TRACER GAS TECHNIQUES FOR MEASUREMENT OF VENTILATION IN MULTI-ZONE BUILDINGS - A REVIEW

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ABSTRACT
There is a need for reliable and easy to use measurement techniques that can provide information about the ventilation and air distribution within buildings, in order to verify performance or trace possible reasons for insufficient air quality. Ventilation air is often unevenly distributed in a building. Recent development of tracer gas methods offer robust techniques, that can cope with such cases in all types of buildings, whether mechanically or naturally ventilated. The paper presents a review of available single tracer gas techniques with special emphasis on new developments for their use in incompletely mixed multi-zone objects. The described methods involve the “decay”, ”step-up”, ”homogeneous emission”, ”inlet pulse” and ”homogeneous pulse” techniques.

INDEX TERMS
Ventilation, Tracer gas techniques, Review

INTRODUCTION
Multi-zone tracer gas techniques
Tracer gas techniques for ventilation measurements in multi-zone buildings are based on the fundamental mass balance equation for the tracer in the investigated object:

\[ V \frac{dC}{dt} + QC = \dot{m} \]  \hspace{1cm} (1)

Where \( V \) is the diagonal zone volume matrix, describing the subdivision of the object into zones (assuming complete mixing in each zone), \( C \) is the column vector of concentrations and \( Q \) is the transport matrix (flow matrix) describing the air flow rates between the different zones. \( \dot{m} \) is the column vector of tracer gas supply rates into the different zones. The flow matrix contains \( n^2 \) unknown air flow rates, \( n \) being the number of zones. As each injection pattern of tracer gives rise to \( n \) independent equations, the concentration response to \( n \) linearly independent injection patterns or initial conditions has to be investigated in order to solve for the unknown parameters. There are several solutions to this problem (Afonso et al. 1986, Axley and Persily 1988, Etheridge and Sandberg 1996):

- repeating the experiment \( n \) times with different injection patterns
- injecting pulses of tracer (in at least \( n \) linearly independent patterns) and measuring the transient responses during a single experiment
- using \( n \) simultaneous tracer gas types during a single experiment

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To determine the complete flow matrix in a system of many zones is time consuming and requires advanced equipment. Additionally, the different elements in the matrix are often determined with large uncertainties, which limits the usefulness of the result.

**Single tracer gas techniques for measuring local mean ages of air**

In order to characterise the ventilation in a multi-zone building it is often sufficient to determine the "local mean ages of air". This quantity does not provide information on where the air comes from (as the flow matrix does), but tells how long the air in the zones on average has spent within the building, accumulating contaminants. Mapping the local mean ages of air in a building often yields sufficient information on the distribution of ventilation air within the building. As there are only n local mean ages of air in a system of n fully mixed zones, it is possible to determine all mean ages of air in one single experiment.

There are three classical techniques for determining the local mean ages of air in a multi-zone system utilising a single tracer gas (Roulet and Cretton 1992).

- Decay technique
- Step-up technique
- Inlet pulse technique

Recently two additional techniques have been described and validated

- Homogeneous constant emission technique (Stymne and Boman 1994, NORDTEST 1997)
- Homogeneous pulse technique (Stymne and Boman 1998; Stymne et al, 2000 )

The last two techniques allow particularly easy tracer gas distribution and sampling techniques (integrating sampling) and are therefore especially suitable for field measurement.

