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The principles of a homogeneous tracer pulse technique for measurement of ventilation and air distribution in buildings.

by

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THE PRINCIPLES OF A HOMOGENEOUS TRACER PULSE TECHNIQUE FOR MEASUREMENT OF VENTILATION AND AIR DISTRIBUTION IN BUILDINGS.

SYNOPSIS

The principles of a new tracer gas technique is described in the paper. The new technique involves pulse injection of tracer gas and has the same advantages as the previously known homogeneous emission technique. It can for example advantageously be used in large buildings and buildings with many rooms and yields information on the distribution of ventilation air within the building. However, contrary to the homogeneous emission technique, yielding the average ventilation performance during an extended time, the new technique allows measurement during short term periods.

The new technique is based on homogeneous pulse injection, which means that pulses of tracer gas are injected in each zone in a zone-divided building, with amounts which are proportional to the zone volumes and integrating sampling of tracer gas concentration. Theoretical and practical aspects of the technique are described.

1. INTRODUCTION

1.1 Existing tracer gas techniques

There are essential four different main principles for tracer gas injection for measuring ventilation characteristics in buildings.

- Step change techniques
- Pulse techniques
- Constant emission techniques
- Constant concentration techniques

These four principles all have their advantages and disadvantages for field measurement of ventilation. They will shortly be discussed below, especially with respect to their usefulness for measuring the local mean age of air in real buildings. Note that here exist several variants of the techniques, which however are outside the scope of this paper to discuss. A comprehensive treatise of tracer gas techniques can be found in a book by Etheridge and Sandberg (1).

1.1.1 Step change techniques

Step change techniques involve the step-down technique (usually called the decay technique) and step-up technique.

1.1.1.1 Step-down technique

When using the *step-down technique* for measuring local mean ages of air, tracer gas is mixed into the whole ventilated system* to a uniform initial concentration (C_0), after which no more tracer gas is supplied and the decay of the local concentration is integrated until no tracer gas is left in the system.

* note. The concept "ventilated system" involves all building spaces, that are somehow connected in a ventilation sense, i. e. all spaces to which air can be transferred from other parts of the system. The only air which can be supplied over the boundary of a ventilated system is ambient air.

The local mean age of air is obtained from the concentration integral divided with the initial concentration.

$$\bar{\tau}_p = \frac{\int_0^\infty C dt}{C_0} \qquad (1)$$

1.1.1.2 Step-up technique

In the step-up technique tracer gas is injected into the supply air at a constant concentration at time t=0 and the local concentration history at a point p is recorded as a function of time. To obtain the local mean age of air, the concentration difference between the equilibrium concentration C_∞ and the concentration at time t is integrated from 0 until equilibrium is attained.

$$\bar{\tau}_p = \frac{\int_0^\infty (C_\infty - C) dt}{C_\infty} \qquad (2)$$

1.1.2 Pulse techniques

In the pulse technique a pulse of tracer gas is injected into the supply air and the local time response of concentration recorded at point p. The local mean age of air is computed from the first moment of the concentration divided with the zeroth moment.

$$\bar{\tau}_p = \frac{\int_0^\infty t \cdot C dt}{\int_0^\infty C dt} \qquad (3)$$

1.1.3 Constant emission techniques

These technique rely on a continuous release of tracer gas at a constant rate in the ventilated system. If the emission rate is so distributed in the system that, in each part (zone) of the system, it is proportional to the zone volume, the emission is said to be homogeneous. If the tracer emission is made homogeneously, the local mean age of air can be calculated from the quotient between the local steady state concentration C_p and the emission rate per volume unit $(\dot{m} / V)$ (e.g. 1, 2, 3).

$$\bar{\tau}_p = \frac{C_p}{\left(\frac{\dot{m}}{V}\right)} \qquad (4)$$

1.1.4 Constant concentration technique

In this technique the injection rate of tracer gas in the different zones of the system is adjusted so that the resulting steady state concentrations are equal in every zone. This technique requires a real time analysis of tracer gas and an injection control device with feedback from the analysis equipment.

