Ventilation Measurements Combined with Pollutant Concentration Measurements Discriminates Between High Emission Rates and Insufficient Ventilation

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ABSTRACT

High local concentrations of a pollutant can be the result of high local emission rates of the pollutant or insufficient ventilation. Using tracer gases to map the ventilation in multi-zone buildings combined with measurements of the local pollutant concentration provide the means to discriminate between these causes. In a similar manner, the propagation rate of pollutants from a source to a target zone and the emission rate of the pollutants at the source may be determined quantitatively.

The paper presents both the theoretical framework for the techniques and experimental examples of the proposed methods.

KEYWORDS

Tracer gas, PFT, ventilation measurements, multi-zone model, pollutant emission rates.

INTRODUCTION

Tracer gases are commonly used to study the ventilation and air distribution in buildings. In addition, they may also be used to simulate contaminant emission in buildings. Monitoring the dispersion of a tracer gas can yield valuable information on the expected pattern of contaminant transport. Due to the possibility of controlling the distribution of emission rates, tracers can be used as reference substances when studying concentrations of contaminants from indoor sources.

Some questions which may arise when investigating the indoor air quality are:

1. How much contaminant is transported from a source in one room into another room?
2. Is a high concentration of a contaminant due to a high emission rate of the contaminant or due to insufficient ventilation?
3. How large is the average area specific emission rate ($\mu g \cdot m^{-2} \cdot h^{-1}$) of a contaminant from an emitting building material?

In order to use tracer gases to study the behaviour of air-borne contaminants, the tracers must mimic the behaviour of the contaminants. The tracer should adsorb to indoor materials and be transported by air movement in a similar manner as the contaminant. Consequently, most gaseous contaminants may be studied, whereas particulate contaminants (e.g. dust) cannot be expected to be transported like a

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tracer gas.

The multi-zone approximation(Sandberg and Sjöberg 1983, Sandberg 1984, Etheridge and Sandberg 1996) provides a theoretical framework for using tracer gases as simulated contaminants. In this theory some simplifying assumptions are adopted. The most important assumption is that the building space can be subdivided into fully mixed subspaces, called zones, in which both the tracer and the contaminant are uniformly distributed. Another assumption is that a steady state condition is present, i.e. transient conditions are not included.

In the present paper we propose some techniques which all have their origin in the multi-zone theory. In the theory section the necessary theoretical tools and concepts are presented. Subsequently the methods of the experiments are presented, followed by some experimental results illustrating the ventilation and the proposed techniques. The paper ends with some concluding remarks.

Theory

In the multi-zone theory the building is subdivided into zones numbered from one to *N*, each assumed to be in a fully mixed state. This means that there are no local differences in the concentration of a contaminant within a zone *i*, regardless of how the contaminant is released into or transferred to that zone. However, no assumption is made about mixing between zones. Furthermore, the ventilation of the building is assumed to be in a steady state in the treatment that follows.

For simplicity, we will only consider constant emission rates $\dot{m}_i$ from sources of an arbitrary contaminant in zone *i*. The steady state solution to the mass balance equation in matrix form may then be expressed as (Etheridge and Sandberg 1996)

$$\mathbf{c} = \mathbf{Q}^{-1}\dot{\mathbf{m}} \qquad (1)$$

where $\mathbf{c}$ and $\dot{\mathbf{m}}$ are column vectors with entries c_i (the steady state concentration in zone *i*) and $\dot{m}_i$, respectively. The inverse of the volumetric flow air transport matrix $\mathbf{Q}^{-1}$ has entries P_{ij}/U_i, where P_{ij} is the transfer probability and U_i is the purging flow rate.

Transfer probability

The transfer of contaminants from a zone *j* into another zone *i* is conveniently characterized by a transfer probability P_{ij}. The transfer probability describes the probability that a contaminant released within a zone *j* will eventually appear in zone *i* on its path out of the building. Note that $P_{ii} = 1$, which means that the transfer probability of contaminants directly emitted in zone *i* trivially equals to unity.

