing is fairly uniform, the average of the local mean ages is a good measure of the inverse of the **specific flow rate** (the air change rate).

Acknowledgement

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