The Role of Ventilation
15th AIVC Conference, Buxton, Great Britain
27-30 September 1994

Determination of Local Mean Ages of Air by the Homogeneous Injection Tracer Gas Technique

H Stymne, C Blomquist, M Sandberg

Department of Built Environment, The Royal Institute of Technology, P O Box 88, S 80102 Gavle, Sweden

Synopsis

The paper describes the application of a new tracer gas technique for studying ventilation. The technique is called the homogeneous injection technique, since it relies on the continuous injection of tracer gas in all parts of a zone-divided ventilated system, with tracer injection rates, which are strictly proportional to the zone volumes. The steady state concentrations of tracer gas in the different zones are proportional to the local mean ages of air. The technique is demonstrated and compared with other tracer gas techniques in an indoor test house with controlled ventilation under different conditions of air mixing and door opening.

It is shown that the homogeneous injection technique is easy to use and has some attractive advantages, compared to the tracer decay technique. It is shown that reliable results are obtained even without artificial mixing of the air.

1. Introduction

There are several different tracer gas techniques available for studying ventilation, all with their advantages and drawbacks. The most useful ventilation concept, when it comes to air quality and contamination control is the local mean age of air. The local mean age of air tells us how long the air in a local volume has spent on average in the building. A long mean age means that contaminants emitted in the building have accumulated to high concentrations, while a low mean age means a well ventilated space. By mapping the mean age of air in a building, one gets a measure of the distribution of ventilation air. The conventional technique for studying the mean age of air is the tracer gas decay technique. However, there are several drawbacks to the decay technique - the most obvious being: difficulty in achieving a uniform initial tracer gas concentration in a multi-room building, a time-consuming measurement of decay in several rooms and difficulty in following the time dependence of the local mean ages.

Recently a new tracer gas measurement technique (homogeneous emission technique - HET) for studying ventilation was presented by Stymne et al. (1992). This technique relies on the fact that the local steady state concentration of a contaminant, which is homogeneously emitted in a ventilated space is proportional to the local mean age of air. This has been shown in several papers by Sandberg (e. g. 1981, 1984) and has also recently been used for computing distribution of local mean ages from computational fluid dynamics simulations (Han 1992). However, the relationship between the local concentration and the local mean age of air had not been suggested as a basis for ventilation measurement with homogeneously emitted tracer gas until Stymne and Säteri (1991) discussed it in connection with future development of the passive tracer gas technique and Stymne *et al* (1992) demonstrated it, using a passive tracer gas technique in a large laboratory hall. The homogeneous emission technique has recently been validated in a field trial using adjustable passive tracer gas sources (Stymne and Boman, 1994).

In the present paper the technique is demonstrated in an indoor test house, using homogeneous injection of nitrous oxide tracer gas and continuous measurement of the tracer gas concentration. Comparison is made with the tracer decay technique and the constant concentration technique.

2. Theory

Ideally homogeneous injection means that tracer gas should be injected from continuously distributed sources in all parts of the ventilated system, at a constant rate per cubic meter. Perfectly homogenous injection is therefore not practically possible. In the practical application, the system is sub-divided into smaller zones, in each of which tracer gas is injected at a rate, which is proportional to the zone volume. In multi-room environments it is most practical to use rooms of ordinary size as zones, while larger rooms may have to be further divided into several zones. The mixing within a single room is usually good enough compared to the mixing between rooms, to be useful for treatment with the multi-zone theory. In the multi-zone theory the zones are treated as fully mixed (uniform tracer gas concentration), while concentration differences can appear between zones.

In the multi-zone theory the concentration vector $\mathbf{C}$, whose elements are the steady state concentrations in the different zones is:

$$\mathbf{C} = \mathbf{Q}^{-1}\dot{\mathbf{m}} \tag{1}$$

where $\mathbf{Q}^{-1}$ is the so called inverse flow matrix and $\dot{\mathbf{m}}$ is the tracer gas emission rate vector. The mean age vector $\overline{\boldsymbol{\tau}}$ is obtained from the $\mathbf{Q}^{-1}$ matrix and the volume vector $\mathbf{V}$:

$$\overline{\boldsymbol{\tau}} = \mathbf{Q}^{-1}\mathbf{V} \tag{2}$$

If the emission rates are proportional to the zone volumes:

$$\dot{\mathbf{m}} = k \cdot \mathbf{V} \tag{3}$$

the concentrations are proportional to the local mean ages of air:

$$\mathbf{C} = k \cdot (\mathbf{Q}^{-1}\mathbf{V}) = k \cdot \overline{\boldsymbol{\tau}} \tag{4}$$

and the local mean age of air in a zone $\overline{\tau}_p$ can be calculated from the tracer gas steady state concentration:

$$\overline{\tau}_p = \frac{C_p}{k} \tag{5}$$

3. Experiment

3.1 Experimental house

The experiment was carried out in an indoor test house in a laboratory. The house (fig. 1) has five "rooms" - living room, bedroom, hall, kitchen and bathroom. The south wall of the test house is an exterior wall, while the other walls are directed towards the laboratory hall.