**Table 1. Multi-zone tracer gas techniques for estimation of local mean ages of air**

<table>
<thead>
<tr>
<th>Technique</th>
<th>initial state</th>
<th>final state</th>
<th>injection place</th>
<th>injection pattern</th>
<th>measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay</td>
<td>uniform concentration</td>
<td>tracer free</td>
<td>no emission</td>
<td>total time integration</td>
<td></td>
</tr>
<tr>
<td>Step-up</td>
<td>tracer free</td>
<td>uniform concentration</td>
<td>air inlets</td>
<td>continuous, proportional to air inflow*</td>
<td>total time integration</td>
</tr>
<tr>
<td>Homogeneous constant emission</td>
<td>steady state</td>
<td>zones</td>
<td>continuous, proportional to volumes</td>
<td>steady state concentration</td>
<td></td>
</tr>
<tr>
<td>Inlet pulse, established</td>
<td>tracer free</td>
<td>tracer free</td>
<td>air inlets</td>
<td>pulse, proportional to air inflow*</td>
<td>first moment integration</td>
</tr>
<tr>
<td>Pulse, homogeneous</td>
<td>tracer free</td>
<td>tracer free</td>
<td>zones</td>
<td>pulse, proportional to volumes</td>
<td>total time integration</td>
</tr>
</tbody>
</table>

* Alternatives are, injection in a common air supply duct, or, if recirculation ratios are equal (or absent) in all inlets - injection in the air inlets with equal concentrations in all inlets.

**DESCRIPTION OF METHODS**

The theoretical foundation for all these different single tracer gas techniques can be deduced from the basic mass balance equation (eq. 1) using different initial conditions and tracer...
injection patterns. The mathematical derivations are given in the appendix to this paper. It should be noted that in the derivations it is assumed that the pertinent initial conditions and tracer injection conditions must be fulfilled throughout each zone. In practice it may be difficult to achieve those conditions for some techniques, as mentioned below.

**Practical Aspects**

**Decay technique**
The initial condition of uniform tracer concentration throughout all zones may be difficult to achieve in practice if there are many zones, even using initial artificial mixing.

**Step-up technique**
The injection condition is that the tracer concentration of all supplied air (incoming outside air) shall be step changed from zero to a common constant concentration. This means that the tracer should either be injected at a constant rate in a common air supply duct or that injections must be made in several supply ducts in proportion to their flow of outside air. If there is no return air or if the return air ratio is equal in all supplies, the (initial) tracer concentration in all supply devices is the same. If no certain information about the distribution of return air is available, then it is difficult to find a correct tracer distribution pattern, unless a common air supply duct is available.

Another problem when using the step-up technique is that only mechanically supplied air is marked with tracer. Infiltration air dilutes the tracer, lowers the concentration and may yield an uneven final concentration distribution; this makes the evaluation ambiguous and uncertain. The advantage of using the step-up technique is that the tracer does not have to be mixed into the room air and that the tracer can be supplied into a single or only a few injection points. This also makes it possible to study relatively large mechanically ventilated buildings.

**Homogeneous constant emission technique**
This technique relies on a homogeneous emission of tracer gas, which means that the emission rates must be proportional to the (well mixed) zone volumes. The injection pattern is therefore simple to determine. Bad mixing within the zones may however be a problem if too large a space is equipped with a single injection point. Only the steady state concentration is of concern, therefore, the initial state is not important. The tracer gas injection can advantageously be performed using passive tracer gas sources, while the steady state concentrations may be determined using either pumped or passive sorption sampling tubes.

**Inlet pulse technique**
In the inlet pulse technique, a short pulse is injected into the common air supply duct. The amount injected will then be distributed to the different zones with amounts, which are proportional to the supply rate of outside air to the zones. Thus the injection pattern resembles that of the step-up technique.

If injection is made in individual air supply devices instead of in a common supply, then, similar to the case of the step-up technique, there will be an uncertainty on how to decide the amount to be injected in each supply device. It is in fact a necessary condition in the pulse and step-up techniques that the distribution patterns of tracer gas equal that of the outside air. Using this pulse technique for measuring local mean ages of air requires that the "first moment" of the concentration (time integral of time×concentration) be computed. This means that pulses must be given simultaneously in all supply devices in all different zones, in order to have a common "time base" for the integration. This is in contrast to the homogeneous
pulse technique, where a "simple" time integration is used, which allows the pulses to be
given at arbitrary times, as long as the flow pattern in the building is stable.