Purging flow rate

The purging flow rate U_i is the amount of supplied “fresh” ventilation air to the building which is effective in diluting contaminants supplied to a specific zone *i*. In the simple case of a single chamber experiment, the purging flow rate reduces to the direct flow rate of fresh air supplied into the chamber and eq. 1 gives the purging flow rate to be

$$U = \dot{m}/c \,, \tag{2}$$

which could also be considered as the definition of purging flow rate in this simple case(Etheridge and Sandberg 1996). In a multi-zone building, the total supply rate of ventilation air to a zone *i* is also composed of contributions from ventilation air supplied to other zones and transported to zone *i*. Using the concept of transfer probability the purging flow rate can be expressed as

$$U_i = \sum_j P_{ij} q_{js} \tag{3}$$

where q_{js} is the air supplied from the surrounding to zone *j* of the building. The maximum value of the purging flow rate is the total ventilation flow rate supplied to the building(Sandberg 1984, Etheridge and Sandberg 1996).

Total supply rate of contaminant

The total supply rate S_i of contaminants into a zone *i* is, in addition to the direct supply, composed of contributions from all other zones in exchange flow contact with zone *i*. Therefore, it becomes

$$S_i = \sum_j P_{ij} \dot{m}_j \tag{4}$$

Steady state concentration

Using eqs 3 and 4, the matrix eq 1 can be expressed in component form where the steady state concentration c_i of a contaminant in a zone *i* is determined by the quotient between the total supply rate of contaminant into zone *i* and the purging flow rate in that zone

$$c_i = S_i / U_i \,. \tag{5}$$

Transport between zones and equivalent flow rate

In order to address transport between zones the first step is to determine the purging flows and the mutual transfer probabilities between two zones. One technique to do this is to place sources with known emission rates of a tracer gas A in the source zone *i* and of tracer gas B in the target zone *j* and then to measure the concentrations of both A, B in both zones. The purging flows and the transfer probabilities are then given by

$$U_i = \dot{m}_i^A / c_i^A \quad , \quad U_j = \dot{m}_j^B / c_j^B \tag{6}$$

and

$$P_{ij} = c_i^B U_i / \dot{m}_j^B \quad , \quad P_{ji} = c_j^A U_j / \dot{m}_i^A \,, \tag{7}$$

respectively. If more zones are of interest, we proceed similarly by adding a new type of tracer gas for each new zone added.

In the two zone case, it may also be illustrative to ask what the equivalent virtual flow rate between the zones would be if they were directly connected by a virtual duct rather than via the multi-zone building. These equivalent virtual flow rates are given by

$$q_{ji}^{eq} = P_{ji}\dot{m}_i^A / c_i^A \quad , \quad q_{ij}^{eq} = P_{ij}\dot{m}_j^B / c_j^B \, . \tag{8}$$

Determining the rate of emission and transport of a contaminant source in a single zone

The case where a contaminant C is emitted at an unknown rate from a source in a single zone *i* can be resolved in the following manner: Place sources of tracer gas A in zone *i* and then measure the concentration of A and C in zone *i*. The contaminant emission rate using eq 6 is then given by

$$\dot{m}_i^C = c_i^C U_i = \dot{m}_i^A c_i^C / c_i^A \, . \tag{9}$$

By placing sources of tracer B in a target zone *j* and measuring the concentration of A and B (and optionally C) in zone *j* yields the rate of supply to zone j from zone *i* using eqs 6, 7 and 9 as

$$S_j^C = P_{ji}\dot{m}_i^C = \frac{c_j^A U_j c_i^C U_i}{\dot{m}_i^A} = \dot{m}_j^B \frac{c_i^C c_j^A}{c_i^A c_j^B} \, . \tag{10}$$

Measuring the concentration of C provides a consistency check since $c_j^C = S_j^C / U_j$.

Determining the rate of emission and transport of a contaminant source in a two or more zones

The case where a contaminant C is emitted at an unknown rate from sources in two zones *i* and *j* can be resolved as follows: Place sources with known emission rates of a tracer gas A in zone *i* and of tracer gas B in zone *j* and then measure the concentrations of A, B and C in both zones. The contaminant emission rates are then obtained by

$$\dot{m}_i^C = \frac{c_i^C U_i - P_{ij} c_j^C U_j}{1 - P_{ij} P_{ji}} \, , \tag{11}$$

where m_j^C is obtained by switching the indices from *i* to *j* , and vice versa. Eqs 6 and 7 can then be used to express all variable in terms of known variables. The extension to three or more zones is straightforward. However, a practical problem may arise with compounding uncertainties as the number of measured variables is increased.

With this technique, we can address the second question in the introduction, since it is possible to discriminate between high emission rates and insufficient ventilation as the cause of high concentrations of contaminants. Furthermore, zones with high emission rates may be traced. This could be very valuable information in sanitation projects.