In this experiment the house was mechanically extract-ventilated at an air change rate of 1 ACH. The total extract flow rate of 176 m^3/h was equally divided between the extract points in the kitchen and the bathroom. Air was admitted through inlet devices in the walls in the living room (outside air) and bedroom (laboratory air). Some air may also infiltrate into the other rooms from the laboratory hall. The rooms were equipped with oscillating mixing fans (one in each room and two in the living room) directed towards the centre of the rooms away from doorways.

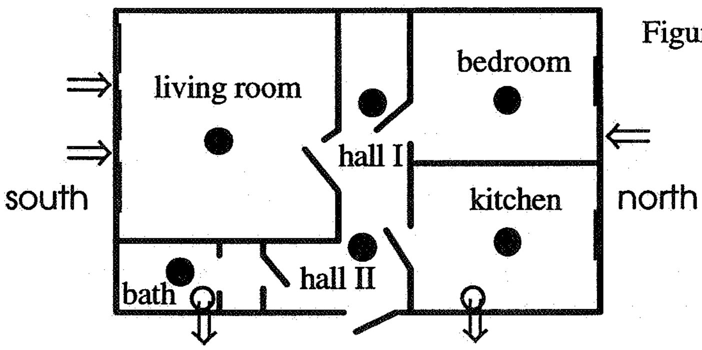


Figure 1. Indoor experimental house

3.2 Experimental layout

Measurements were made during the following conditions:

a) internal doors open (except bathroom)	mixing fans off
b) internal doors open -"-	mixing fans on
c) internal doors closed	mixing fans off
d) internal doors closed	mixing fans on

Tracer gas injection points were at the floor level in the middle of each room. The hall was divided into two zones (hall I and hall II) each with its own tracer gas injection point. The air sampling points were positioned at a height of 1.2 m in the middle of each room (zone). The following nitrous oxide tracer gas measurement scheme was followed for each experiment:

a) Six hours homogeneous injection, with injection rates proportional to the zone volumes.
b) four hours decay period
c) four hours constant concentration period
d) four hours decay period

Continuous measurement of tracer gas concentration at all six measurement points was made during each experiment with a sampling cycle period of approximately 7 minutes.

3.2.1 Homogeneous injection

The approximate injection rates used in the different zones are given in table 1.

Table 1. Approximate injection rates

room	liv. room	bedroom	hall I	hall II	kitchen	bathroom
rate g/h	26.2	15.3	7.9	7.9	16.0	5.0
g/(h,m^3)	0.47	0.43	0.44	0.44	0.46	0.33

As can be seen, the emission rates per cubic meter are not exactly equal in all zones. In most zones, this depends on the difficulty in programming an exact rate, while in the bathroom it depends on a calculation error.

3.2.2 Constant concentration

During the constant concentration period the target value was chosen to be 50 ppm.

4. Measurement

The tracer gas measurement and injection was made using a Brüel & Kjær infrared analyzer model 1302 and dosing and sampling unit model 1303, which was programmed to perform all the steps in a measurement cycle, one after the other. The dosing and sampling were made by use of 4 mm polyethylene tubes. During injection the Brüel & Kjær equipment mixes the tracer gas with air in order to avoid density differences between the injected tracer gas and the air. The equipment was checked against a calibration gas mixture (96 ± 2 ppm N_2O in nitrogen), and showed 92.5 ppm. No correction was made for the discrepancy.