There are also other shortcomings of the pulse technique. One is that only mechanically
supplied air is marked with tracer, which introduces an error if infiltration is present. Another
is that it may be difficult to inject a sufficient amount of tracer in a very short time to allow
the whole time history to be recorded with a satisfactory signal to noise ratio. Errors in the
"tail" are amplified when multiplying concentration by time in order to compute the first
moment. However, Jung and Zeller (1996) and Bonthoux et al. (1999) have shown that
injections of long duration are permitted if computed values of the local mean ages of air are
corrected, depending on the shape and duration of the injection.

Homogeneous pulse technique
The condition of the injection is that the pulses shall be injected with equal amounts per
volume units within the whole building, which can be difficult to achieve. It may be effected
through spot injection of a short pulse into a zone and quickly mixing the air within the zone,
through mixing during the duration of the injection or by distributing the tracer amount evenly
in the zone.

It has been shown (Stymne and Boman, 1998) that all pulses do not need to be given
simultaneously. As long as the flow patterns within the building are unchanged, the pulses
may be injected at any convenient pace. The integration, however, must be performed from
the moment of first injection until all tracer gas has disappeared from the system. Integrating
sampling may advantageously be performed using either pumped or passive sorption
sampling tubes.

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APPENDIX

Basic relationships for multi-zone tracer techniques

The mass balance equation for the instantaneous zone concentration (C) of tracer gas in a system of fully mixed zones (with volumes V) in matrix form can be written (e.g. Sandberg and Sjöberg 1983, Sandberg 1984)

\[ \mathbf{V} \frac{d\mathbf{C}}{dt} + \mathbf{Q} \mathbf{C} = \mathbf{m} \]  

(A1)

where \( \mathbf{C} \) is the tracer concentration vector, \( \mathbf{Q} \) is the air transport matrix (flow matrix), \( \mathbf{V} \) is the diagonal zone volume matrix, \( \mathbf{m} \) is the tracer injection rate vector and \( t \) is the time.

The row sums of \( \mathbf{Q} \) yield the air flow supply vector \( \mathbf{q}_s \) (the direct inflow of fresh air to the zones)

\[ \mathbf{q}_s = \mathbf{Q}(1) \]  

(A2)

where \( (1) \) is the unity column vector (all elements equal 1)

The row sums of the \( \tau \) matrix yield the air mean age vector \( \overline{\tau} \)

\[ \overline{\tau} = \tau(1) \]  

(A3)

where the \( \tau \) matrix can be written

\[ \tau = \mathbf{Q}^{-1} \mathbf{V} \]  

(A4)

The steady state concentrations (at constant emission rate \( \mathbf{m} \)) can be obtained from eq. A1.

\[ \mathbf{Q} \mathbf{C}_\infty = \mathbf{m} \]  

(A5)

A similar equation can be written for the total time integrated pulse responses \( \mathbf{I} \) after pulses with amounts \( \mathbf{m} \)

\[ \mathbf{Q} \mathbf{I} = \mathbf{m} \]  

(A6)

where

\[ \mathbf{I} = \int_0^\infty \mathbf{C} \, dt \]  

(A7)

Decay technique

At \( \mathbf{m} = 0 \) eq. A1 and A4 give

\[ \mathbf{V} \frac{d\mathbf{C}}{dt} = -\mathbf{Q} \mathbf{C}; \quad \mathbf{Q}^{-1} \mathbf{V} \frac{d\mathbf{C}}{dt} = -\mathbf{C}; \quad \tau \frac{d\mathbf{C}}{dt} = -\mathbf{C} \]  

(A8)

Integrating both sides and using \( \mathbf{C}_0=\mathbf{C}_0(1) \) and \( \mathbf{C}_\infty=(0) \) gives

\[ -\tau(\mathbf{C}_\infty - \mathbf{C}_0) = \tau \mathbf{C}_0(1) = \mathbf{C}_0 \overline{\tau} = \int_0^\infty \mathbf{C} \, dt \]  

