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Experimental testing of a homogeneous tracer pulse technique for measurement of ventilation and air distribution in buildings.

by

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SYNOPSIS

A number of single tracer gas techniques (decay, step-up, homogeneous constant emission, inlet pulse and homogeneous pulse) suitable for measuring the local mean ages of air in multi-zone buildings exist, each having their advantages and drawbacks. The characteristics of the different available techniques are compared from theoretical and practical points of view. The homogeneous pulse technique has not been experimentally validated before. This technique relies on pulses of tracer gas being injected into the different zones in amounts, which are proportional to the zone volumes. Some advantages with the "homogeneous pulse" technique, compared with the "inlet pulse" technique, are that the pulses can be injected at any time path, that they must not necessarily be short and that the evaluation of local mean ages of air involves a simple total time integration of concentration, making it possible to utilise integrating air samplers (e. g. adsorption tubes).

The homogeneous pulse technique is tested against the decay technique in a five-room indoor test house, using both automatic and manual injection of tracer gas. It is shown that this technique yields results as accurate as the decay technique. Using manual injection (with syringe), however, requires special caution in order to achieve a uniform distribution of the injection in a room and to avoid redistribution while walking between rooms.

1. INTRODUCTION

1.1 Multizone tracer gas techniques

Most 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:

$$\mathbf{V}\frac{d\mathbf{C}}{dt}+\mathbf{QC}=\dot{\mathbf{m}} \tag{1}$$

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 the instantaneous tracer concentrations in the zones. **Q** is the transport matrix (flow matrix) describing the air flow rates between the different zones. $\dot{\mathbf{m}}$ 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 fully solve for the unknown parameters. There are several solutions to this problem (e. g. Afonso *et al.*. 1986, Axley and Persily 1988a, 1988b, 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

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.

1.2 Single tracer gas techniques for measuring 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 it is a measure of how long the air in the zones in average has spent within the building. 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 in principle possible to determine all mean ages 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 (e. g. Roulet and Cretton 1992).

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

Recently a fourth technique has been described and validated

- Homogeneous constant emission technique (Stymne and Boman 1994, NORDTEST 1997)

In the present paper a fifth technique is presented and experimentally validated:

- Homogeneous pulse technique (Stymne and Boman 1988)

1.3 Requirements and conditions

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.

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

	initial state	**final state**	**injection place**	**injection pattern**	**measure**
Decay	uniform concentration	tracer free		no emission	total time integration
Step-up	tracer free	uniform concentration	air inlets	continuous, proportional to air inflow*	total time integration
Homogeneous constant emission	tracer free	steady state	zones	continuous, proportional to volumes	steady state concentration
Inlet pulse, established	tracer free	tracer free	common air supply	pulse, proportional to air inflow*	first moment integration
Pulse, homogeneous	tracer free	tracer free	zones	pulse, proportional to volumes	total time integration

* 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.

1.4 Practical Aspects

1.4.1 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.

1.4.2 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.

1.4.3 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 (average) steady state concentration may be determined using either pumped or passive sorption sampling tubes.

1.4.4 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 in 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 equals 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.

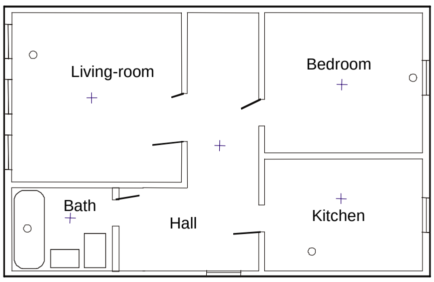
There are also other shortcomings of the pulse technique. One is that only mechanically supplied air is marked with tracer, which introduces an error if infiltration is present. An other is that it may be difficult to inject a sufficient amount of tracer in a very short time to allow the whole time history to be recorded with a satisfactory signal to noise ratio. Errors in the "tail" are amplified when multiplying concentration with 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.

1.4.5 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. The integration may advantageously be performed using either pumped or passive sorption sampling tubes.