The constant concentration technique has not been considered for evaluating local mean ages of air. It is used in order to determine the direct inflow (q_p) of ventilation air into the zones.

$$q_p = \frac{\dot{m}_p}{C} \tag{5}$$

where $\dot{m}_p$ is the injection rate in zone p and C is the target concentration.

1.2 Field measurement requirements

In order to be useful for routine field measurement of ventilation, the used technique should be simple, quick and inexpensive. Expensive equipment and expertise should not be tied up during a long measurement. The necessary initial conditions should be possible to establish.

Tracer gas methods are the only ones, which can be used to measure how the air is actually distributed in the building space. The air distribution patterns are usually described using the concept of "local mean age of air" or its inverted value "local ACH". Other possible alternatives are "local purging flow rate" and "ventilation effectiveness".

Methods which allow air sampling in bags or in adsorption tubes and subsequent analysis in a laboratory are generally preferred over on-site real time analysis. Diffusive sampling in adsorption tubes is commonly used with the passive tracer gas technique (e. g. homogeneous emission technique).

The decay technique with bag sampling at intervals is sometimes used. The decay technique is however critically depending on the necessary uniform initial concentration of tracer gas, which can be very difficult to achieve in large buildings and buildings with many rooms.

Pulse techniques are seldom utilised for mapping the distribution of local mean ages of air, because it requires the first moment of tracer concentration to be calculated in several positions. This requires on site monitoring of concentration versus time, during the whole pulse response.

In this paper a new pulse technique (the homogeneous pulse technique) is presented, which is useful for routine field measurement of ventilation. It relies on a homogeneous pulse injection pattern and allows integrating sampling, for example with passive diffusive samplers.

2. THEORETICAL CONSIDERATIONS OF THE HOMOGENEOUS PULSE TECHNIQUE

2.1 The analogy between steady state concentration and integrated pulse response.

The principle of the homogeneous pulse technique can most easily be explained through an analogy with the constant emission technique in multi-zone systems.

The reason is the well-known fact that the steady state concentration C_∞ of a tracer with constant emission rate $\dot{m}$ has a direct relationship to the integral from zero to infinity of the concentration response (dosage) from a short pulse with a released amount of m, if the air flow patterns are stable within the ventilated system (ref. 4, 5).

Thus, if the time response at a location **i** from a short pulse with a released amount of $\mathbf{m_j}$ injected at a location **j**, is represented by

$$C_{ij}(t) = m_j \cdot f_{ij}(t) \tag{1}$$

where f_{ij} is a characteristic response function, a continuous release of tracer at location **j** would yield a steady state concentration at location **i** of

$$C_{ij}^{\infty} = \dot{m}_j \cdot \int_0^{\infty} f_{ij}(t)dt \qquad (2)$$

We can therefore conclude that the integral of a short pulse response

$$I_{ij} = \int_0^{\infty} C_{ij}(t)dt = \frac{m_j}{\dot{m}_j} C_{ij}^{\infty} \qquad (3)$$

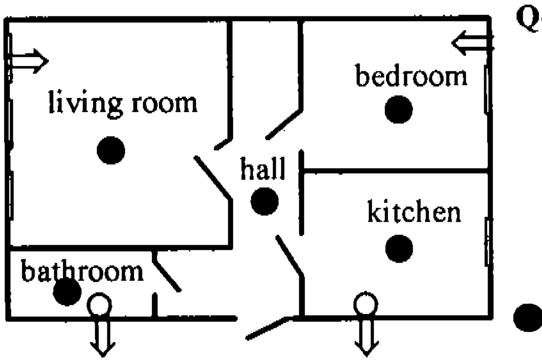
where C(t) is the concentration response from the pulse with amount m and C_{∞} is the corresponding steady state concentration of a tracer with constant emission rate of $\dot{m}$. In this discussion we will use this analogy throughout.

2.2 Determination of the flow matrix in multi-zone systems.

The flow matrix **Q** in a system consisting of **n** zones, each of which is fully mixed can be determined by injection of tracer gas with a constant rate in one zone at a time (or more general in **n** different linearly independent patterns) and measure the equilibrium concentrations in each zone for each pattern. The equilibrium concentrations are given by the matrix equation system:

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

where $\mathbf{C}^{\infty}$ is the quadratic matrix of steady state concentrations C_{ij}^{∞} in zone **i** resulting from the **j**th release pattern and $\dot{\mathbf{m}}$ is the quadratic release pattern matrix. This equation system has been used in ref. (6) to determine the flow matrix in a 5 room indoor experimental house displayed in figure 1, where the tracer gas injection was made in one room after the other. Mixing fans were used in each room.