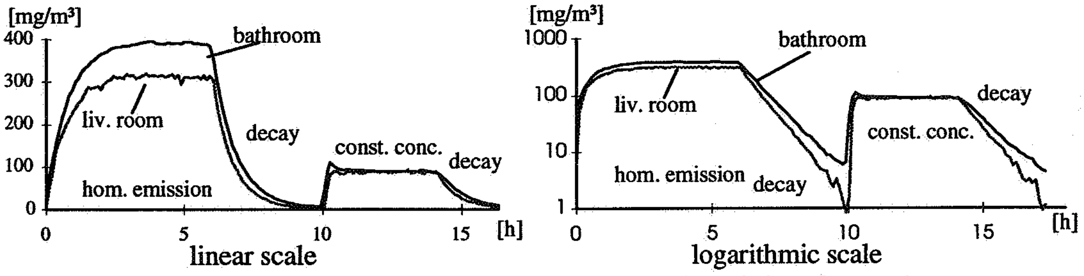


Figure 2. Example of measurement cycle (doors closed - mixing fans on)

5 Calculations

5.1 Mean age of air

5.1.1 Homogeneous emission technique

The time averaged local tracer concentration C_p (mg/m^3) from 3 to 6 hours after the beginning of the injection is calculated for all six measuring points. The total injection rate (mg/h) in the house is calculated and divided by the total volume (176 m^3) to get the average specific injection rate per cubic meter S_t. The local mean age of air is computed through division of the average local concentration with the specific emission rate S_p.

$$\bar{\tau}_p = C_p / S_p \tag{6}$$

S_p is a corrected value of S_t, in order to make a correction of any (small) deviation of local specific injection rate from the average value. It is not possible to make a proper correction for different specific injection rates in the different zones, because this would require knowledge of transfer probabilities between different zones. Here a simplified approach is adopted. Of the excess (or deficit) injection rate in a zone (V_iS_i-V_iS_t), only a volume weighted part (V_i/V_t) is accounted for in that specific zone. Therefore:

$$S_p = S_t + \frac{V_i}{V_t}(S_i - S_t) \tag{7}$$

5.1.2 Constant concentration technique (CCT)

The average dose $\dot{m}_p$ and the average concentration C_p in each zone is calculated for the constant concentration period. The local air supply rate is calculated from:

$$q_p = \dot{m}_p / C_p \tag{8}$$

5.1.3 Decay technique (DT)

The lowest "noisy" part of the decay curve is cut off. The last exponential part of the remaining decay curve is extrapolated to infinity. The area under the curve from the beginning of the decay until the cut off value is computed and corrected with the area under the extrapolated exponential part of the curve. The resulting area is divided by the concentration value at the beginning of the decay curve.

5.2 Accuracy

The accuracy of determination of mean age of air with tracer gas technique depends on four different factors:

- equipment calibration
- initial conditions
- bad mixing in a zone
- evaluation error

these factors are further discussed in the **appendix**.

Table 2 gives approximate estimates of the relative uncertainties, which are taken from informed guesses, equipment data and experimental data for the kitchen in the present experiment. The total inaccuracy of mean age determination is calculated from the square root of the sum of squares of the individual components.

Table 2. Estimated relative uncertainties (in %) from different components

	--------doors open--------				--------doors closed--------			
	---no mix---		----mix----		---no mix---		----mix----	
	HET	DT	HET	DT	HET	DT	HET	DT
calibration	5	3	5	3	5	3	5	3
initial	5	5	5	5	5	5	5	5
mixing	8	8	3	3	3	3	1	1
evaluation	2	11	1	1	1	2	-	2
total	11	15	8	7	6	7	7	6

The uncertainty of the "mixing" component is the relative standard deviation of the concentration during constant emission, which is thought to also reflect the spatial uncertainty in concentration. The "evaluation" component is the relative standard deviation of the concentration divided by the square root of the number of measurements for the homogeneous emission. For the decay technique this component is firstly the inaccuracy in the initial value (which is the standard deviation during the last part of the constant concentration period divided by two) and secondly the inaccuracy of the determination of the area under the first minutes of decay. The "calibration" and "initial" components are reasonable estimates.

6 Results

6.1 Local mean ages of air

The results from the measurements are shown in table 3 and figure 3.

Table 3. Local mean ages of air measured by different techniques.

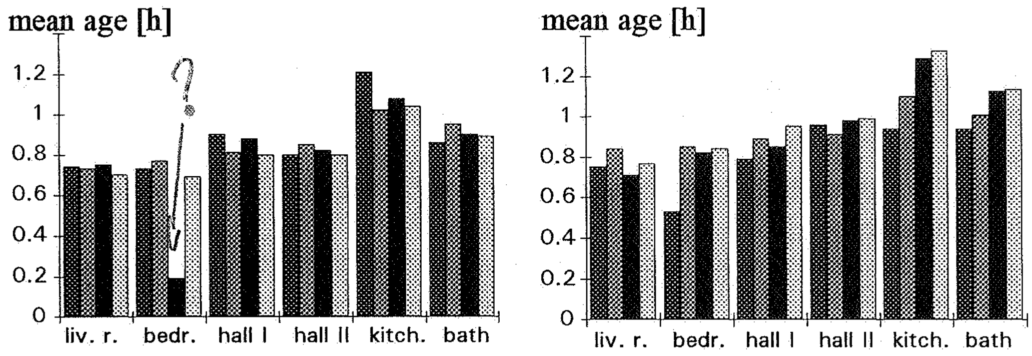
HET=homogeneous emission technique, DT=decay technique