2. EXPERIMENTS

In order to validate the homogeneous pulse technique, a number of experiments were performed in full scale in an indoor test house at the Dept. of Built Environment, University of Gävle (Figure 1).

2.1 Test facility



Room volumes in the test house[m^3]

Living room	55
Bedroom	36.25
Hall	36.25
Kitchen	35
Bathroom	12.5
Total	175

Figure 1. *The indoor house test facility. The circle symbols indicate the positions of the air supply (living-room and bed-room) and extract (kitchen and bath). The cross symbols indicate the concentration measurement points.*

The test house was mechanically ventilated with extract ducts in the kitchen and the bathroom. Most air was supplied through openings in the living-room and the bedroom (the latter being closed in experiment C). The extract flows and the status of the internal doors were altered for the different experiments.

2.2 Experimental conditions

Three sets of experiments were performed, each including a homogeneous pulse experiment and a conventional decay under the same circumstances.

2.2.1 Experiment A and B

Extract flows: kitchen 113 m^3/h, bathroom 57 m^3/h

$\Rightarrow$ nominal time constant $\tau_n = V_{tot}/Q_{tot}$ = 1.03 ±0.02 h

Air supply openings: living-room and kitchen

Pulse injection: automatic with 10 minutes interval, using tubes and valves

Tracer gas: N_2O

Door status: Exp. A - all closed, except to kitchen

Exp. B - all closed, except to kitchen and living-room

The tracer (pure N_2O) was injected into the rooms using automatic injection equipment which consists of a computer coupled to a set of electronically positioned valves. The tracer was distributed via narrow (2 mm) tubes to mixing fans in each room. Injections were made in one room after the other at 10 minute intervals. The mixing fans were in operation only during the time of injection. The concentration measurements were performed using a BINOS infrared analyser. Concentration measurements were carried out in each room of the test house and in the supply air. A complete cycle of 6 measurement points needed 3 minutes to be completed. The temperature was 21 – 24ºC during the experiments.

2.2.2 Experiment C

Extract flows: kitchen 47 m^3/h, bathroom 46 m^3/h

$\Rightarrow$ nominal time constant $\tau_n = V_{tot}/Q_{tot}$ = 1.89 ±0.03

Air supply openings: living-room

Pulse injection: manually using syringe

(trial 1 with 2 min. interval, trial 2 quickly)

Tracer gas: SF_6

Door status: all open, except to bathroom

During the manual injection a 25 ml glass syringe with teflon piston was used. The syringe was filled with the required amount of pure SF_6 gas outside the test house. During the injection, a mixing fan was in operation in the room of injection. Effort was made to distribute the tracer as evenly as possible in the room volume. Two trials with manual injections of SF_6 were made, the only difference being that during "trial 1" there was approximately 2 minutes between the injections in the different rooms, while in "trial 2" the pulses were given without any unnecessary delay. The concentration measurements as well as the decay measurements were made using the Brüel&Kjær multi-channel infrared analyser. A complete cycle of 6 measurement points needed approximately 4 minutes to be completed.

3. RESULTS

3.1 Experiment A and B - automatic injection

The results of the automatic injection of N_2O in the different rooms and comparison with decay measurements are shown in table 2. In figure 2 the concentration response and the corresponding time integrals for experiment A are displayed. In the computation any background signal was subtracted.

Table 2. *Pulse data for experiment A and comparison with decay for exp. A and B*

position	room	injected amount N_2O l	injected amount $m^3/m^3 \times 10^6$	time-integral ppm,h	τ from pulse h	τ from decay h	τ from pulse h	τ from decay h
					A	A	B	B
1	liv.room	3.87	69.3	46.3	0.67	0.67	0.95	0.97
2	bedroom	2.50	69.3	67.7	0.98	1.02	1.00	1.02
3	hall	2.49	69.5	64.5	0.93	0.92	1.13	1.06
4	kitchen	2.40	69.3	72.7	1.05	1.07	1.07	1.05
5	bath	0.90	69.2	72.2	1.04	1.09	1.04	1.06
	extract (weighted values for bath and kitchen)				1.05	1.07	1.06	1.06