Q-matrix obtained from constant emission [m^3/h]

Livingroom	287	-193	-70	3	4
Hall	-297	479	-8	-91	-45
Bedroom	-15	-70	118	-5	-1
Kitchen	5	-108	-22	138	-14
Bathroom	6	-74	-15	1	80

Figure 1. *The indoor test house and the* **Q**-*matrix obtained from constant emission tracer gas experiments.*

Using the analogy between steady state concentrations and integrated pulse responses, a similar equation corresponding to eq. (4) can be set up for pulse injection:

$$\mathbf{I} = \mathbf{Q}^{-1}\mathbf{m} \qquad (5)$$

where **I** is the quadratic matrix of integrated pulse responses I_{ij} in zone **i** resulting from the **j**th pulse release pattern and **m** is the quadratic pulse release pattern matrix.

These matrices can easily be transformed to the τ-matrix through multiplication from the right by $\mathbf{m}^{-1}\mathbf{V}$, where **V** is the diagonal zone volume matrix.

$$\mathbf{C}^{\infty}\dot{\mathbf{m}}^{-1}\mathbf{V} = \mathbf{Q}^{-1}\mathbf{V} = \tau \qquad (6)$$

$$\mathbf{I}\mathbf{m}^{-1}\mathbf{V} = \mathbf{Q}^{-1}\mathbf{V} = \tau \qquad (7)$$

This means that the τ-matrix can be determined either from the steady state concentrations and the emission rates per unit volume, or from the integrated pulse responses and the injected amounts per volume unit.

In order to illustrate this, the expected pulse responses with the flow matrix obtained in ref. (6) and displayed in figure 1 is computed from the numerical solution of the differential equation system:

$$\mathbf{V}\frac{d\mathbf{C}}{dt} + \mathbf{QC} = \mathbf{0} \text{ with } \mathbf{C}(0) = \mathbf{1} \qquad (8)$$

which describes the concentration versus time in the different zones when a unit pulse amount per volume unit is injected in one zone at a time and the mixing within each zone is instantaneous. The result is displayed in figure 2.