	liv. room	bed room	hall I	hall II	kitchen	bath	aver. age	extract age
volume[m^3]	55.8	36	17.8	18	34.7	13		
	Doors open - no mixing							
HET [h]	0.74	0.73	0.90	0.80	1.21	0.86	0.86	1.04
DT [h]	0.75	0.53	0.79	0.96	0.94	0.94	0.78	0.94
	Doors open - mixing							
HET [h]	0.73	0.77	0.81	0.85	1.02	0.95	0.83	0.98
DT [h]	0.84	0.85	0.89	0.91	1.10	1.01	0.92	1.06
	Doors closed - no mixing							
HET [h]	0.75	0.19	0.88	0.82	1.08	0.90	0.73	0.99
DT [h]	0.71	0.82	0.85	0.98	1.29	1.13	0.92	1.21
	Doors closed - mixing							
HET [h]	0.70	0.69	0.80	0.80	1.04	0.89	0.80	0.97
DT [h]	0.77	0.84	0.95	0.99	1.33	1.14	0.96	1.24

The average age in the house is calculated from a volume averaged mean of all the local mean ages. The mean age of the extract air corresponds to the nominal time constant and is computed from the mean ages in the extract rooms, weighted with the nominal extract flow rates in those rooms.

6.2 Air distribution patterns

As can be seen in figure 3 there are many similarities between the mean age distribution patterns determined with the two techniques. There is however a tendency for the mean ages determined by the decay technique to be slightly higher, and have a greater variation between the different experimental conditions than those determined by the homogeneous injection technique. It is obvious that the estimated mean ages are not greatly affected by the experimental conditions (door and mixing status). There are two striking exceptions, both occurring in the bedroom. These two low values are obviously erratic. The reason is unknown, but is believed to be caused by an equipment error yielding too low concentration readings. The error does not seem to affect the result in the other zones.



homogeneous emission technique

decay technique

Figure 3. The distribution of mean ages as determined by the two methods. Each group of bars represent a room and the four bars in each group represents from the left to the right a) *open doors - no mixing*, b) *open doors - mixing*, c) *closed doors - no mixing* and d) *closed doors - mixing*.

6.3 Air flow estimates

It is not possible to unequivocally calculate air flow rates from mean ages determined by tracer gas experiments, unless the mean age of the extract air can be measured. However in this controlled experiment, it is known that the extract air is equally divided between the two extract points (kitchen and bathroom). Therefore the mean age of the extract air can be calculated from the average of mean ages of air in the two extract rooms. The total ventilation flow rate can then be calculated from the total volume of the house divided by the mean age of the extract air and compared with the known value (176 m^3/h) or estimates from constant concentration tracer experiment.

It is also possible to calculate the air flow rates in the supply rooms (living room and bed room), when their doors are closed and compare them with estimates made by the constant concentration measurements. Those rooms can be considered isolated, with no inter-zonal flows from the other zones, when their doors are closed. The supply air flow rate in an isolated zone is calculated from the zone volume divided by the local mean age of air. The comparison is shown in table 4.

Table 4. Comparison of air flow estimates with different techniques.

	no mixing				mixing			
			total*				total*	
	liv. room	bed room	doors closed	doors open	liv. room	bed room	doors open	doors close
HET	74	-**	169	177	80	52	178	181
DT	79	44	186	145	72	43	165	141
CCT	69	69	164	175	80	53	176	171

*true total ventilation flow rate is 176 m^3/h, -** obviously erratic value not included

It can be seen that the estimated total ventilation flow rate closely agrees with the true value in all four cases for the homogeneous injection and the constant concentration technique. The agreement is worse for the decay technique. Also the agreement with the constant concentration determination of supply rates is better for the homogeneous injection technique than for the decay technique.

7 Discussion

The homogeneous emission technique gives essentially the same information on ventilation performance as the tracer decay technique, but has several practical advantages over the latter.