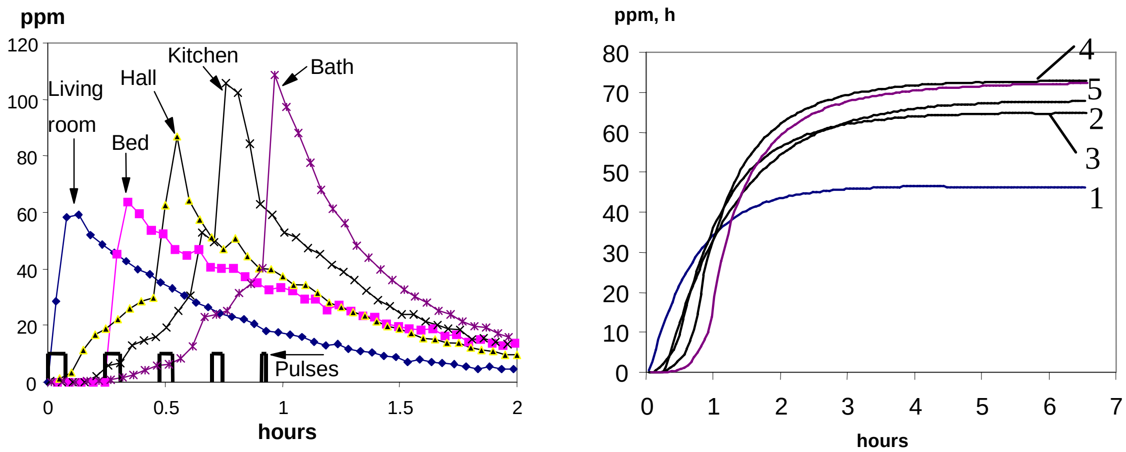


Figure 2. *Display of the concentration and the time integrated response as a function of time* in *experiment A.*

Results from the automatic injection experiments (A and B) show good agreement with results obtained from decay experiments (see table 2). The deviation is highest in the measurement point placed in the hall in experiment B where the pulse method overestimates the local mean age with 6.6 %. The average age in the test house determined by pulse experiments deviates less than 2 % from the average age determined by decay experiments. The extract flow weighted mean ages of the pulse measurements (1.05 and 1.06 [h]) are very close to the determination with the decay technique (1.07 and 1.06 [h]). The nominal time constant as measured with orifice plates in the extract ducts amounted to 1.03 [h]). The deviation is thus less than 4%. This deviation can be compared to the uncertainty in determining the local mean age using the decay method: ± 5 % according to NORDTEST (1988).

3.2 Experiment C - manual injection

The results of the manual injection of SF_6 in the different rooms and comparison with decay measurements are shown in table 3. In figure 3 the concentration response and the corresponding time integrals for trial 1 are displayed. In the computation any background signal was subtracted.

Table 3. *Pulse data for experiment C and comparison with decay.*

position	room	injected amount SF_6 ml	injected amount mg/m^3	time-integral mg,m^{-3},h	τ from pulse h		τ from decay h	
					trial 1	trial 2	trial1	trial 2*
1	liv.room	42	4.65	6.87	1.47	1.40	1.80	1.35
2	bedroom	27.8	4.67	7.49	1.61	1.62	2.10	2.06
3	hall	27.8	4.67	8.80	1.89	1.82	1.91	1.80
4	kitchen	26.8	4.66	8.62	1.85	1.88	1.91	1.93
5	bath	9.6	4.67	8.97	1.94	1.83	1.87	1.85
6	(exhaust)			8.37	1.79	1.81	1.85	1.89

* (mixing fans in operation in each room during decay)