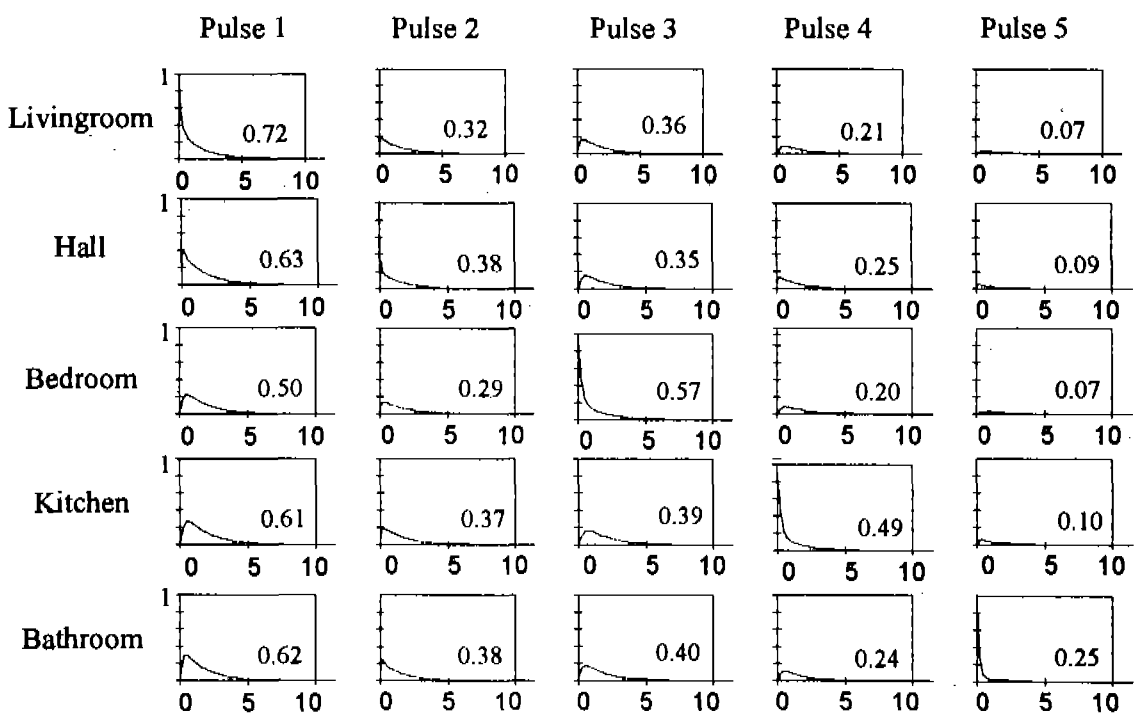


Figure 2. *Diagrams displaying the simulated concentration responses in the different rooms as a function of time (hours) when pulses of tracer gas are injected in the room marked with an asterisk with a unit amount per room volume. The values enclosed in the diagrams represent the computed pulse response integrals and hence also the entries in the τ-matrix.*

2.3 Determination of the local mean age of air in multi-zone systems.

The τ-matrix obtained from the numerical integration of the pulse responses displayed in figure 2 is shown below.

$$\tau = \begin{pmatrix} 0.72 & 0.32 & 0.36 & 0.21 & 0.07 \\ 0.63 & 0.38 & 0.35 & 0.25 & 0.09 \\ 0.50 & 0.29 & 0.57 & 0.20 & 0.07 \\ 0.61 & 0.37 & 0.39 & 0.49 & 0.10 \\ 0.62 & 0.38 & 0.40 & 0.24 & 0.25 \end{pmatrix} \tag{9}$$

The local mean ages of air in a multi-zone system can be obtained from the row sums of the τ-matrix:

$$\bar{\tau} = \tau \mathbf{1} \tag{10}$$

where **1** denotes the unit vector

$$\mathbf{1} = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}; \qquad \bar{\tau} = \begin{pmatrix} 1.68 \\ 1.70 \\ 1.62 \\ 1.97 \\ 1.89 \end{pmatrix} \tag{11}$$

This result is in close agreement with that obtained in the original paper (6).

2.4 Determination of the local mean age of air without knowledge of flow matrix.

In order to determine the flow matrix and the full τ-matrix as many independent experiments as there are zones must be performed. However, to determine the local mean age $\bar{\tau}$ -vector, only a single experiment is necessary. From eq. 7 and eq. 10 the $\bar{\tau}$ -vector can be obtained directly:

$$\bar{\tau} = \mathbf{I}\mathbf{m}^{-1}\mathbf{V}\mathbf{1} \tag{12}$$

If pulses are injected in the different zones with amounts which are proportional to the zone-volumes $\mathbf{m} = k\mathbf{V}$ then eq. 12 reduces to:

$$\bar{\tau} = \frac{1}{k}\mathbf{I}\mathbf{1} \tag{13}$$

which means that the local mean age in a zone is equal to the sum of all individual integrated pulse responses in that zone divided with the injected amount per volume unit.

$$\bar{\tau}_i = \frac{1}{k}\sum_j \int_0^\infty C_{ij}(t)dt \tag{14}$$

Because there is a finite number of pulses and the individual pulse responses are independent of each other, the tracer concentration is the sum of all pulse responses

$$\bar{\tau}_i = \frac{1}{k}\sum_j \int_0^\infty C_{ij}(t)dt = \frac{1}{k}\int_0^\infty \sum_j C_{ij}(t)dt = \frac{1}{k}\int_0^\infty C_i(t)dt \tag{15}$$

This holds true even if the pulses in the different zones are not injected simultaneously, but at different times as long as the flow patterns in the system is not changing. Eq. (15) tells that the local mean ages of air in a zone-divided system can be determined with integrating sampling, if pulses of tracer gas are injected into the different zones with amounts which are proportional to the zone volumes and the sampling is made from the moment of the first injection and continued until all tracer gas is ventilated out of the system.