Determining the average area specific emission rate of contaminant in several zones

Sometimes the source of a contaminant is known, e.g. floor coverings emitting 2-ethylhexanol, and the emission is expected to be proportional to the exposed area of the source. In such case it is possible to utilize tracer emission as a reference in order to estimate the average area specific emission rate of the contaminant $k_C = \dot{m}_i^C / A_i$, where A_i is the area of the material emitting the contaminant in zone *i*.

This is achieved by placing sources of a tracer gas A with emission rates proportional to A_i in all

zones, i.e. $\dot{m}_i^A = k_A A_i$, and measuring both the tracer concentration and the contaminant concentration in one or several places. The ratio between the concentrations of contaminant and tracer will then be equal to the ratio between the area specific emission rates of contaminant and tracer

$$\frac{c_i^C}{c_i^A} = \frac{S_i^C}{S_i^A} = \frac{k_C \sum_j P_{ij} A_j}{k_A \sum_j P_{ij} A_j} = \frac{k_C}{k_A} . \qquad (12)$$

The advantage of this technique is that only one type of tracer gas sources is required, even though emitting sources are located in several zones. If the tracer gas emission rates would instead be proportional to zone volumes in each zone, the steady state concentration of tracer in any zone *i*, will be proportional to the "local mean age of air" $\bar{\tau}_i$ in that zone. This relation forms the basis for the so called "homogeneous emission technique" for measuring ventilation conditions in buildings(Stymne and Boman 1998, Stymne and Boman 1994).

Method of experiments

Test building

The experiment is performed in an indoor test house at the ventilation laboratory at University of Gävle in Sweden (see Figure 1). The building space is subdivided into five zones.

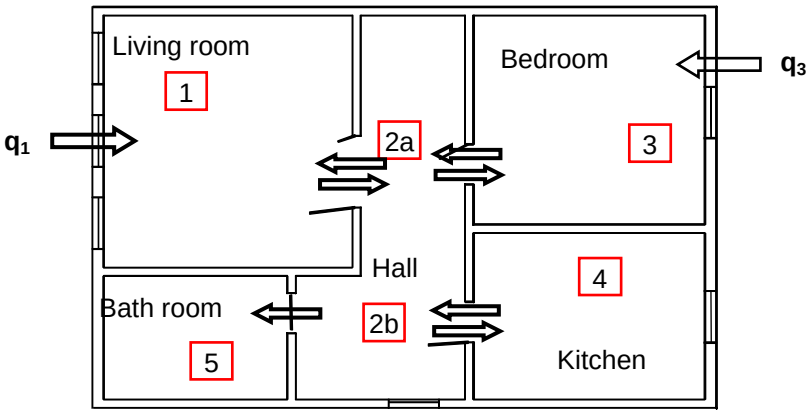
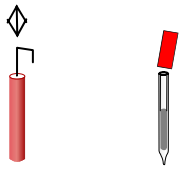


Figure 1. Plan of the test house used in the experiments

The test house extract ventilation is set up to yield extract flow rates of 12 l/s in the kitchen and 12 l/s in the bathroom. The supply air is introduced via an opening above the windows in the living room and in the bedroom. In the present setup, the supply rates to the living room is 12-13 l/s, to the bedroom is 8-9 l/s, and the leakage supply rates to the other rooms is approximately 1 l/s(Blomqvist 2007). The total volume of the test house is 175 m^3.

Tracer gases

For tracer gas emission we have chosen to use passive tracer gas sources. Two different perfluorocarbon tracers (PFTs) were used, perfluorobenzene (tracer A) and perfluorotoluene (tracer B). These two PFTs are commonly used in measurement of ventilation in buildings. The emission rates from the tracer sources can easily be adjusted (see Figure 2a). Air samples for analysis are taken on SKC charcoal adsorption tubes (see Figure 2b) using a calibrated sampling pump. Captured amounts of tracers are measured using liquid extraction and subsequent GC/ECD analysis.



Figur 2. a) Adjustable passive tracer gas source b) charcoal adsorption tube used for pumped sampling of PFTs.

Results, analysis and discussion

In this paper, only preliminary results using two tracer gases are presented. Validation of the proposed techniques with a simulated contaminant will be presented in a future work.