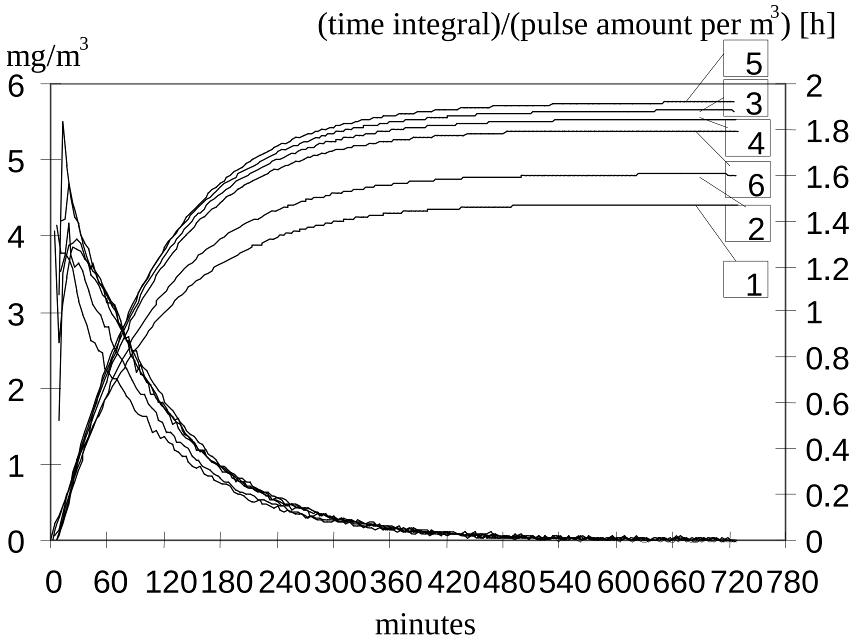


Figure 3. *SF_6 concentration (left scale) and time integrated concentration (right scale) as a function of time in the different rooms. The integrals are normalised with the pulse amount per m^3.*

Both trials with manual injections yielded similar results for the local mean ages of air, not differing more than 5% in any room. The mean of the two local mean ages in the extract rooms (bathroom and kitchen) amounted to 1.89 [h] and 1.85 [h] respectively in trial 1 and trial 2. Both of these values are very close to the nominal time constant 1.89 ±0.03. However, measurements in the common extract yielded 1.79 [h] and 1.81 [h]. This shows somewhat less satisfactory agreement with the known nominal time constant, but still within 5%. Comparison with the decay technique shows a satisfactory agreement for all rooms except the bedroom and the living room. The bedroom has small direct inflow of air in this case.

Although the door is open to the hall, this should result in a relatively large value for the local mean age in the bedroom. The decay technique yields 2.10 [h] (and 2.06) in accordance with the expectations, while the pulse technique yielded only 1.61 [h] (and 1.62) which must be incorrect. The reason for this is not known, but may depend on an uneven inital tracer distribution and especially bad mixing in this room. Nearly all ventilation air is supplied to the living room. Thus, this room should show the lowest mean age of air. Though the two pulse measurements and the decay measurement with mixing fans in operation all show a low mean age (1.47, 1.40 and 1.35 [h] respectively, the decay measurement without mixing shows a strongly deviating mean age of 1.8 [h]. The last value is probably not typical for the room mean value. The reason for this is unclear.

4. DISCUSSION

The agreement between the result of the homogeneous pulse technique and the decay technique is excellent, in the experiments where the pulses are automatically injected via tubes. Using manual injections of tracer gas with a syringe, the agreement was also generally satisfactory, but a discrepancy between the two techniques appeared in one of the rooms. When using the automatic injection, the pulses were given at a rather slow rate from behind a mixing fan, the injection times lasting from 67 seconds in the bathroom to 271 seconds in the living room, and air mixing was performed in the room of injection during the pulse. This procedure probably yielded a good mixing of the tracer into the room air. With the manual procedure on the other hand, injections were made relatively quickly and air mixing was of considerably shorter duration. The high density of the sulphurhexafluorid gas may also have contributed to a less satisfactory distribution of the tracer gas, when using a syringe. There is also a risk, when the injection is made manually, that some of the just injected tracer will redistribute to another room, due to the drag induced, when the person leaves the room.