- no demand of a uniform initial tracer concentration, which can be difficult to achieve in multi-room systems.
- a "steady state" technique, which makes it possible to integrate over longer time for increased accuracy.
- possible to monitor variations of ventilation as a function of time.
- easier and more reliable data interpretation and calculation, especially in badly mixed systems.

However there are also some disadvantages:

- long time needed for equilibration before measurement
- adjustable tracer injection units needed for each zone
- continuous injection consumes more tracer gas

All three disadvantages are eliminated using passive tracer gas technique, for which adjustable tracer gas sources are now available. However, further development will also overcome these disadvantages when using "active" techniques. The long equilibration time can for example be appreciably shortened using increased initial injection rates.

8 Conclusions

The homogeneous emission tracer gas technique for measuring local mean ages of air is shown to be easy to use and to yield improved accuracy, compared to the tracer decay technique. The technique has great future potential, either using "active" or "passive" tracer gas techniques and can in most cases substitute the decay technique for ventilation studies.

APPENDIX

Discussion on sources of uncertainty

Equipment calibration
HET: Relative uncertainties in calibration of measurement equipment and injection rate are of importance.
DT: No absolute calibration is necessary, but linearity and zero point deviations are important.

Initial conditions:
HET: Deviation from ideal homogeneous emission rates is important.
DT: Deviation from initial uniform concentration is important

Air mixing:
HET: Bad mixing in a zone results in large variations of concentration as a function of time and may also yield a time averaged concentration at the measuring point which deviates from the room mean value.
DT: Concentration variations due to bad mixing causes difficulty in tracing the true initial value and the important first part of the decay (see evaluation). It may also mean that the measurement point is not representative of the zone.

Evaluation
HET: The inaccuracy in evaluation depends on the standard deviation in the estimate of the time average of the concentration, which is inversely proportional to the square root of measurement time (or number of readings). In the present case it also depends on the inaccuracy in the estimate of injection rates.

DT: There are several difficulties in the evaluation, which cause uncertainties in the estimate of the mean age:

- *extrapolation of measurement from the last measurement point to infinity.* The last part of the curve should always decay exponentially to zero. However, in practice it is often difficult to locate the final exponential part of the curve. A small deviation of the zero setting of the instrument or some background value, will seriously affect the slope of the lowest part of the logarithmic plot of the decay curve. Making a background subtraction afterwards to give a final exponential decay will always be ambiguous.

- Determination of initial concentration

It is very important to get a correct value of the initial concentration since the area under the decay curve is to be divided by this value. This concentration value must be taken before the decay starts, i. e. when there still is a uniform concentration in the whole system. Bad mixing or beginning the decay from a constant concentration measurement (as in the present case) may yield a large uncertainty in the value of the initial concentration.

- Tracing the first part of the decay curve

The differences in the decay in different zones are often concentrated in the first few minutes of decay. After this initial period all curves in a system of coupled zones tend to decay exponentially with the same time constant. A time delay in measurement will make the interpretation of the first part difficult. Even more severe are the concentration fluctuations due to bad mixing in this important part of the decay. Due to the relatively large concentration in the beginning of the decay, this part represents a relatively large portion of the computed area under the decay curve.

Acknowledgements

Financial support from NORDTEST and the Swedish Council for Building Research is gratefully acknowledged.

References

Han H (1992)
"Calculation of ventilation effectiveness using steady-state concentration distributions and turbulent airflow patterns in a half scale office building".
In Murakami *et al.* (editors), Proceedings of the International Symposium on Room Air Convection and Ventilation Effectiveness, Tokyo 1992, pp 187-191.

Sandberg M (1981)
"What is Ventilation Efficiency?"
Building and Environment **16**, pp 123-135, [1981].

Sandberg M (1984)
"The multi-chamber theory reconsidered from the viewpoint of air quality studies"
Building and Environment **19**, 1984, pp 221-233.

Stymne H, Säteri J O (1991)
"The Development of the PFT-Method in the Future."
In Säteri, J.O. (editor): "The Development of the PFT-Method in the Nordic Countries". Swedish Council for Building Research, Document D9:1991, pp 109-120.

Stymne H, Sandberg M and Holmgren O (1992)
"Ventilation Measurements in Large Premises".
Proceedings of Roomvent'92 - Air Distribution in Rooms, Denmark 1992, Vol. 2, pp. 33-47.

Stymne H and Boman CA (1994)
"Measurement of Ventilation and Air Distribution, Using the Homogeneous Emission Technique".
Proceedings of Healthy Buildings '94, International Conference, Budapest, 1994.