Local mean age of air

A good starting point in investigations of multi-zone ventilation is to map the local mean age of air in the zones (see Table 1). In this experiment, tracer gas A sources with emission rates proportional to the room volumes were used. The total average local mean age of air is approximately two hours corresponding to an air change rate ACH=0.5 h^{-1}, which is reasonable at the present conditions.

Table 1 Local mean ages of air

Zone	$\bar{\tau}$ •h^{-1} (Door 5 closed)	$\bar{\tau}$ •h^{-1} (Doors 3 and 5 closed)
1. Kitchen	2.63	2.65
2. Hall	2.34	2.11
3. Bedroom	1.93	1.65
4. Living room	1.90	1.84
5. Bathroom	2.36	2.40

Transport between bathroom and bedroom

Tracer gas A and B sources were placed in the bathroom and bedroom, respectively. The concentrations of A and B were measured in both zones and eqs 6-8 are used to evaluate the transport pattern (see Table 2)

Table 2 Transport between bathroom (5) and bedroom (3)

	Doors open	Door 5 closed
U_3	57.2 m^3•h^{-1}	52.7 m^3•h^{-1}
U_5	44.2 m^3•h^{-1}	22.6 m^3•h^{-1}
P_{35}	0.15	0.00
P_{53}	0.59	0.41
q_{35}^{eq}	6.0 m^3•h^{-1}	0.0 m^3•h^{-1}
q_{53}^{eq}	33.9 m^3•h^{-1}	21.8 m^3•h^{-1}

Upon closing the bathroom door the purging flow in the bathroom is halved. Approximately 60% of the bedroom air eventually exit the building through the bathroom fan as shown by P_{53}. When the bathroom door is closed 40% still exits through the bathroom. The backflow from the bathroom to the bedroom is fairly small and ceases completely upon closing the bathroom door. The equivalent flow from the bedroom to the bathroom is the flow rate required to match the supply rate of B to the bathroom given the concentration of B in the bedroom. Clearly, a substantial flow rate is needed. The concentration of B in the bedroom is also dissipated to other rooms as well. Thus, the concentration of B is lower than it would be if the bedroom and bathroom would be a “true” two-zone system as assumed in the calculation of the equivalent flow rate.

Transport between kitchen and living room

Tracer gas A and B sources were placed in the living room and kitchen, respectively. The concentrations of A and B were measured in both zones and eqs 6-8 are used to evaluate the transport pattern (see Table 3).

Table 3 Transport between kitchen (1) and living room (4)

	Doors open	Door 4 closed
U_1	42.5 $m^3 \cdot h^{-1}$	71.9 $m^3 \cdot h^{-1}$
U_4	67.4 $m^3 \cdot h^{-1}$	23.1 $m^3 \cdot h^{-1}$
P_{14}	0.19	0.00
P_{41}	0.88	0.91
q_{14}^{eq}	5.0 $m^3 \cdot h^{-1}$	0.0 $m^3 \cdot h^{-1}$
q_{41}^{eq}	37.3 $m^3 \cdot h^{-1}$	21.0 $m^3 \cdot h^{-1}$

In this case. most of the air from the living room eventually exit through the kitchen fan. Interestingly, the fraction increases when the living room door is closed, whereas the purging flow in the living room is reduced as expected since the bedroom influx does not contribute. In a similar manner as the above case, the back flow from the kitchen to the living room is small and ceases as the door is closed. Note that the equivalent flow from the living room to the kitchen closely matches the purging flow when the living room door is closed.

As evident from the plan of the building in Figure 1, the ventilation flows appear to cross in the hall where one flow mainly from the bedroom cross the stronger flow from the living room to the kitchen.

CONCLUSIONS

Techniques for measuring emission rates of contaminants in multi-zone buildings have been derived using multi-zone theory. By using PFT tracer gases to map the ventilation flows, ventilation effects can be removed from the local concentrations of contaminants to yield the emission rates of contaminants. The latter is obviously more interesting when sources of contaminants are to be located, whereas the former is often used in practice. The advantage of the proposed techniques compared to conventional PFT techniques is that “true” emission rates of contaminants from building materials may be determined in situ. The techniques presented here could therefore be of use in sanitation projects. The

validation of the techniques will be presented in a future work.

Preliminary experiments have been performed to analyze the ventilation in the building that will be used for the validation experiments. The results show that the ventilation of the building could be characterized as an overall cross flow from the living room to the kitchen and from the bedroom to the bathroom.

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