Using the homogeneous pulse technique is it essential that the injected amount is evenly distributed in the zone. Any bad initial distribution within a zone, will result in a distorted result. Therefore, high density tracer gas should not be injected directly, without mixing with air or another gas to make it buoyant neutral. Furthermore, the tracer should either be directly injected in an even pattern, or measures should be taken to quickly mix the air within the zone during and shortly after an injection.

5. CONCLUSION

It is shown experimentally that the use of the homogeneous pulse technique yields as accurate results as the more established tracer decay technique for determination of local mean ages of air in multi-zone systems . It is however essential when making an injection in a zone, that the injected amount is uniformly distributed within the zone.

Using the homogeneous pulse technique, the initial and final state both have zero tracer concentrations. Together with the fact that injections in the different zones can be made at different times, this is a great advantage in the practical application, because integrating sampling can begin before the first injection is made, and be finished well after the tracer is judged to have disappeared from the building. This opens the possibility of using either pumped or diffusive (passive) air sampling on adsorption tubes, a technique, which is already common when using passive PFT techniques.

6. APPENDIX

6.1 Basic relationsships for multizone tracer techniques

The mass balance equation for the instanteneous 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)

$$\mathbf{V}\frac{d\mathbf{C}}{dt}+\mathbf{QC}=\dot{\mathbf{m}} \qquad \text{(A1)}$$

where

- **C** is the tracer concentration vector
- **Q** is the air transport matrix (flow matrix)
- **V** is the diagonal zone volume matrix
- $\dot{\mathbf{m}}$ is the tracer injection rate vector
- t is the time

The row sums of **Q** yields the air supply vector $\mathbf{q}_s$

$$\mathbf{q}_s = \mathbf{Q}(\mathbf{1}) \qquad \text{(A2)}$$

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

The row sums of the $\boldsymbol{\tau}$ matrix yields the air mean age vector $\bar{\boldsymbol{\tau}}$

$$\hat{\mathbf{o}} = \hat{\mathbf{o}}(\mathbf{1}) \qquad \text{(A3)}$$

where the $\boldsymbol{\tau}$ matrix can be written

$$\hat{\mathbf{o}} = \mathbf{Q}^{-1}\mathbf{V} \qquad \text{(A4)}$$

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

$$\mathbf{QC}_\infty = \dot{\mathbf{m}} \qquad \text{(A5)}$$

A similar equation can be written for the total time integrated pulse responses I after pulses with amounts m

$$\mathbf{QI} = \mathbf{m} \qquad \text{(A6)}$$

where

$$\mathbf{I}=\int_0^\infty \mathbf{C}\,dt \qquad \text{(A7)}$$

6.1.1 <u>Decay technique</u>

at $\dot{m}$=0 eq. A1 and A4 gives

$$\mathbf{V}\frac{d\mathbf{C}}{dt}=-\mathbf{QC};\quad \mathbf{Q}^{-1}\mathbf{V}\frac{d\mathbf{C}}{dt}=-\mathbf{C};\quad \hat{\mathbf{o}}d\mathbf{C}=-\mathbf{C}dt \qquad \text{(A8)}$$

Integrating both sides and using $\mathbf{C}_0$=C_0(**1**) and $\mathbf{C}_\infty$=(**0**) gives

$$-\hat{\mathbf{o}}(\mathbf{C}_\infty-\mathbf{C}_0)=\hat{\mathbf{o}}C_0(\mathbf{1})=C_0\bar{\hat{\mathbf{o}}}=\int_0^\infty \mathbf{C}dt \qquad \boxed{\bar{\hat{\mathbf{o}}}=\frac{\int_0^\infty \mathbf{C}dt}{C_0}} \qquad \text{(A9)}$$