In figure 3 the concentration versus time in the different zones are calculated from the individual pulse responses displayed in figure 2 under the assumption of successive injections into the different zone with 0.1 hours intervals. Instantaneous mixing within a zone is assumed. The calculated integrals closely agree with the local mean ages of air.

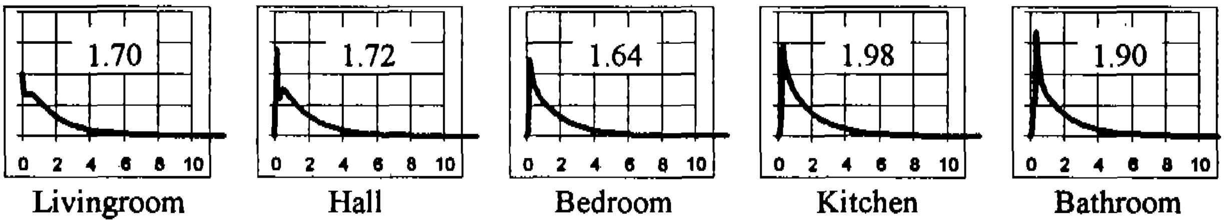


Figure 3. *Tracer concentration as a function of time in the different rooms, when pulses are injected in one zone after the other with 5 minutes interval, with amounts proportional to the zone volumes. The values enclosed in the diagrams represent the computed pulse response integrals and hence also the local mean ages of air.*

3. PRACTICAL ASPECTS

3.1 Measurement of the integrated pulse response.

At every location where the local mean age of air is to be measured, the local concentration must be integrated from the moment that tracer gas injection is started in the system, until all injections have been performed and all tracer gas has been removed by the ventilation air. Such integration can be performed either using real time analysing instrument, recording the time history and making the integration afterwards, or using integrating sampling and making the analysis afterwards in the laboratory. In most cases, integrating sampling is more convenient and less expensive. For determination of the mean ages of air, the details of the time history is namely not interesting, only the integrated value is relevant.

Integrating sampling can be performed actively or passively. For active sampling a pump is used, which draws air either continuously or discontinuously through an adsorbent bed which adsorbs the tracer gas or alternatively collects the sampled air in a sample bag for later analysis. Passive sampling relies on diffusion of tracer gas towards an adsorbent, contained in a sampling equipment (diffusion tube or sampler badge) with a well defined geometry , in which it is adsorbed and retained for later analysis. Ideally, for specimen that are completely adsorbed the rate of collection in a well designed diffusion sampling equipment is proportional to the air concentration, according to Fick's first law of diffusion. Therefore, the sampled amount is proportional to the desired integrated concentration history.

3.2 Injection of tracer gas

In the homogeneous pulse technique, pulses of tracer gas must be injected in all zones of the building, which forms the ventilated system. The amount of tracer gas injected in a zone is to be proportional to the zone volume. The injection equipment must therefore be constructed so that the injected amount of tracer can be easily controlled.

There are several possible principles for controlling the injection, which are however outside the scope of this paper to discuss.

The division of the building space into zones is a crucial matter. The smaller the zones, the better will the injection approach the ideal homogeneous case. However, the air in a room of ordinary size is usually well mixed and such a room may be treated as a single zone, unless special effects like air short-circuiting is suspected. In all cases, regardless of the zone volume, the injected tracer should be mixed into the air in the zone to yield a uniform concentration immediately after injection. The smaller the zones, the easier is the mixing, so it may be worthwhile to make several injections at evenly distributed different positions even in rooms of normal size.

4. CONCLUSIONS

A new tracer gas technique - the homogeneous pulse technique - for measuring the local mean ages of air in buildings is proposed and discussed from theoretical and practical points of view. In this technique, pulses are homogeneously distributed within the building space. It is not necessary to inject all pulses simultaneously. Especially in large buildings and buildings with many rooms, it is valuable that the pulse distribution can be made in any pace (as long as the air flow patterns in the building do not change). The local mean ages of air can be simply evaluated from the amount of tracer collected in integrating samplers, which may be of the passive diffusive types, commonly used in passive tracer gas technique. The samplers must be active from the moment that tracer gas injection begins until essentially all tracer gas is ventilated out from the building space.

5. REFERENCES

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