(A9)

\[ \overline{\tau} = \frac{\int_0^\infty \mathbf{C} \, dt}{\mathbf{C}_0} \]

Step-up technique

If the tracer injection rates are proportional to the supply rate of air to the zones

\[ \mathbf{m} = k \mathbf{q}_s = k \mathbf{Q}(1) \]  

(A10)

which yields a uniform final concentration in the whole system of \( \mathbf{C}_\infty=k \)

\[ \mathbf{V} \frac{d\mathbf{C}}{dt} = -\mathbf{Q}(\mathbf{C} - k(1)); \quad \tau \frac{d\mathbf{C}}{dt} = (\mathbf{C}_\infty(1) - \mathbf{C}) \]  

(A11)

Integration yields:

\[ \tau(\mathbf{C}_\infty - \mathbf{C}_0) = \int_0^\infty (\mathbf{C}_\infty(1) - \mathbf{C}) \, dt \]  

(A12)

Using conditions \( \mathbf{C}_0 = (0) \quad \mathbf{C}_\infty = \mathbf{C}_\infty(1) \)

\[ \tau(1) = \overline{\tau} = \frac{\int_0^\infty (\mathbf{C}_\infty(1) - \mathbf{C}) \, dt}{\mathbf{C}_\infty} \]  

(A13)
Homogeneous emission:

If the tracer injection rates are proportional to the zone volumes

\[ m = kV(1) \quad (A14) \]

Eq. A5 gives:

\[ QC_{\infty} = kV(1); \quad Q^{-1}V(1) = \frac{1}{k}C_{\infty} \]

\[ \tau(1) = \bar{\tau} = \frac{1}{k}C_{\infty} \quad (A15) \]

Homogeneous pulse

If the injected amounts are proportional to the zone volumes

\[ m = kV(1) \quad (A16) \]

Eq. A6 gives:

\[ QI = kV(1); \quad Q^{-1}V(1) = \frac{1}{k}I \]

\[ \tau(1) = \bar{\tau} = \frac{1}{k}I \quad (A17) \]

It has also been shown by Stymne & Boman (1998) that it is not necessary to inject the pulses simultaneously for eq. A17 to hold.

Inlet pulse technique

If the injected amounts are proportional to the delivery rate of outside air to the different zones

\[ m = kQ(1) \quad (A18) \]

Eq. A6 gives:

\[ I = \int Cdt = k(1) \quad (A19) \]

Thus all integrated responses are similar and equal to k. The mean age vector can obviously not be obtained using a simple integration of the pulse responses in this case. It is necessary to go to the basic equation A1 and solve for the "first moment" of the pulse responses.

It is assumed here that the injection time is infinitesimally short and that the delivered tracer gas is immediately mixed into the zones to which they are delivered.

Immediately after the injection the zone concentrations will then be given by eq. A1 with

\[ V \frac{dC}{dt} = -QC; \quad \tau \frac{dC}{dt} = -C \quad (A20) \]

Multiplying by t and integrating both sides yields:

\[ \tau \int_{t_0}^{t_\infty} tdt = -\int_0^{t_\infty} tCdt \quad (A21) \]

where \( \int_0^{t_\infty} tCdt \) is called the "first moment of the concentration"

Integrating by parts, the left hand integral can be written:

\[ \int_{t_0}^{t_\infty} tCdt = t_2 C_2 - \int_{0}^{t_\infty} Cdt = \int_{0}^{t_\infty} Cdt \quad \text{as} \quad C_2 \to (0) \quad \text{at large} \quad t \quad (A22) \]

Using eq. A19

\[ \tau \int_0^{t_\infty} Cdt = \bar{\tau} \int_0^{t_\infty} Cdt \]

\[ \tau(1) = \bar{\tau} = \frac{\int_0^{t_\infty} Cdt}{k} \quad (A23) \]