6.1.2 <u>Step-up technique</u>

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

$$\dot{\mathbf{m}}=k\mathbf{q}_s=k\mathbf{Q}(\mathbf{1}) \qquad \text{(A10)}$$

which yields a uniform final concentration in the whole system of $C_\infty=k$

$$\mathbf{V}\frac{d\mathbf{C}}{dt}=-\mathbf{Q}(\mathbf{C}-k(\mathbf{1}));\quad \hat{\mathbf{o}}\frac{d\mathbf{C}}{dt}=(C_\infty(\mathbf{1})-\mathbf{C}) \qquad \text{(A11)}$$

integration yields:

$$\hat{\mathbf{o}}(\mathbf{C}_\infty-\mathbf{C}_0)=\int_0^\infty (C_\infty(\mathbf{1})-\mathbf{C})dt \qquad \text{(A12)}$$

using conditions $\mathbf{C}_0 = (\mathbf{0}) \qquad \mathbf{C}_\infty = C_\infty(\mathbf{1})$: $\boxed{\hat{\mathbf{o}}(\mathbf{1}) = \bar{\hat{\mathbf{o}}} = \frac{\int_0^\infty (C_\infty(\mathbf{1}) - \mathbf{C})dt}{C_\infty}}$ (A13)

6.1.3 Homogeneous emission:
If the tracer injection rates are proportional to the zone volumes

$$\dot{\mathbf{m}} = k\mathbf{V}(\mathbf{1}) \tag{A14}$$

Eq. A5 gives: $\mathbf{QC}_\infty = k\mathbf{V}(\mathbf{1})$; $\quad \mathbf{Q}^{-1}\mathbf{V}(\mathbf{1}) = \frac{1}{k}\mathbf{C}_\infty$; $\boxed{\hat{\mathbf{o}}(\mathbf{1}) = \bar{\hat{\mathbf{o}}} = \frac{1}{k}\mathbf{C}_\infty}$ (A15)

6.1.4 Homogeneous pulse
If the injected amounts are proportional to the zone volumes

$$\mathbf{m} = k\mathbf{V}(\mathbf{1}) \tag{A16}$$

Eq. A6 gives: $\mathbf{QI} = k\mathbf{V}(\mathbf{1})$; $\quad \mathbf{Q}^{-1}\mathbf{V}(\mathbf{1}) = \frac{1}{k}\mathbf{I}$; $\boxed{\boldsymbol{\tau}(\mathbf{1}) = \bar{\boldsymbol{\tau}} = \frac{1}{k}\mathbf{I}}$ (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.

6.1.5 Inlet pulse technique
If the injected amounts are proportional to the delivery rate of outside air to the different zones

$$\mathbf{m}=\mathrm{k}\mathbf{Q}(\mathbf{1}) \tag{A18}$$

Eq. A6 gives: $$\mathbf{I} = \int_0^\infty \mathbf{C}dt = k(\mathbf{1}) \tag{A19}$$

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

$$\mathbf{V}\frac{d\mathbf{C}}{dt} = -\mathbf{QC}\,; \quad \hat{\mathbf{o}}\frac{d\mathbf{C}}{dt} = -\mathbf{C} \tag{A20}$$

multiplication by t and integrating both sides yields:

$$\hat{\mathbf{o}}\int_{t_1=0}^{t_2=\infty} td\mathbf{C} = -\int_0^\infty t\mathbf{C}dt \tag{A21}$$

where $\int_0^\infty t\mathbf{C}dt$ is called the "first moment of the concentration"

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

$$\int_{t_1=0}^{t_2=\infty} td\mathbf{C} = t_2\mathbf{C}_2 - \int_0^\infty \mathbf{C}dt = -\int_0^\infty \mathbf{C}dt \text{ as } \mathbf{C}_2 \to (\mathbf{0}) \text{at large t} \tag{A22}$$

using eq. A19 $\quad \hat{\mathbf{o}}\int_0^\infty \mathbf{C}dt = k\hat{\mathbf{o}}(\mathbf{1}) = \int_0^\infty t\mathbf{C}dt$; $\boxed{\hat{\mathbf{o}}(\mathbf{1}) = \bar{\hat{\mathbf{o}}} = \frac{\int_0^\infty t\mathbf{C}dt}{k}}$ (A23)

7. ACKNOWLEDGEMENT

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